

A wire indent profiling system for the assessment of crosstie bond and splitting propensity

by

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B.S., Kansas State University, 2015

AN ABSTRACT OF A DISSERTATION

submitted in partial fulfillment of the requirements for the degree

DOCTOR OF PHILOSOPHY

Alan Levin Department of Mechanical and Nuclear Engineering
Carl R. Ice College of Engineering

KANSAS STATE UNIVERSITY
Manhattan, Kansas

2025

Abstract

Concrete railroad ties represent a critical component of transportation infrastructure. A majority of concrete crossties are created from prestressed concrete, relying on the interaction between steel tendons, or strands, and the concrete to produce prestressing force in the ties. Inadequate prestressing force or splitting significantly reduces the service life or load bearing capacity of the crossties. Smooth steel tendons do not provide reserve capacity to prestressed members, as any instantiated crack cannot be arrested; therefore, indentations are added to the steel tendons to provide reserve capacity and reduce the distance over which the prestressing force is transferred from the steel tendon to the concrete, defined as the transfer length. The geometry of these indented features significantly impacts the transfer length and splitting propensity of manufactured concrete railroad ties.

Indentation geometry has been shown to have a direct influence on the performance of prestressed members. Thus, it is important to measure critical indent features to ensure that indents are being formed to the right tolerances and provide the desired wire-concrete performance. However, the measurement of such features has proven challenging in practice. Certain standards, namely ASTM A881, outline indent features to measure for quality control for wires of a given size, but fall short of describing how or where measurements will be performed. Such measurements are often done manually, suffer from poor accuracy, and are time consuming. The time-consuming nature of the measurements makes it impractical to sample enough indents to adequately statistically characterize the manufacturing process. Most importantly, the current standards do not identify which features, or combinations of features, contribute to, or reduce, wire-concrete bond performance. It is possible for indented wires to pass the requirements of the measurement standards but fail to produce desirable wire-concrete performance; this is often only discovered after the crossties have been manufactured.

This research addresses the shortcomings of the current measurement standards, identifies which indent features most significantly contribute to wire-concrete performance, and outlines the development of an Indent Profiling System that is capable of extracting all important indent features. An automated, high resolution, non-contact measurement system was created and used to measure dozens of wires from modern industry, historical crossties, and lab specimens with well-defined geometry. This system measures all unique indents formed by a complete revolution of the indent rollers, providing statistically relevant sample sizes that were previously impossible using manual measurements. To identify which wire features, or combinations of features, correlate strongly with performance hundreds of prestressed prisms were created as part of a larger FRA project titled “Developing Qualification Tests to Ensure Proper Selection and Interaction of Pretensioned Concrete Railroad Tie Materials”. These prisms used the same wires that were scanned by the Indent Profiling System and were created with a variety of concrete covers, release strengths, and aggregates to assess wire-concrete performance. The known indent geometry provided by the Indent Profiling System was successfully used in conjunction with the prism tests to identify how geometry influences factors such as transfer length and splitting propensity. Lastly, a new ASTM measurement standard was proposed titled *Standard Practice for Measuring Indented Steel Wire Geometrical Parameters*, providing guidance on how the most important indent features are to be measured, using automated or manual methods, so that results can be repeatable from individual-to-individual or from lab-to-lab. The application of this research will help ensure that poor wire-concrete performance is identified prior to production.

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Major Professor
B. Terry Beck

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List of Abbreviations and Acronyms

AML	American Manufacturing Institute
ASTM	American Society for Testing and Materials
CL	Crack Length
FFT	Fast Fourier Transform
FRA	Federal Railroad Administration
ISO	International Organization for Standardization
KSU	Kansas State University
LSI	Laser Speckly Interference
TDI	Technology Development Institute
TL	Transfer Length
VI	Virtual Interface

Acknowledgements

The author gratefully acknowledges the Federal Railroad Administration (FRA) for providing the funding that made this research possible. The Indent Profiling System was a component of the FRA project “Developing Qualification Test to Ensure Proper Selection and Interaction of Pretensioned Concrete Railroad Tie Materials”. The cooperation and resources provided by Nucor-LMP is also gratefully acknowledged. A special thanks to John Bloomfield at the Technology Development Institute (TDI), previously known as the Advanced Manufacturing Institute (AMI), for his implementation of concepts of the automated wire Indent Profiling System into a practical functioning system with excellent performance.

Great gratitude is extended to the undergraduate research assistants that helped collect data pertaining to test prisms and crosstie scans; thanks to Bjorn Funk, Alex Kim, Brent Hess, Diego Sanchez-Moreno, and Hunter Lanier. To the graduate research students Mark Haynes, Naga Narendra Bodapati, Adrijana Savic, and James Scott for their contributions of supporting material and data in this research.

Furthermore, thanks to the FRA members of the KSU research group, Robert Peterman, Chih-Hang John Wu, Kyle Riding (now University of Florida) for years of feedback and assistance on the major FRA research projects. In addition to past and present graduate council committee members Youqi Wang and Jack Zin. Finally, endless thanks to Major Professor B. Terry Beck for his endless collaboration and support; none of this would be possible without him.

Dedication

To my mother and father, who always encouraged me to follow my passions.

To the educators, who made this research possible.

To my lifelong friend and wife, Megan, who encouraged me every step along the way.

Preface

The Indent Profiling System is a non-contact laser-based device capable of measuring the indentation geometry of steel wires used in the manufacture of concrete railroad ties. It was designed to address the shortcomings of the current measurement methods, both manual and automated, to assess the quality of indented steel wires. The manual methods provide insufficient sample sizes due to the time-consuming nature of the measurements; furthermore, the collected information is challenging to extract in a repeatable manner using manual procedures using current standards. An automated measurement system was developed previously by Mark Haynes to measure indentation geometry [37] which significantly removed the measurement variability from operator to operator; however, the system took hours to operate and could not capture statistically significant sample sizes. The Indent Profiling System remedies these issues by analyzing all of the unique indents formed by the indent rollers during the manufacturing process and extracting the geometric features in an expedient, repeatable, and accurate manner.

During the first phase of this research the key objective was to design and implement an automated Indent Profiling System to produce unbiased, statistically-relevant sample sizes. After motion control and data acquisition of the system was implemented, calibration techniques and data manipulation steps were developed to enhance the quality of the data being received. Then, the system was applied to measure specimens of known geometry to verify the correct and reliable operation of the system and to quantify expected measurement uncertainties.

The second phase of this research involved the application of the Indent Profiling System to measure the indent characteristics of a multitude of indented wires. A sampling of these wires were from those used in modern industry, a subset was comprised of wires that were extracted from historical crossties that had been in track for upwards of multiple decades, and another set of wires were those created with known “machined indents” for use with system validation. In conjunction with transfer length and splitting propensity data of concrete prisms tests used by this research, the Indent Profiling System results were then used to extensively investigate which geometric parameters of indented wires contribute most significantly, or detrimentally, to prestressed member performance criteria.

During this research, the Indent Profiling System proved its ability to accurately extract indentation geometry of the wires subjected to test. The calibration procedures and wire cast correction algorithms ensured that wire scans were generated with micron levels of precision. From these calibrated scans, the system could extract dozens of geometric parameters, analyzing hundreds of unique indents at a time. This allowed for manufacturing variations to be analyzed from indent to indent and on a row-by-row basis. Furthermore, the results from the Indent Profiling System were correlated with empirical performance characteristics of prisms constructed using the same wires. Strong correlations were developed that related indentation features with wire-concrete performance criteria such as transfer length and splitting propensity. The Indent Profiling System represents a unique departure from current manual measurement methodologies, collecting large quantities of data that can adequately statistically characterize the manufacturing process; thereby furthering the understanding of how indentation geometry directly contributes to desirable performance characteristics of concrete railroad ties.

Chapter 1 - Introduction

The main focus of the research effort provided here is on the creation of an automatic non-contact laser based Indent Profiling System for the purpose of rapidly assessing geometrical characteristics of indented wires used in the manufacture of prestressed concrete. The process of measuring geometrical indent characteristics by traditional means is a time consuming process, which severely limits the frequency of testing and prevents the acquisition of statistically relevant sample sizes.

In parallel with the concrete prism transfer length and splitting propensity testing conducted in conjunction with this project, this system was used to identify which indent characteristics were directly related to important performance criteria in prestressed concrete ties. The effects of 34 different wires and indent geometries were evaluated using this system. During the testing phase, these same wires were used to evaluate the splitting propensity and transfer lengths of more than one hundred prestressed concrete prisms. The ability to obtain detailed indent geometry characteristics quickly was essential in order to provide enough data to establish statistically-relevant correlations with concrete prism results. This dissertation details the automation of this Indent Profiling System and its application to measure geometric characteristics of indented steel wires and how these characteristics correspond to critical performance criteria in prestressed members. Furthermore, an ASTM draft proposal is presented that prescribes how operators are to take consistent measurements of indentation geometry to ensure consistency from operator to operator and from lab to lab. This proposed draft covers indentation geometry that ASTM A881 and ISO 10138-2 requires as well as indentation geometry that has been proven to correlate strongly with wire-concrete bond performance.

1.1 Background

Prestressed concrete railroad ties have become increasingly utilized in the United States and are an essential component for high speed railway lines. In order for these prestressed concrete ties to function adequately over their expected service life, the ties must be designed to withstand the extremely large impact loads applied near the member ends. To optimize the design of the ties, the prestressing force must be fully introduced into the railroad tie at a location well before the rail load is applied. The length required to transfer the prestress force into the concrete member is referred to as the “Transfer Length” [1],[2],[3].

Extensive research has been conducted by the project team during the past 9 years to establish the concrete strength and prestressing steel properties that must be provided to ensure that transfer lengths will be shorter than the distance from the end of the tie to the rail seat location [4]-[33]. In the FRA-funded research project titled “Quantifying the Effect of Prestressing Steel and Concrete Variables on the Transfer Length in Pretensioned Concrete Crossties,” the researchers were able to successfully identify the key wire indent geometry features that correlate with transfer length for a given concrete strength--specifically the indent volume and the indent sidewall area. This has included not only a systematic investigation of the influence of the detailed geometrical characteristics of the prestressing steel wires [6],[11]-[13],[16]-[17],[19],[24],[26], but also the study of other variables such as release strength and concrete mix. Furthermore, of critical importance to this research has been the development of a rapid non-contact optical method of assessing transfer length [5],[7],[10],[14],[15],[20],[23],[27],[34],[35]. The goal of this work has

been the practical development of a robust, accurate system that can be used to measure transfer length as a quality control parameter.

Furthermore, the previous research found that certain indent characteristics were common in concrete railroad ties where splitting along the prestressing tendon has occurred [36]. The characteristics common to ties that have experienced splitting include a larger indent depth along with a shallow indent sidewall angle.

While the findings in the previous research program were very helpful to understanding concrete tie behavior, there still did not exist the means to eliminate the risk of prestressing wires with undesirable indent characteristics from being utilized in the manufacture of ties. This is primarily due to the fact that there has not been a viable means to automatically inspect the indented-wire indent properties without a significant time delay between sampling and measurement results.

With advancements in laser-based measurement tools, there now exists the technical ability to be able to inspect the key wire indent parameters that influence tie performance in a matter of minutes. Hence, there is an unprecedented opportunity to be able to directly implement the existing research findings to prevent wires with harmful indent characteristics from being installed in concrete railroad ties. Automated measurement of the indent characteristics would be most beneficial at the steel wire drawing facility, so that wire indent quality could be monitored in an ongoing basis and necessary process adjustments made so that wires with poor indent characteristics are never shipped to concrete tie producer plants.

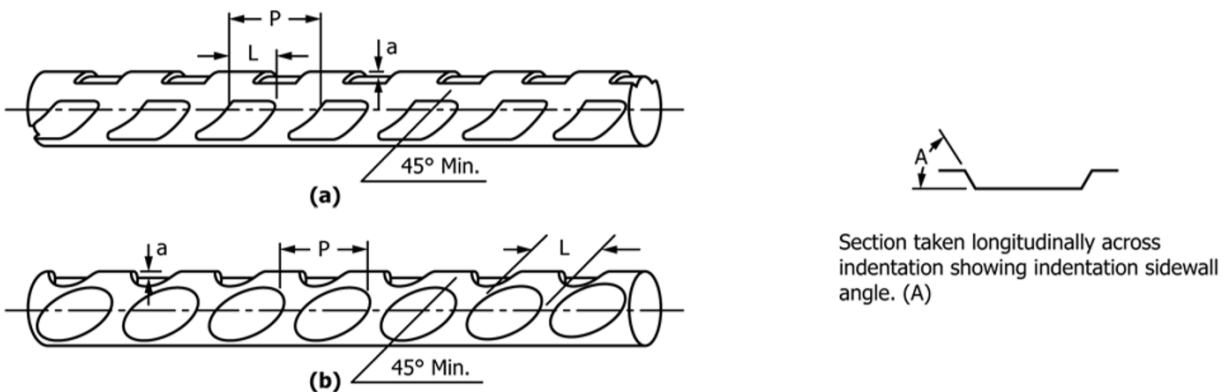


Figure 1.1: ASTM A881 Geometrical Feature Requirements

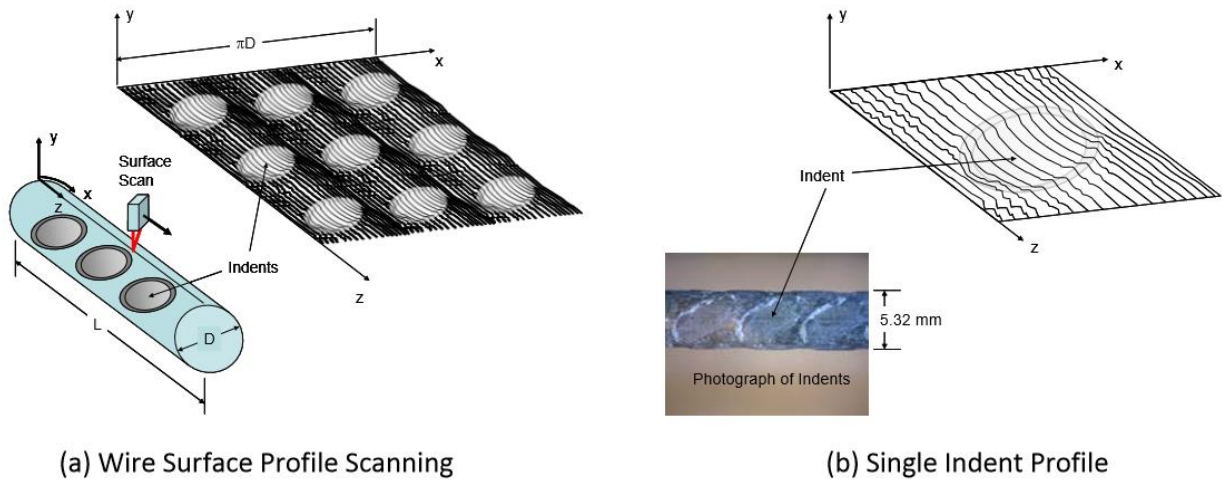
The current standard for prestressing steel reinforcement wire design is ASTM A881-2016. This document specifies the requirements for the material, mechanical properties, indentation geometry, packaging and other general requirements of the reinforcement wire. This includes the indent geometry requirements for the indent edge wall angle (A), indent depth (a), indent length (L), and pitch/period (P). These dimensions are illustrated in the Figure 1.1.

ASTM A881-2016 also states that the indent will be orientated at an angle of at least 45° . Table 1.1, shown below, indicates acceptable values for two wire types within the standard. The 5.32mm (.2094in) diameter wire was within the scope of the previous research.

Table 1.1: ASTM A881 Wire Indent Dimensions

Nominal Wire Diameter,		Depth, a , in. [mm]	Nominal Length, L ,		Nominal Pitch, P ,	
in.	[mm]		in.	[mm]	in.	[mm]
0.198	[5.03]	$0.005 + 0.001, -0.002$ [0.13 + 0.02, -0.05]	0.138 ± 0.02	[3.5 ± 0.5]	0.217 ± 0.02	[5.5 ± 0.5]
0.2094	[5.32]	0.0045 ± 0.0014 [0.115 ± 0.035]	0.138 ± 0.02	[3.5 ± 0.5]	0.215 ± 0.011	[5.46 ± 0.29]

The standard does not provide a detailed requirement as to how the indents shall be measured. This is left to be decided amongst the purchaser and supplier. The current standard does not state which geometrical features of the wire contribute the greatest to the wire's performance. The current methods of using depth micrometers and probes do not analyze the full non-uniform surface profile of the indents. As such, geometrical features such as the indent edge wall angle are not constant and can vary significantly throughout the indent feature. Furthermore, extraction of these features is very time-consuming.

**Figure 1.2: Schematic of Indented Wire Measurement (Point Laser)**

Such features as indent pattern shape, depth of indent, lateral dimensions of indent, and tilt of indent, have been shown to directly affect bond. Having detailed indent surface profile data has enabled researchers to test out different transfer length and pullout correlation scenarios with a variety of potentially important indent parameters (beyond the gross indent parameters measured under ASTM A-881 standards) and establish which have the most influence as well as the relative extent of the influence on bond quality. This was accomplished by using readily available laser-based surface metrology equipment to obtain surface scans of samples of the different wires and indent patterns, containing one or more indents. The previous wire scanning system developed a detailed digitized surface profile mapping of the wire indent features, such as is depicted in Figure 1.2; this figure is from a modification to the *Developing a Prism Qualification Test to Ensure Adequate Splitting Resistance in Pretensioned Concrete Railroad Ties* FRA project [51]. To the degree possible, the mapping was extended over multiple indents such as is shown in Figure 1.2(a), and it was also possible to focus on a single indent at a time for isolation of key geometrical features as suggested in Figure 1.2(b).

Since it is clear that all indents will not be identical, multiple indents are required to provide a valid statistical sampling of the geometrical characteristics. Furthermore, the indent rollers in Figure 1.3(a) have a “repeat” associated with the number of teeth around their circumference as

seen in Figure 1.3(b). The earlier system was not capable of addressing this “repeat cycle” because of the large amount of time required to capture the data since the scanning laser sensor utilized only a point-wise measurement of the wire surface position, as suggested in Figure 1.2(a) [37][48].

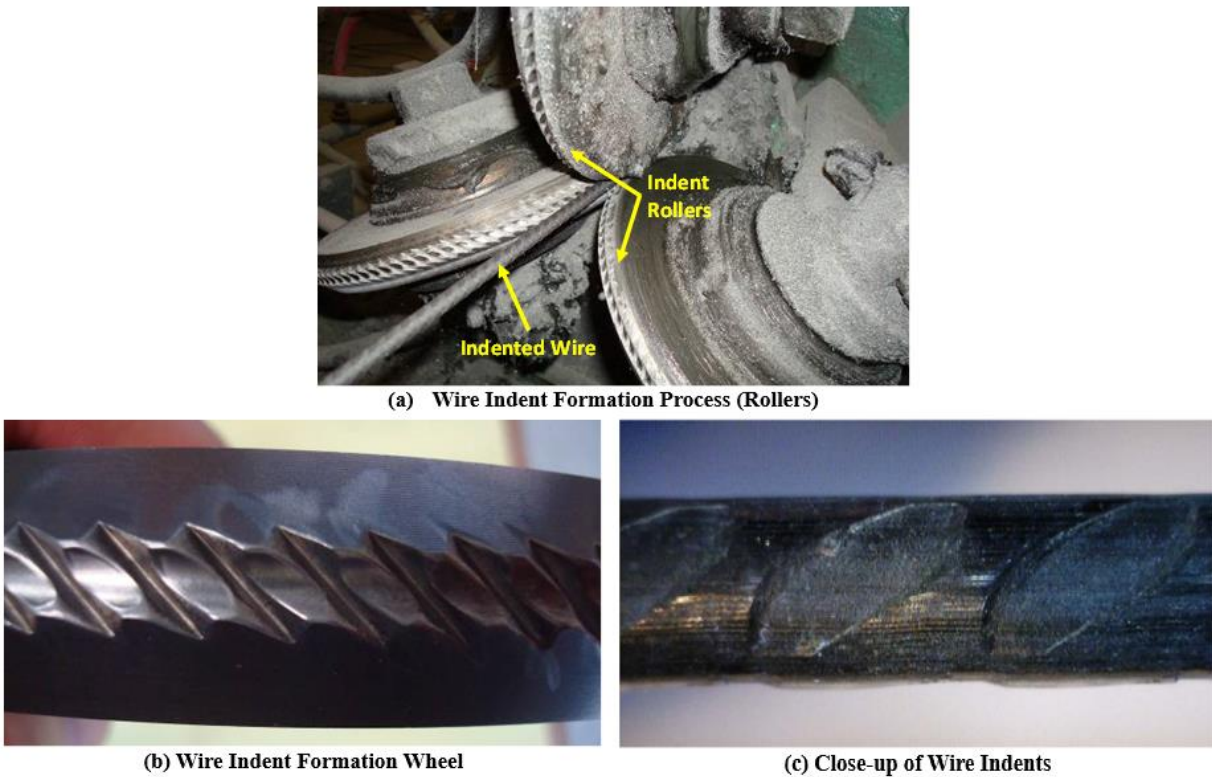


Figure 1.3: Manufacture of Prestressing Wire Indents

1.2 Objectives

This dissertation is meant to highlight the current limitations of measurement standards, methodologies, and automated equipment pertaining to the evaluation of the indentation geometry of indented steel wires used in prestressed concrete cross-ties. Currently, measurement standards such as ASTM A881 and ISO 10380-2 cover only a handful of indentation parameters. These standards often do not prescribe how the limited amounts of indentation geometry are measured, the tools used, or the accuracy of the equipment used. This prevents consistency of measurements between operator-to-operator and lab-to-lab, severely mitigating the usefulness of these standards. Many of the indentation geometry measurements required by these standards are not dictated; instead, they are agreed upon between the producer and consumer. Furthermore, these standards do not identify how specific indentation geometry leads to favorable, or unfavorable, wire-concrete performance; wires can have geometry that passes the requirements of the standards but fail to have sufficient performance during integration into the prestressed concrete system. Manual measurements of these parameters are time-consuming, preventing their applicability in a real-time manufacturing environment; furthermore, they are error prone and fail to capture statistically relevant sample sizes that are useful in characterizing the produced wire and assessing its quality.

A laser-based measurement system was created for a prior FRA project to address the deficiencies with the manual measurement processes [37][48]. This system was the state of the art leading up to this research. The system utilized a point displacement laser that traversed along the length of wire to generate a scan of the wire surface and programmatically extract indentation geometry. This system represented a significant improvement in terms of repeatability, as the extracted geometry was now independent from operator-to-operator and from lab-to-lab. However, it could only extract features on a small segment of wire and could not generate statistically relevant sample sizes due to how long it took for the system to generate wire scans. This limited its ability to be used in a real-time manufacturing environment or assess the quality of a full segment of wire that captures one full revolution of the indent rollers. A more advanced measurement system was needed to address these shortcomings.

This dissertation overviews the creation of a laser-based Indent Profiling System as part of the larger FRA project titled *Developing a Prism Qualification Test to Ensure Adequate Splitting Resistance in Pretensioned Concrete Railroad Ties* [51]. This system was mechanically designed, assembled, and automated by John Bloomfield from the Technology Development Institute. The author developed algorithms to filter erroneous data from the scans, correct for sensor misalignment, account for off-bore rotations caused by nonconcentric specimen chucking or inherent wire bow, and scan segment splicing based on preliminary data from the Indent Profiling System. The author then highlights algorithms to identify individual indents and extract numerous indentation geometry parameters. This system is accurate, can reliably extract indentation geometry from operator-to-operator, captures statistically relevant sample sizes, and operates fast enough to be amenable to be implemented in a plant environment to regularly evaluate indented steel wire as it is being manufactured.

The author used the Indent Profiling System to measure three primary sets of indented steel wires. A subset of wires was from those used in recent industry. These wires were used to create concrete prisms from prior FRA projects and the current one [51] in order to assess the effect of wire geometry on wire-concrete performance metrics such as transfer length and splitting propensity. Another subset of wires was extracted from crossties that were removed after years in service in track [43]; these represented wires that exhibited excellent wire-concrete system performance and served as a useful historical sample of specimens that work well in practice. A third subset of wires were fabricated with machined indents of known geometry as part of a prior FRA project [37] and were used to validate calibration of the Indent Profiling System and evaluate the accuracy of the indent geometry extraction algorithms.

The multitude of wire data was used to correlate indent geometry data against wire-concrete performance metrics such as transfer length and splitting propensity obtained by prisms using the same indented wires at reduced concrete covers, release strengths, and aggregate mix types. This allowed the author to assess which geometric properties had favorable, or unfavorable, influence on performance criteria; this resulted in critical observations in improvements that current measurement standards need to include in order to cover parameters that typically correlate to good system performance. The statistically relevant sample sizes that the Indent Profiling System is capable of measuring raises serious concerns about the acceptance criteria of current measurement standards and the author proposes Go-NoGo criteria to address these newfound issues.

Finally, a draft ASTM proposal titled *Standard Practice for Measuring Indented Steel Wire Geometrical Parameters* is provided that issues guidance on where critical indentation geometry should be manually or programmatically measured; this standard proposal is currently on track for

acceptance. Formulas are provided that calculate indentation geometry based on lessons learned during the development of the Indent Profiling System. Furthermore, sensitivity analysis is performed on the formulas outlined in the proposed ASTM standard in order to evaluate the sensitivity of the measured parameters based on critical dimensions and measurement tool uncertainty. The analytical results of the sensitivity analysis are then confirmed by stochastic methods.

The contributions of the author have yielded a capable Indent Profiling System that can characterize all unique indents contained by a segment of wire, that reliably and independently extracts the geometry regardless of the operator, and operates quickly enough to be useful in a plant environment. Furthermore, it is shown how specific indentation parameters correlate to favorable wire-concrete performance. Changes to current standards are proposed and new standards will help standardize the measurement process of indented wire geometry. These represent significant advancements in the measurement technology, measurement standards, and understanding of the physical processes of wire-concrete performance in the field of prestressed concrete railroad ties that utilize indented steel wires.

1.3 Organization of the Dissertation

Chapter 2 presents the current methods for measuring indent geometry and the inherent difficulties and shortcomings associated with them. This provides the motivation for the development of the optically based Indent Profiling System used in conjunction with the extensive transfer length and splitting propensity measurements utilized by this research.

Chapter 3 highlights the development of the Indent Profiling System. Comparisons are made with the earlier version of the wire scanning technology and the significant advantages of the line scan laser are discussed.

Chapter 4 introduces the interface layout of the Indent Profiling System. The basics of operation are provided, including movement control of the wire specimen being scanned, and data processing settings along with data visualization is presented.

Chapter 5 emphasizes the need for sensor calibration and software elimination of off-bore rotations caused by wire bow. Initial checkout scans are then compared to “master” specimens of known dimensions to verify the accuracy of the calibrations.

Chapter 6 provides the scan manipulation steps and algorithms that are used to extract useful indent features. The processing procedure is generalized enough to allow for any arbitrary indent geometry to be processed in the future.

Chapter 7 overviews the data collected via the Indent Profiling System for a variety of wire types. A high-level overview of the data is provided, the important features are highlighted, the statistical validity is discussed, and comparisons are made with specimens of known indent geometry utilizing machined indents.

Chapter 8 shows the use of the collected indent geometrical parameters in correlations to determine which features contribute the most favorably, or detrimentally, to prestressed member performance. Specifically, the indent data is compared with the extensive transfer length and splitting propensity measurements conducted as part of the larger FRA research project and

previous projects to better understand which indent parameters contribute to desirable crosstie performance.

Chapter 9 presents the capability of the Indent Profiling System to detect the repetition of the indent rollers used to manufacture the indented wires. This represents the ability of the system to measure the entire pattern of the indented wires during the manufacturing process and showcases the statistically relevant sample sizes that the system is capable of.

Chapter 10 discusses the use of Go/No-Go criteria for determining if a wire should be subject to rejection. The use of the developed correlations or mutual agreement between the producer and the consumer can be used to assess the validity of the produced wire.

Chapter 11 presents the conclusions, the high-level takeaways, and the recommendations from the data that the Indent Profiling System has provided. The need is highlighted for more in-depth indent geometry measurement standards that focus on the features that relate most strongly to performance criteria.

Appendix A highlights a proposed draft of an ASTM standard that prescribes how operators are to take consistent measurements of indentation geometry to ensure consistency from operator to operator and from lab to lab. This proposed draft covers indentation geometry that ASTM A881 and ISO 10138-2 requires as well as indentation geometry that has been proven to correlate strongly with wire-concrete bond performance.

Appendix B overviews the sensitivity analysis of the measurement formulas outlined in Appendix A. This governs how the uncertainty of the measurement tools and locating methods affect calculated indentation parameters. Stochastic methods are used to validate the analytical results of the sensitivity analysis.

Appendix C contains the generated reports of the scanned and processed wires relevant to the context of this dissertation.

Appendix D provides an excerpt from the LabVIEW programs that control critical components of the Indent Profiling System for those curious about the visual programming interface.

Chapter 2 - Methods of Indent Geometry Measurement

2.1 ASTM A881

The measurement standard most commonly used by industry in the United States for indented, low-relaxation steel reinforcement wire design for use in prestressed concrete is ASTM A881-2016 [38]. This standard documents the requirements for the material, mechanical properties, packaging, other general characteristics, and most importantly, the requirements for the indentation geometry of the wire. The material properties to be measured by ASTM A881 include tensile strength, load at one percent elongation, elongation after fracture, and a bend test. However, the material properties specified by the standard are largely irrelevant to the scope of this research.

The required geometrical parameters specified by this standard are directly applicable to two specific indentation types, chevron and elliptical. It further specifies general criteria that the indented wires must meet: the indentations shall be in three rows that are equally spaced about the circumference of the wire, with one row of indents inclined oppositely in direction to the other two. A dictation on the quality of the indents is also made, pitch and shape should be consistent with no more than 10% being malformed across a two-foot segment of wire, judged visually. Criteria for what counts as a deformity is mutually agreed upon between the producer and consumer.

Furthermore, it includes the indent geometry requirements for the indentation sidewall angle (A), indent depth (a), indent length (L), indent pitch/period (P), and orientation angle as illustrated in Figure 1.1. The allowable depth (a), nominal length (L), and nominal pitch (P) are allowed to fall in a range depending on the nominal diameter of the wire, tabulated in Table 1.1. Indentation sidewall angle is measured along the center of an indent. The maximum and minimum allowable values, along with the measurement procedure to obtain the parameter, are once again left to a mutual agreement between the producer and consumer. Indent depth is found by taking the average of six or more random indentations measured at the deepest depth. Additionally, the requirement is made for the orientation angle to be no less than 45° , but no provisions are made to state the method of measurement used to determine such a parameter.

This measurement standard suffers from a variety of shortcomings. Firstly, it does not provide detailed requirements as to how the indentations shall be measured or even how many are to be measured. These decisions are left to be made by the producer and consumer. Second, the standard does not state the resolution of the measurement devices used; a depth micrometer with a resolution of 0.001" (25.4 μ m) would be a poor choice for a shallow indent with a 60-80 micron depth. Third, where are the critical measurement points to be located, and how are parameters such as orientation angle to be measured in a reliable way? Is orientation angle determined visually? Which reference point is used to determine maximum depth of the indentation since the depth potentially varies across the width of the indent, measured about the circumference of the wire? What constitutes a deformed indent? When is a deformity severe enough to be detrimental to the performance characteristics of the wire?

The current methods of using depth micrometers and probes do not fully analyze the complete non-uniform surface profile of the indents. Additionally, geometrical features such as indent sidewall angle are not constant and vary throughout the indent feature. Furthermore, the extraction of these features is time consuming. Finally, perhaps most importantly, the current standard does not state which geometrical features of the wire contribute most significantly to the wire's

performance. Such features as indent volume, indent sidewall angle, pattern shape, indent depth, and indent width have been shown to directly affect transfer length [37] and splitting propensity, but many of these parameters are not included in ASTM A881.

2.2 ISO 10138-2

Another measurement standard which is commonly used to assess prestressing steels and wire indentations is ISO PrEN 10138-2:2009 [40], henceforth referred to as ISO 10138-2. It covers the general requirements for prestressing steel wire, strands, and rods. Similar to ASTM A881-2016, this standard provides criteria that the steel must satisfy along with the measurement of indent geometry that is within the scope of this research. The indentation characteristics which are subject to measurement are as follows: indent length (L), indent depth ($a_{\max}$), indent spacing (c), indent distance (e), average diameter, and ovality. The geometrical characteristics apply to the “chevron” indent patterns that are summarized in Figure 2.1.

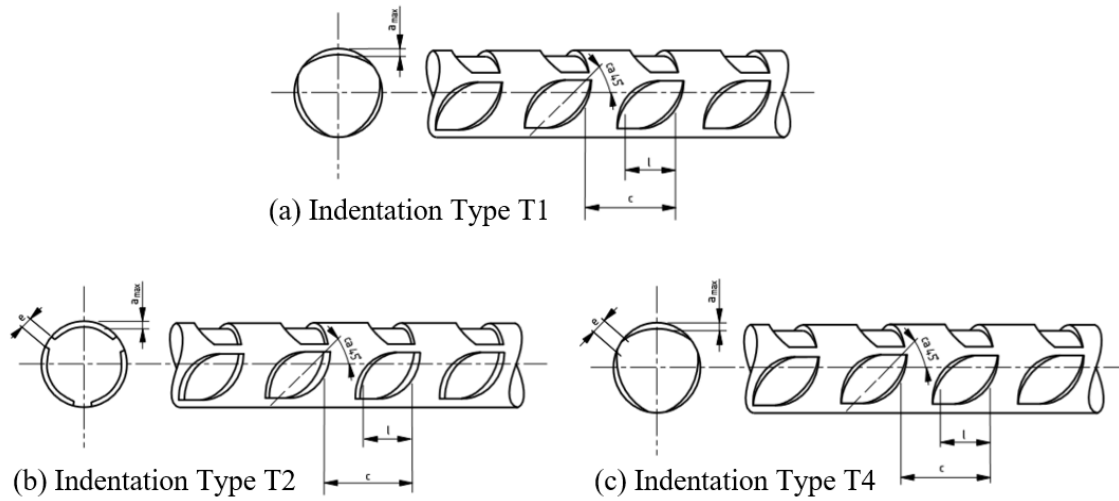


Figure 2.1: ISO 10138-2 Geometrical Feature Requirements

ISO 10138-2 is similar to ASTM A881 in many regards. One line (row) of indentations shall be at a contrary angle to the others, additionally, the nominal depth, length, and spacing must fall in a range of allowable values based on wire diameter. The example dimensions for the common chevron indentation of type T4 are provided in Table 2.1. Nominal diameter (d) is measured by traditional means, in which a wire of a given length and mass yields the average diameter since the density of steel is a known quantity. Ovality is evaluated by computing the difference between the maximum and minimum diameters in any section of the wire. Further guidance for the measurement of indent length, depth, spacing, and distance are not provided by the standard in any capacity.

Table 2.1: ISO 10138-2 Wire Indent Dimensions (Indent Type T4)

Dimensions in mm

Nominal wire diameter d	Indentation depth $a_{\max}$		Length l	Spacing c	Sum of indentation distances $\sum e$	
	Range of nominal values					Tolerance on chosen nominal depth
	from	to				
≤ 5	0,06	0,13	$\pm 0,03$	$3,5 \pm 0,5$	$\sum e \leq 0,2\pi \cdot d$	
> 5 to 8	0,09	0,16	$\pm 0,04$	$5,0 \pm 0,5$		
> 8 to 11	0,10	0,20	$\pm 0,05$	$8,0 \pm 0,5$		

Unfortunately, ISO 10138-2 suffers the same shortcomings as the previously discussed standard. Little guidance is given in the measurement process to ensure reliability and accuracy of the geometrical features. Determination of critical measurement points is not provided and there is no discussion about the number of observations necessary to determine if a wire is consistent during the manufacturing process from indent to indent. Furthermore, it does not identify which geometrical parameters are significantly related to performance criteria and does not necessarily prevent wires with poor indent characteristics from being shipped to concrete tie producer plants.

2.3 Early Wire Scanning Measurement Technology

To measure indent geometry features in greater detail, a non-contact method based on displacement laser technology was developed at Kanas State University prior to the current research effort [37]. The operation of the system and the scanning process it used is illustrated in Figure 1.2, which shows a point laser traversing along the length of an indented wire to capture line scans of the complex surface features. A depiction of an early version of the wire scanning measurement technology is contained in Figure 2.2, as seen in Mark Haynes's thesis [37].

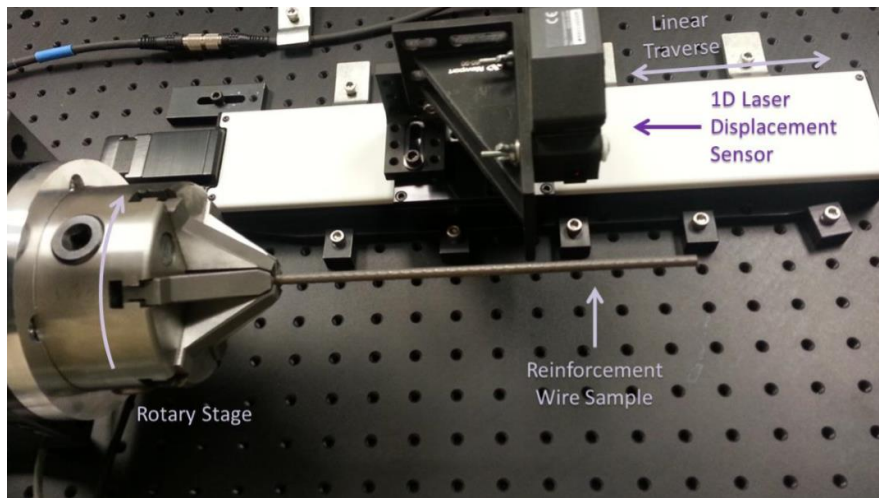


Figure 2.2: Early Indent Profiling Technology

Steps were taken to minimize mechanical misalignment of the system, an important process when measurements on the order of microns are being conducted. Additionally, great care needed to be

applied to correctly remove the cast of the wire “bow” and minimize off-bore rotations due to the large unsupported length of the wire. The system was comprised of a rotary stage and a linear stage to provide automation control. While the system had very high precision due to the use of a displacement point laser, it did not come without disadvantages since traversing the length of the wire was a time consuming process. The primary disadvantage of a point laser is implied in the name of the device; it can only measure a single point at a time. It took upwards of 10 hours to scan and process a segment of wire of only one inch in length, which constitutes 9 full indents that are included in a single scan for a 5.32mm wire. A significant improvement in measurement technology was necessary to reduce scan times and to make the system practical to implement in a production environment requiring a statistical sampling of indent features.

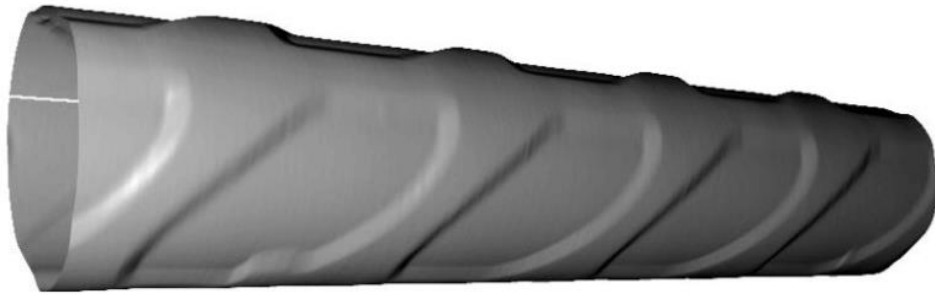


Figure 2.3: Early Scan of WF Wire Type

An example of the high resolution that the early wire profiling system was capable of is highlighted in Figure 2.3, as seen in Mark Haynes’s thesis [37]. The uncertainty of the displacement laser measurement was a fraction of a micron leading to noise free scans. From the high resolution scans, algorithms were developed to extract useful geometrical features including indent depth, pitch, length, sidewall angle, width, volume, sidewall area, and orientation. Once the indent features were extracted, sets of parameters were successfully correlated with transfer length measurements on concrete prisms comprised of the same wires that were subjected to scanning. It was found that certain indent features such as indent volume and indent sidewall area had a significant influence on performance criteria namely, transfer length. This early wire scanning system was the precursor to the one that is the primary focus of this dissertation. It is also the original device that provided the impetus to reevaluate current wire measurement standards to more accurately reflect the parameters that are directly related to indented wire performance.

2.4 Limitations of Current Measurement Methods

In summary, the insufficiencies with current measurement standards pertaining to indented steel wires are as follows: First, common measurement standards such as ASTM A881 and ISO 10138-2 do not identify which geometrical parameters contribute most significantly to the performance of the indented wire. Second, the measurement procedures for obtaining the required indent features for the standard do not provide repeatable, reliable results between different operators. Often the measurement process is determined by mutual agreement between the producer and the consumer and is not a standard measurement that can be compared with other manufacturing processes or products. Third, determining indent geometry for the current measurement standards is a laborious endeavor; it is time consuming and does not integrate easily into a production environment. Often, wire samples are sent out to measurement labs only when process changes

have been made to check for compliance with the measurement standards. This is hardly ideal since the manufacturing process of indented steels wires varies on an hourly basis as the indent roller teeth wear down, rather than on a sparse interval as the testing schedule provides. Finally, sample sizes are not statistically relevant due to the time it takes to collect the data and the inherent uncertainties with the current measurement processes. The small sample sizes fail to capture the intricacies of the manufacturing process since no two indents are identical and significant variance can be seen across neighboring indent rows.

The early wire scanning technology took great strides to address the insufficiencies with the current measurement standards and attempted to more accurately understand the relationship between geometrical indent features and favorable performance criteria. The system could collect high resolution data and extract a variety of indent features above and beyond those dictated by current measurement standards. Some key indent features were found that corresponded with desirable wire performance. Additionally, it could extract features in a reliable, predictable manner across a wide variety of tested wires. However, the system was too slow to be a device that would be applicable to a production environment and mostly found use as a research tool. The system could not collect statistically relevant sample sizes that accurately characterize the manufacturing process of the wires due to the considerable time it took to operate.

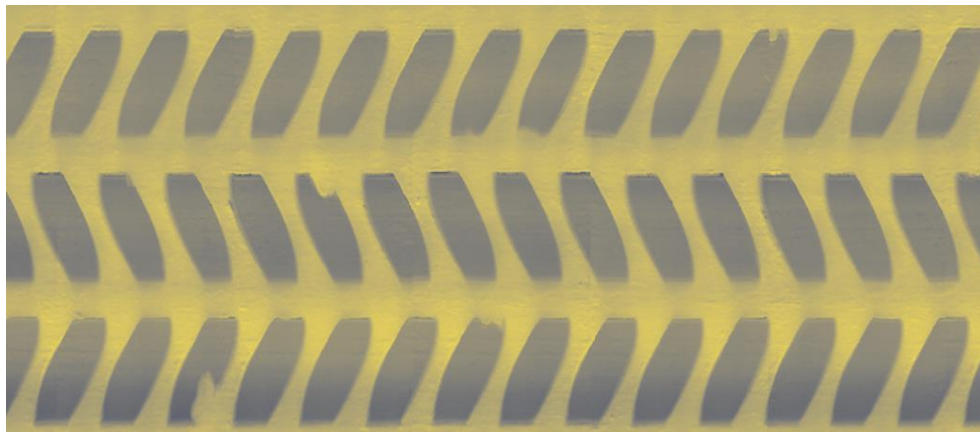


Figure 2.4: Indent Profiling System Scan

A device is needed that has the desirable capabilities of the early wire scanning system and addresses the majority of its faults. Such a device is described in great detail in the remainder of this dissertation. The Indent Profiling System that was the direct result of this research effort is significantly faster and collects statistically relevant sample sizes. A scan from the Indent Profiling System can be viewed in Figure 2.4, which depicts a 26-inch length of wire comprised of over 330 indents. Coincidentally, this is the same wire from Figure 2.3. This device proved to be a valuable research tool and provide the necessary data to evaluate which indent features are important to measure and how these same features correspond to wire performance.

Chapter 3 - Development of the Indent Profiling System

The desire to create a more capable wire scanning system led Kansas State University researchers to partner with Nucor-LMP (an indented prestressing wire manufacturer) and the Technology Development Institute (formerly Advanced Manufacturing Institute), a company that specializes in prototype development, to create a non-contact wire Indent Profiling System to provide an unbiased evaluation of the indent characteristics that are critical to the performance of concrete railroad ties. This system provides physical measurements of the wire indentations by using a 2-dimensional line laser that is focused on a wire as it rotates about its longitudinal axis. Then, the key indent parameters that have been previously shown to be strongly correlated with transfer length [37] and splitting potential are automatically determined from the resulting scan.

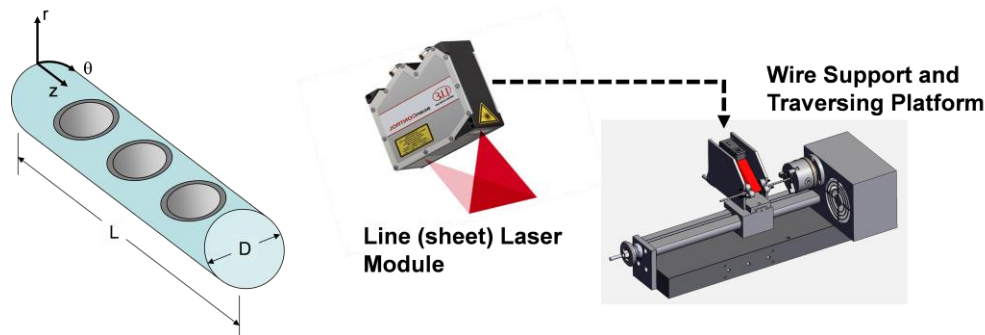


Figure 3.1: Schematic of Proposed Indent Profiling System

A simplified schematic representation of the system is illustrated in Figure 3.1. Rotation of the wire underneath the sheet laser results in the effective “unwrapping” of the indent profile. This section reviews the development of the Indent Profiling System.

3.1 Initial Specifications

The ability for wire manufacturers to ideally implement the wire indent research findings will require more statistical data to be collected about indent variations along the wire length, so that proper tolerances for the key indent parameters can be established. Thus, a system was needed that can assess the multitudes of wire sizes and indent features that are common in industry. Therefore, it is desirable that the system is able to measure wires with nominal diameters ranging from 4mm to 12mm. These constitute a significant portion of wires that are produced in industry. Additionally, the system should be able to measure wires of varying depth; shallow indents are on the order 50 μ m and the deepest indents that can be made in practice are nearly 300 μ m. Characterization of the entire indent pattern formed by the indent rollers was a primary goal of this research. This necessitated the collection of statistically relevant sample sizes to obtain a better grasp of the manufacturing intricacies of the indented wires. Indent rollers are typically 8 inches in diameter; therefore, the system should be capable of measuring 25-inch (640mm) lengths of wire at a minimum. Finally, quick scan acquisition led to the requirement of a line-based scanner, 20 μ m spacing between points, and resolutions at or below about 2 μ m. The desired initial system design specifications are given in the list below.

- (a) Range of Indent Depth (50-300 μm)
- (b) Resolution of Local Depth (2 μm)
- (c) Range of Wire Diameters (4-12 mm)
- (d) Optical Line Sensor (2 μm resolution, 1280 points over 25mm width)
- (e) Wire Surface Roughness (10-15 μm)
- (f) Length of Scanning Carriage Travel (30 inches)

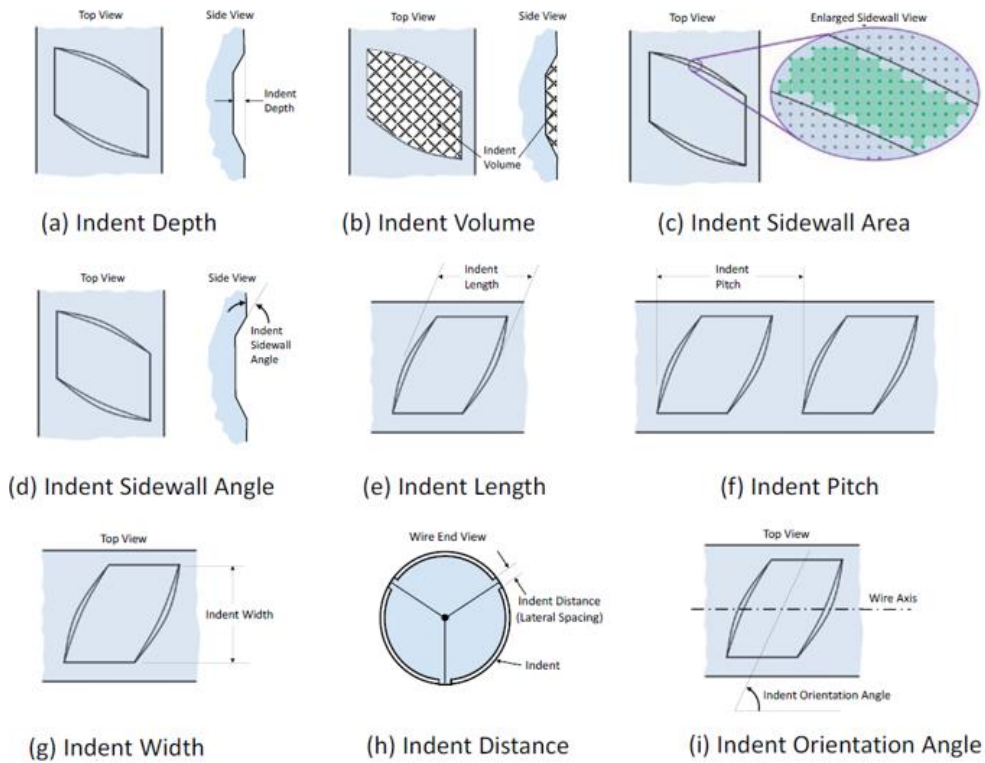


Figure 3.2: Key 3D Wire Indent Geometrical Features

The primary 3D indent features to be measured by the Indent Profiling System are given below and are illustrated in Figure 3.2. Note that the specific geometrical features required to be measured by ASTM A881 and ISO 10138-2 are identified in this list. Additionally, the list of measured features includes parameters that have been identified from previous research to influence transfer length and splitting propensity and may be critical quality control parameters [22][36][37][41]. The indent parameters to be captured along with targeted nominal uncertainties are listed below in Table 3.1.

Table 3.1: Indent Parameter Uncertainty

Figure Index	Parameter	Desired Uncertainty	Relevant Standard
a	Indent Depth	$\pm 3\mu\text{m}$	ASTM A881, ISO 10138-2
b	Indent Volume	$\pm 0.020\text{mm}^3$	
c	Indent Sidewall Angle	± 2 degrees	ASTM A881
d	Indent Sidewall Area	$\pm 0.005\text{mm}^2$	ASTM A881
e	Indent Length	$\pm 20\mu\text{m}$	ASTM A881, ISO 10138-2
f	Indent Pitch	$\pm 20\mu\text{m}$	ASTM A881, ISO 10138-2
g	Indent Width	$\pm 20\mu\text{m}$	
h	Indent Distance	$\pm 20\mu\text{m}$	ISO 10138-2
i	Indent Orientation Angle	± 2 degrees	ASTM A881

3.2 Component Selection

One of the primary requirements of the Indent Profiling System was to obtain statistically relevant sample sizes. As such, significant lengths of wire would have to be scanned in short order to be of use in a production environment. This required a departure from the displacement point laser that was used in the precursor to this system in favor of a line-scan based laser module. A specific line-scan laser module was recommended by John Bloomfield, an automation engineer from the Technology Development Institute, for the profiling system. The module was a Keyence LJ-V7060, which was later demonstrated by Keyence representatives, and was then confirmed for system integration. Line scan lasers offer a considerable increase in data acquisition rates in comparison to point lasers; increases in scan rates are on the order of multiple magnitudes. This is due to the fact that line lasers cast a sheet of light that is then received on an imaging array, thus allowing hundreds or thousands of data points to be collected in a single measurement. A blue line-scan laser (405nm) was selected for this high accuracy application. It is well known that laser uncertainty is related to the spot size of the laser, the point of greatest focus, and spot size is a function of laser wavelength. Higher frequency lasers have shorter wavelengths and are therefore capable of higher accuracies.

A commercially available laser line scan module, a Keyence LJ-V7060, was selected with a line width of 16mm, allowing it to view multiple indent profiles in a single measurement. The module can collect 800 points of data across the 16mm reference distance, with an average profile data interval of $20\mu\text{m}$ displacement between measurement points. Furthermore, it is possible to achieve repeatability of ± 0.4 microns with the module when it is measuring a sufficiently diffuse surface. The previous wire indent measurement system utilized a pointwise laser and had a spatial resolution of a few tenths of a micron; whereas, the current light sheet system has a spatial resolution on the order of a few microns. However, the measurement process is greatly enhanced by the compromise between high spatial resolution and measurement speed. Additionally, prior research indicated that the extreme resolutions of the previous system was unnecessary as far as the measurement of indented wire geometry was concerned [37].

Stepper motors and a small lathe chassis were selected to provide the automation of the system. Motion control of the rotation of the wire and the translation of the lathe carriage allowed for wires of 30 inches in length to be completely scanned by the selected laser module. Due to the high

spatial resolution that the laser line scan module provided, angular resolution of the wire rotation needed to be of similar or greater accuracy. For this purpose, an optical encoder with a maximum angular resolution of 7200 positions (line scans) per 360-degree revolution was selected. The high angular resolution that the optical encoder can provide allows for the “super sampling” of data to help eliminate noise due to localized reflections from the metal wire surface.

3.3 System Layout Overview

Once hardware selection was finalized after interactions between the FRA team at KSU and John Bloomfield from the Technology Development Institute, the construction of the Indent Profiling System took place. John Bloomfield was instrumental in the system hardware design, assembly, and automation implementation of the system. The prototype design illustrated in Figure 3.1 was not far off from the final system design. A photograph overviewing the layout of the final Indent Profiling System can be seen in Figure 3.3. The base component of the system is a small Sherline lathe chassis with a distance between centers of 30 inches and a swing of 4 inches. Two stepper motors provide automation control of the system. One motor is connected via a pulley to the head of the lathe and provides rotation control of the wire rotation with an angular resolution of 0.05 degrees. The second stepper motor is attached to the lead screw of the lathe and controls the translation of the lathe carriage to sub-micron precision.

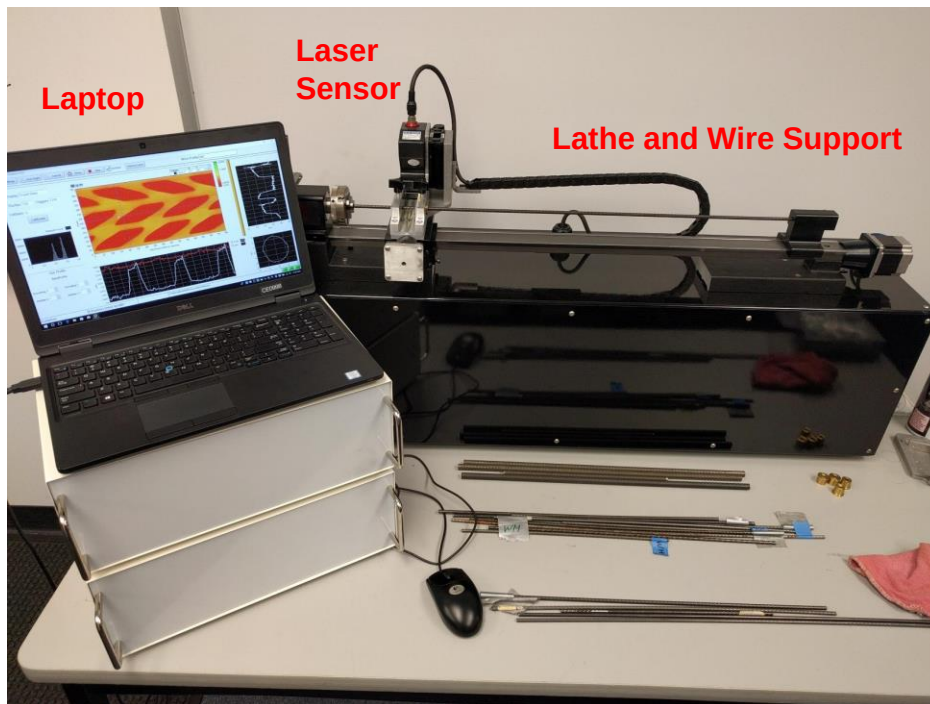


Figure 3.3: Layout of Indent Profiling System

An aluminum frame is mounted on the lathe carriage; to this frame the laser line-scan module is mounted with the laser sheet of the plane intersecting the bore axis of the lathe coincidentally. A precision linear translation stage separates the line scanner from the aluminum frame. The laser module is adjusted in elevation via a micrometer stage to align the sheet laser with the bore axis of the lathe. The aluminum frame houses brass bushings to help guide the indented wire along the bore axis of the lathe. It should be noted that the indented wire is spooled after manufacture, and all wires can exhibit some bending. A close-up view of the scanning head, micrometer stage, and

bushing guide for the alignment of the wire is shown in Figure 3.4. The bushings shown in Figure 3.4 help to guide the wire, keeping it more aligned as the scanning operation traverses the entire length of the wire segment under test. Below the lathe and scanning assembly is a black metal box, to which the lathe is affixed. This box houses all of the laser controllers, motor controllers, power converters, and industrial computer equipment to operate the scanning system. A laptop or desktop is used to interface with the Indent Profiling System. This concludes the overview of the Indent Profiling System layout.

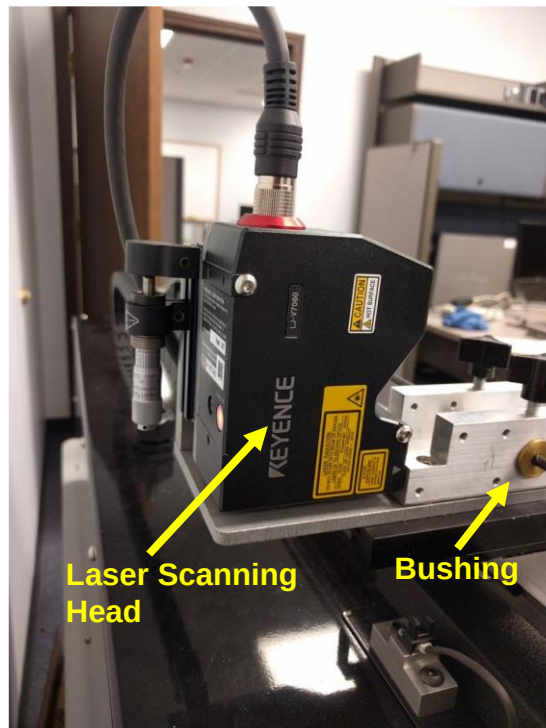


Figure 3.4: Close-up of Scanning Head and Bushing Guide

Chapter 4 - Scanning Process

This section summarizes the use of the software and its interface to scan a segment of indented wire and process the resulting geometrical features. The indent profiler can be generalized into two primary system components, the hardware and the software. The hardware is used in the data acquisition stage, and the software is used to capture, store, manipulate the scan files, and process the data. The operator interfaces with the scanning hardware and processes the data using two separate programs, the first of which is a program used to acquire the detailed wire indent geometry via the line-scan module and lathe assembly and is aptly named “Wire Scanner”. This program is used to upload scanner settings to the laser head, name files, calibrate the scanning system, and capture scan segments for later processing. It is important to note that this program requires the computer to be physically tethered to the scanning hardware during the data streaming process and cannot be used as a standalone application.

The processing of the captured indent geometry provided by the Indent Profiling System is accomplished with a standalone application called “Wire Scan Reporter”. This program utilizes saved indent scans, and thus, can be used independently of the Indent Profiling System hardware. This program provides the capabilities to align the generated scans if required, isolate individual indents, omit particular indents from inclusion in the final reports in the event of damage, extract useful indent geometrical features, and generate comprehensive reports of the processing results. This section is not intended to be a comprehensive user guide of the system, but rather, provides insight into how the indented wire geometry is scanned, how the data is stored, and how it is processed via the aforementioned programs. The wire featured in the interface examples in the following scanning process sections can be seen in Figure 4.1; the digital microscope image is of wire type WF.

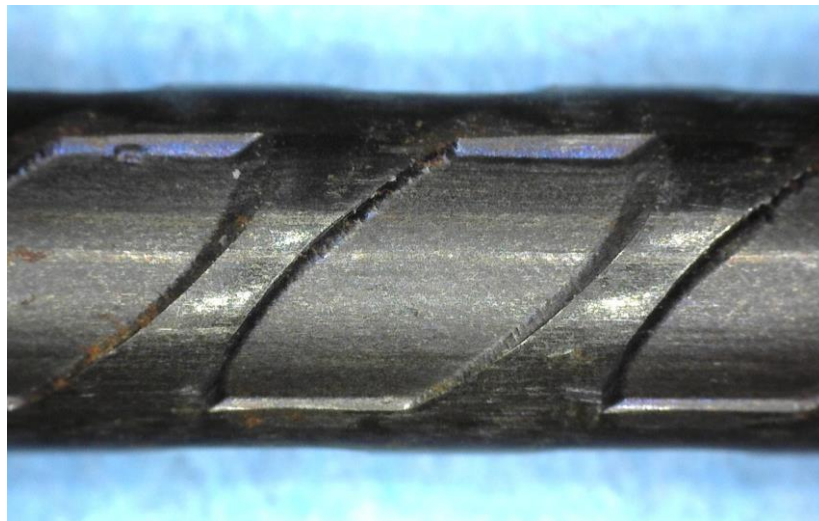


Figure 4.1: Wire Type WF

4.1 Interface Layout

As stated previously, the primary objective of the wire scanning program was to interface with the scanning hardware, receive the data stream, and visualize the data. It can also be used to calibrate the alignment of the Indent Profiling System, control the movement of the scanning system via automation or direct user command, change scanner settings, apply data filters to refine the data,

and visualize the data as it is being received. It is critical to note that John Bloomfield performed the mechanical design and assembly of the system, provided automation of the system by implementing motion control and a user interface to facilitate interaction with the system (seen extensively in this section) via LabVIEW, and integrated the data processing and extraction algorithms developed by the author to extract the indentation geometry of the wires. John Bloomfield is a wizard with LabVIEW and the author would like to highlight his contributions and expertise during system development. The author provided input on the user interface design and functionality and how the user interacts with the programs. The interface layout of the wire scanner program is provided in Figure 4.2, this is the main screen that the user interacts with during the data capture stage.

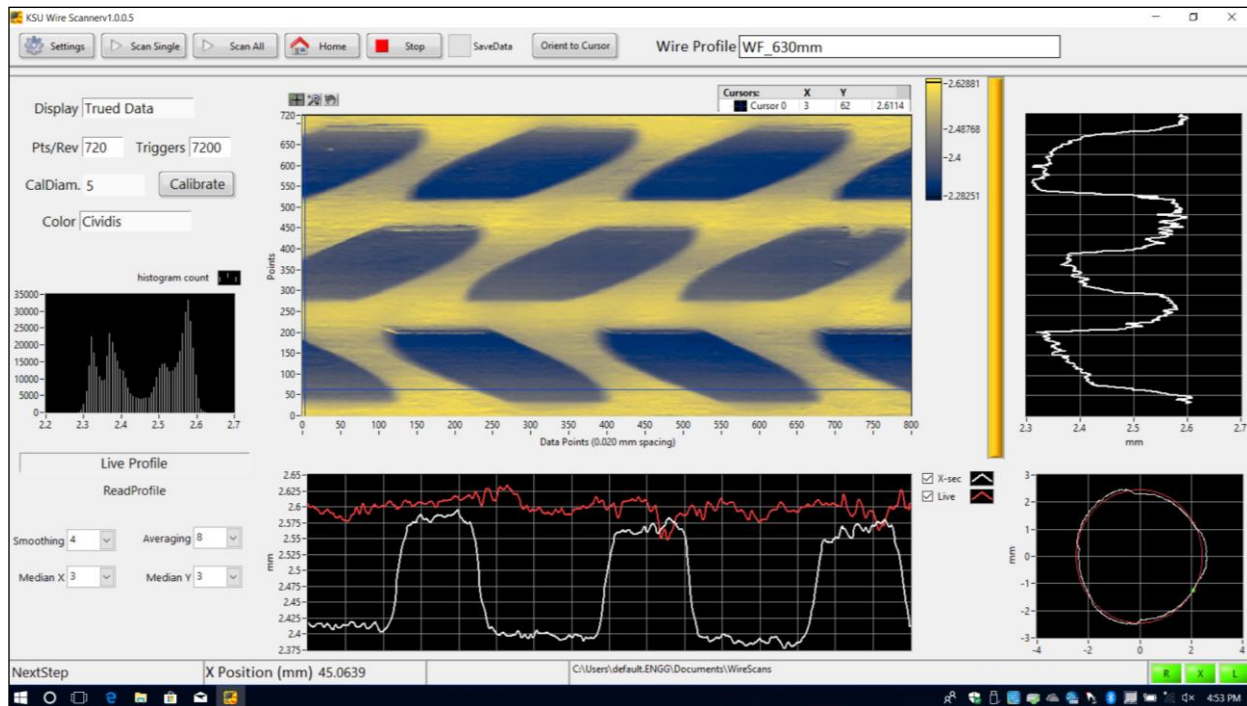


Figure 4.2: Wire Scanner Interface

The top bar of the wire scanner interface, read from left to right, contains the basic system settings, scan command buttons, homing and system stop control buttons, selection of data saving, orient to cursor command, and the wire profile naming box. The system settings allow the user to change the target velocity and acceleration of the rotation and control linear movement. Additionally, it can be used to set the desired scan width and total scan length of the specimen. Maximum scan width is limited to 16mm due to the design limits imposed by the line laser and is nominally left at 15mm to omit scan noise at the edges of the laser sheet. Maximum scan length can be set to 640mm, or 760mm if the tailstock of the lathe assembly is removed. The Scan Single command will capture a single scan segment at the current carriage location; whereas, Scan All will capture all of the scan segments to satisfy the scan length and scan width specified in the system settings (for example, a scan width of 15mm and total scan length of 60mm will generate 4 scans). The Save Data checkmark box controls whether or not the data will be saved to storage, and is typically disengaged when the system and the indented wire are being aligned. The Home button will cause the carriage to return to the point closest to the lathe chuck and will align the rotation of the lathe head to zero degrees, the Stop button aborts any commanded movement. The Orient to Cursor

button is used after a Scan Single command is given and a captured scan is received; the user can then put a crosshair on the scan window that will be the newly desired origin of the scan, this is traditionally placed on the center of a rib between the indent rows. Finally, the Wire Profile naming box allows the user to specify the name of the scan, typically, this is the specimen identifier and the length of the scan.

In the center of the screen the most recently captured scan is displayed (also called the “heat-map” frequently throughout this dissertation). It is worthy to note that this is a misnomer, and it should be called a “height-map” instead. The height scale of the scan can be adjusted via the bar directly to the right of the scan display. The crosshair dictates which of the data profiles will be displayed in the black boxes both to the bottom and to the right of the scan capture “heat-map” window. In white, the bottom box shows the selected data profile along the longitudinal length of the wire, and the right box shows the measured circumferential profile that wraps around the wire. The red line in the bottom box shows the current signal from the laser head which can be at an arbitrary location with respect to the crosshair origin. The bottom right box displays the profile shape of the scan at the crosshair location, analogous to if the wire were to be sliced like a loaf of bread. This shape is typically trilobal for indented wires due to how the wire is squeezed by the indent rollers during manufacture.

On the left side of the interface is a histogram showing the binned height measurements of the captured scan. After calibration corrections and wire bow removal have automatically been applied, this should form a bimodal distribution for an ideally manufactured wire; however, typical manufacturing variations from indent row to intent row prevent this from being realizable. Figure 4.2 clearly shows that this is indeed the case with wire type WF; later, this will be the subject of detailed discussion in Chapter 7. The left side of the interface allows the operator to display the type of data (raw or trued), the number of desired line-scans per revolution (pts/rev), and the number of encoder pulses to trigger. Additionally, the user can select the height map coloring scheme. Detailed discussion of the calibration method will be elucidated in following chapter, Chapter 5. Furthermore, the filter settings, shown in the bottom left-hand corner of Figure 4.2, will be elaborated on in the subsection directly following this one, Section 4.3.

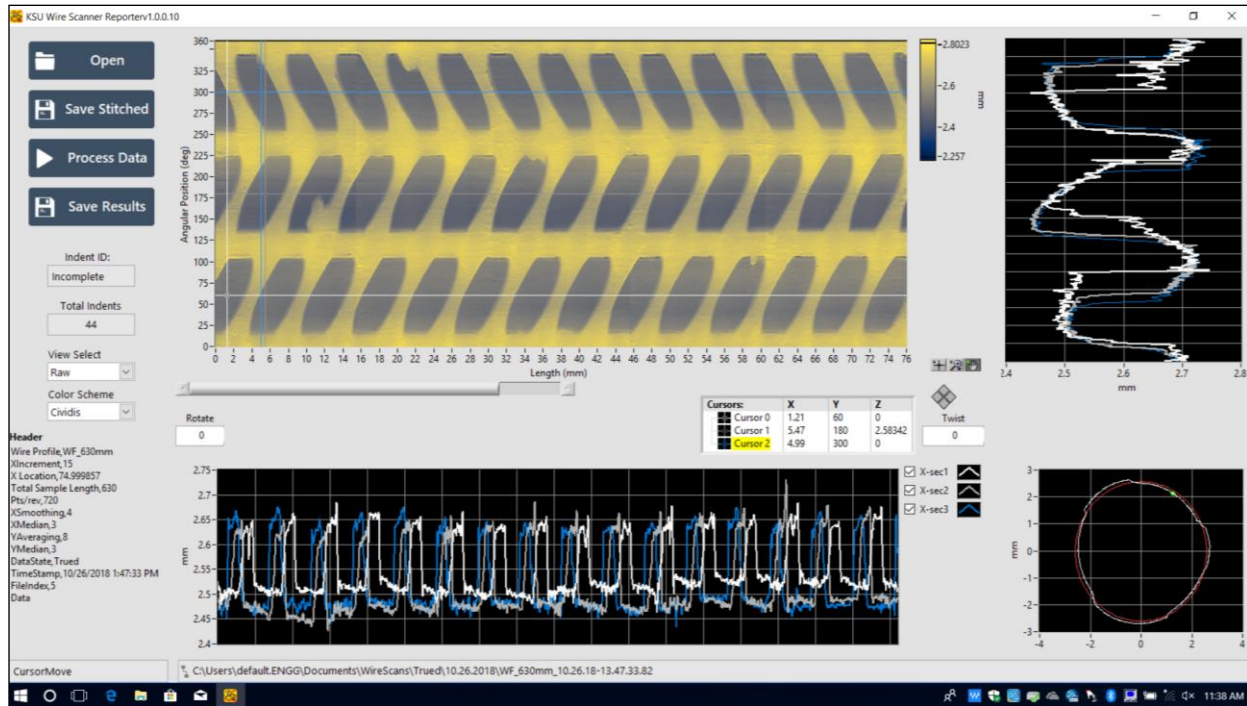


Figure 4.3: Wire Scan Reporter Interface

As stated at the beginning of the section, the processing application can be used independently of the Indent Profiling System hardware since it relies on loaded scans rather than a live data stream. The objective of this program is to load the captured scan segments, allow the operator to align the scan if necessary, and, most importantly, extract the indent geometrical features. The Wire Scan Reporter program is similar in appearance to the previous program, the interface of the Wire Scan Reporter program is provided in Figure 4.3 and Figure 4.4, with wire type WF as the example specimen once again.

The heatmap display port, the data profile windows, and the wire profile window are similar in appearance to the previous program with the following exceptions. First, the heatmap viewport shows the combined scan segments that were loaded from the selected files and provides a scrollbar to view the wire along the length of the cumulative scan. Second, three data crosshairs are provided so that the data profiles of all three indent rows can be visually compared; note how no red line is available to show the current laser line-scan reading since this application does not need to be connected to the Indent Profiling System to operate. Third, two boxes are provided for the operator to adjust the alignment of the scan if necessary (rotation and twist). Some wires are produced with a 30° twist per 2-foot length; thus, they must be straightened out with software for the processing algorithms to successfully extract the indent feature geometry.

The left side of the interface contains the following information and commands, explained from top to bottom, and are summarized as follows: The Open button allows the operator to select which contiguous scan segments are to be loaded. Once loaded, the continuous spliced scan is displayed in the heatmap viewport in the center of the screen. The Save Stitched button will save the continuous, spliced scan to file; this allows a single scan file to be loaded later instead of selecting a multitude of individual scans. Saving the entire continuous scan affords the luxury of being able

to easily visualize the entire scan in secondary programs for data visualization. The Process Data button will extract the indent geometric features using the algorithms highlighted in Chapter 6 - (Process for Extracting Indent Geometry), and the results are then placed in a report file. The Save Report button saves the generated report file to storage in the location where the scan files were loaded from. The Indent ID box shows which indent is currently selected by “cursor 0”, stating the indent row and indent number of the selected indent. The Total Indents box details the number of complete indents that were found via the indent isolation algorithm. View Select will show the currently loaded continuous scan on the main viewport if “Raw” is selected, the detected indent boundaries are shown when “Partitioned” is selected; note that, only the valid, complete indents are shown if “Fitted” is selected, and they are only accessible after successfully processing the data. The color scheme of the height-map can once again be chosen. The Header information on the bottom left side of the interface will be the information that will be stamped at the beginning of the results file.

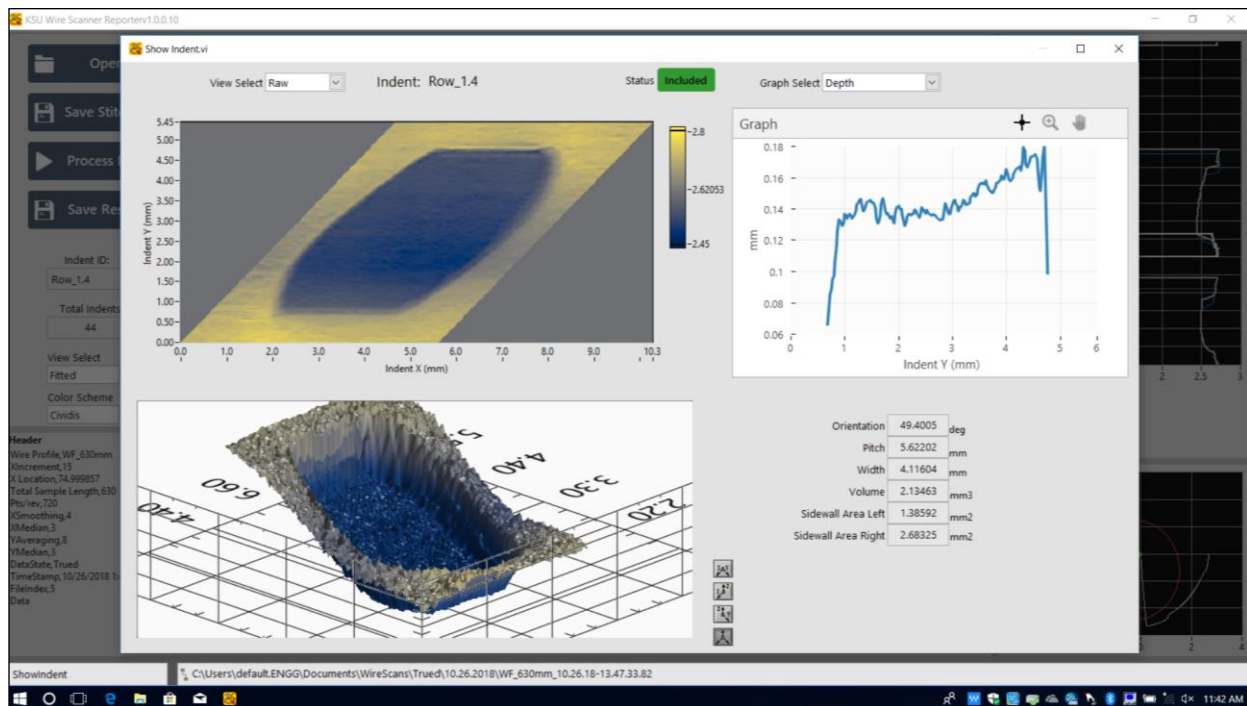


Figure 4.4: Wire Scan Reporter Interface (Indent Viewer)

The Wire Scan Reporter has an additional useful feature, the ability to look at a specific indent; this functionality is highlighted in Figure 4.4. The selected indent is shown in heatmap form in the top left corner, and a three-dimensional render of the scan is shown in the bottom left corner, typically with a highly exaggerated axis in the height direction. The heat map and three-dimensional rendering can be switched between the raw data view and the fitted data view. The raw data view displays the indent from the scan data directly, whereas the fitted data view omits the raw data and shows the trapezoid profiles of best fit that match the indent geometry. The fitting of trapezoidal profiles, once again, will be the subject of further discussion in Chapter 6. Furthermore, the right-hand side of the interface in this view shows geometrical indent features that were extracted for the particular selected indent in tabulated form. Geometrical values that vary as a function of location along the indent can be selected in the plot located in the top right corner of the interface. Finally, the status tab allows the operator to choose whether the selected

indent should be included or excluded from the report file. As a default, this option is set to include the indent in the report, however, in the rare circumstance that a scanning issue is preventing the feature extraction algorithms from obtaining realistic values, the operator can simply choose to omit the data. The programs summarized in this section are easy to use and an operator can learn how to successfully utilize the system in less than half an hour. For the sake of posterity and completeness, a sample of the LabVIEW virtual interfaces that run the Indent Profiling System and the programs summarized in this section can be viewed in Appendix B. It is by no means comprehensive due to the complexity of the program but should serve as an example as to how the Labview program operates.

4.2 Traverse Control, Rotation Control, and Carriage Homing

Movement control, traverse and rotation, can be commanded automatically by the program, or manually by the user. In either case, non-contact optical limit switches prevent the carriage from impacting any hard stops on the lathe structure. The operator can also utilize the Stop command to abort any commanded movement. The operator can manually command rotation of the lathe head, and thus, wire specimen, by using [RCtrl + ↑] and [RCtrl + ↓], and linear motion by using [RCtrl + ←] and [RCtrl + →].

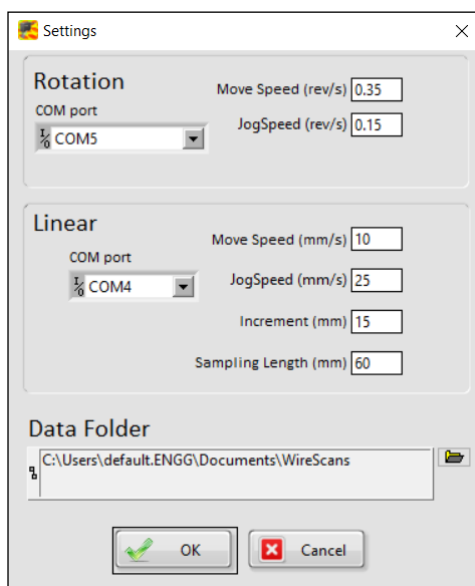


Figure 4.5: Movement Control Default Settings

Movement speeds are dictated by the system settings tab in the “Wire Scan” program; move speed is the velocity that is commanded by manual control, jog speed is the velocity used by automation control. A depiction of the default motion control settings is shown in Figure 4.5. By default, the rotation move speed is 0.35revs/s and the rotation jog speed is 0.15revs/s. The default linear motion control has a move speed of 10mm/s, and a jog speed of 25mm/s. Under the default settings it takes about 25 seconds to manually traverse the length of the bed. Furthermore, manual rotation control is slow so that the operator can more easily set the angular position of the wire being scanned. In automatic mode, it takes approximately 3 seconds to take a single scan and approximately 2 seconds for the carriage to translate into position to proceed with the next measurement; thus, it takes around 5 minutes to scan a 2-foot length of wire. After the wire

specimen has been scanned the Home command can be used, which returns the carriage to the location closest to the lathe chuck.

4.3 Filter Settings and Data Visualization

The final group of settings that are accessible in the “Wire Scan” program pertain to scan data line refinement. These settings can be seen in the bottom left corner of the wire scan program interface in Figure 4.2. Non-contact laser-based systems, despite the tremendous accuracies that the hardware is capable of, do not produce perfect data, particularly when working with data on the scale of microns. A more detailed discussion of the measurement accuracy due to the optical uncertainty of this particular system is given in Section 5.4. Two of the settings, averaging and smoothing, contribute most significantly to refining the quality of the laser line scan data being received by the Indent Profiling System.

The first of these settings, averaging, is made possible due to the high resolution rotary encoder that was selected to measure the angular position of the specimen being subjected to scanning. The rotary encoder is capable of providing 7200ppr (pulses per revolution). For a wire of 5.32mm nominal diameter, this corresponds to the ability to measure angular position with a circumferential resolution of $2.3\mu\text{m}$ on the surface of the wire. Since the line-laser module has an axial resolution of $20\mu\text{m}$ between points this indicates that the rotary encoder has a resolution that is nearly an order of magnitude larger than the laser sensor. Since, for mesh refinement reasons, it is desirable to have axial and circumferential resolutions that are similar in value, the excess resolution that the rotatory encoder provides allows for the effective “super sampling” of data. The averaging setting allows the Indent Profiling System to capitalize on this method. By capturing excess data about the measurement point the adjacent profiles can be averaged together to help filter out noise. This profile averaging process can be visualized in Figure 4.6, which could easily be confused with a modern art piece; the colored lines indicate individual line-scans while the black line is the average of all adjacent colored profiles. By default, this setting uses 8 profiles to perform averaging on; in this case, the 4 profiles on either side of the reference profile, the center profile, are all averaged together, thus reducing measurement uncertainty.

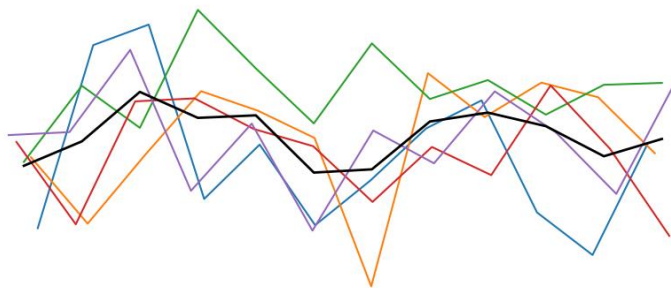


Figure 4.6: Profile Averaging

The second setting used for data line refinement is boxcar averaging. This simple method involves the refinement of a single profile by averaging a point with its neighboring points within a certain proximity. If the measurement uncertainty is sufficiently random, this proves to be an exceptionally effective method in reducing the apparent scatter of the data and contributes significantly to mesh refinement and data visualization. The method of boxcar averaging is illustrated in Figure 4.7, where a typical indent centerline profile is simulated with an average depth of $100\mu\text{m}$, and an indent sidewall angle of 20° . These numbers are typical of indented wires

that are 5.32mm in diameter. Note that the angle is exaggerated in the plot due to the axes having highly different aspect ratios. A measurement uncertainty of $8.3\mu\text{m}$ is applied to the ideal profile and boxcar averaging is carried out on the simulated data. The reason for the $8.3\mu\text{m}$ measurement uncertainty will be made clear in Section 5.4. From the plot, it is apparent that 5-point boxcar averaging, in which a single point is averaged with the two points on either side, provides a significant improvement in scan quality. More aggressive smoothing could be applied by utilizing a greater number of adjacent points; however, this runs the risk of rounding out the sharp transitions of shallow indentations with steep walls which would compromise the accuracy of the feature extraction later as the slope contains few points axially. 5-point Boxcar smoothing offers a good compromise between minimizing the erraticity of the measured data while not being detrimental to the feature extractions process. Boxcar smoothing, coupled with the profile averaging listed above can produce line-scans with significantly less measurement noise.

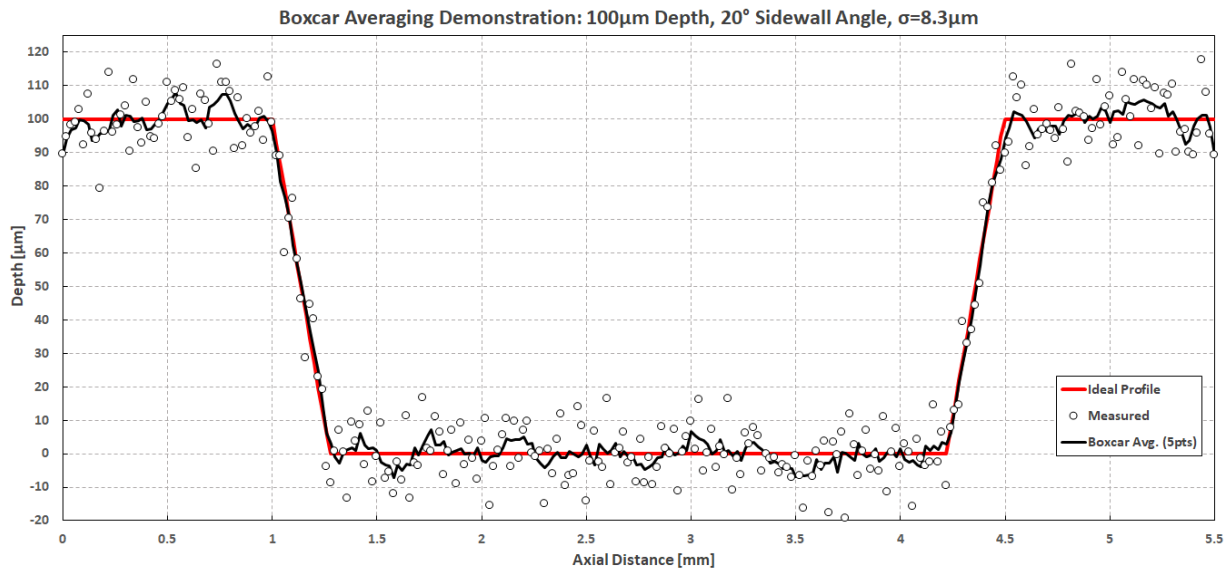


Figure 4.7: Boxcar Averaging on Simulated Data

Further processing steps are applied to the line scans prior to being subjected to the averaging and smoothing refinements. Points that are generated that fall outside of the 4-12mm wire diameter scanning range are rejected and patched with the data of neighboring points. To put it simply, a point that represents a measured radius of less than 2mm or greater than 6mm is deleted since it is likely erroneous, this missing point is then replaced by a point that is interpolated from the next valid adjacent data along the scanned profile. These errant points are often the result of corner reflections on the wire surface that cause the scanner to record unrealistic data. Any errant points that fall within the valid wire diameter scanning range are subjected to statistical filters to determine their validity; since the uncertainty of the system is known (which is a focus of discussion in the following chapter) the system can remove points that are statistically unlikely to exist by comparing the errant value to neighboring points. In this process, the average of a certain number of adjacent points is taken; if a point exists further away from this average by four times greater than the standard measurement uncertainty of the system, then it is highly improbable to be statistically valid and is likely a measurement error. It is important to note that 99.994% of observed data should fall within 4 standard deviations of the mean, so this is a rather simple way

to reject clearly invalid data. The offending point is then deleted and replaced with a point that is interpolated between the next valid data points. After the errant points have been removed and the averaging and smoothing steps have been applied, the scan mesh is left in a high-quality state. Figure 4.8 illustrates the scan refinement process on a scanned wire; once again, the height axis is exaggerated to help portray the effect.

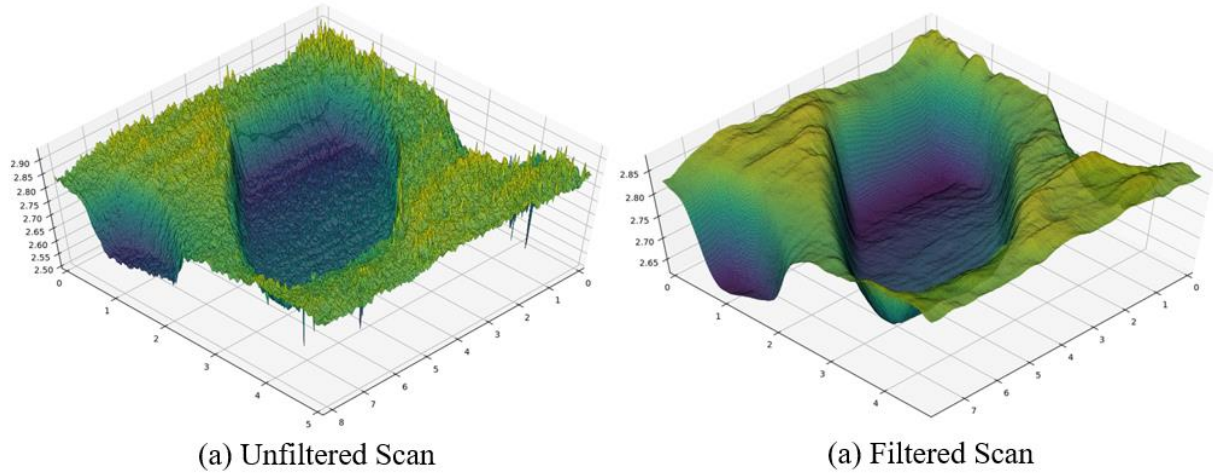


Figure 4.8: Scan Refinement of Wire Type WF

4.4 Scan File Format

Now that the scanning and filtering processes have been explained, the final discussion of this section will encompass the layout of scan file format. During the scanning process the wire is rotated along its longitudinal axis. As it does so, the light sheet of the laser module captures height profiles of the indented wire geometry at specific encoder pulses. As the wire is rotated the scanning process essentially “unwraps” the height profile of the indented wire and converts it into a two-dimensional array that contains the height information at a given location. This is called the height-map or heat-map. This height-map is made from the composite of the high-resolution slices and is illustrated in the upper right corner of Figure 4.9.

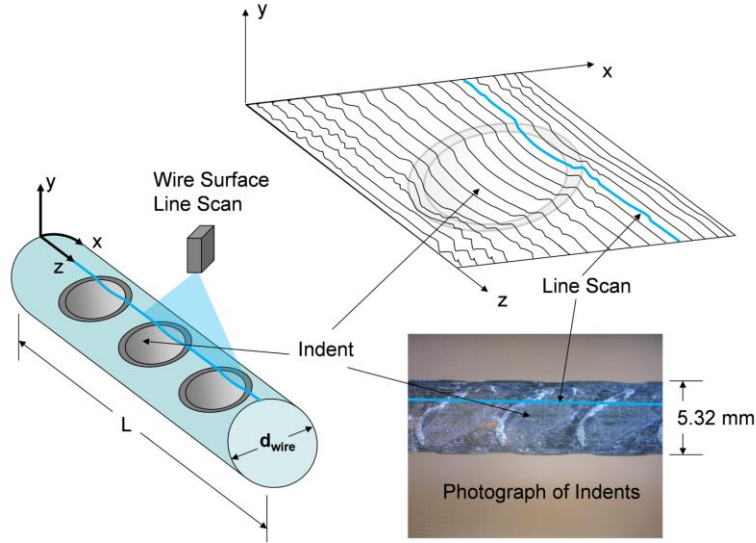


Figure 4.9: Schematic of Indented Wire Measurement (Sheet Laser)

The axial spacing of the data points is held constant by the sheet laser module, maintaining an axial spatial resolution of $20\mu\text{m}$ between points. It is desirable to maintain a uniform grid spacing for mesh manipulation; therefore, the circumferential resolution must also approximately be $20\mu\text{m}$. It is OK to have a circumferential resolution that is not exactly $20\mu\text{m}$, departure from this value has little effect on the data extraction process, it just makes mesh visualization easier since vertex decimation is trivialized. A depiction of the scanning grid based on spatial resolutions is summarized in Figure 4.10. The circumferential spacing is dictated by Eqn. 4.1, which shows that the circumferential resolution is a function of the nominal wire diameter, d_{wire} , and the number of encoder triggers per revolution, n . A 5.32mm diameter wire and an encoder set to 720 pulses per revolution, yields a circumferential resolution of $23\mu\text{m}$, which is sufficiently close to the goal of $20\mu\text{m}$. From the aforementioned relation, it is obvious that wires of larger diameter will need a higher number of encoder pulses for data acquisition since the circumference of the wire is physically larger if uniform grid spacing is to be honored.

$$\Delta d_{\theta} = \pi \times \frac{d_{\text{wire}}}{n} \quad (4.1)$$

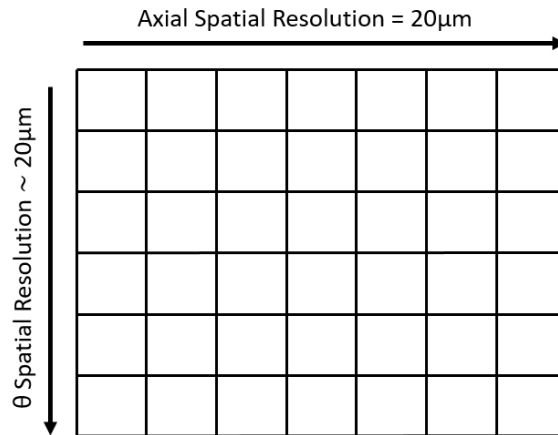


Figure 4.10: Scanning Grid Spacing

The scan file format is composed of the header information that is listed in the Wire Scan program and the two-dimensional height-map of the scanned segment. The layout of the scan file is shown in Figure 4.11. Each row of the two-dimensional data array represents a single line scan with 800 measured height values, corresponding to the scan line width of 16mm with a spatial resolution of 20 μ m, and is the result of a single encoder pulse. A 5.32mm wire will need 720 profile captures to maintain a roughly equal grid spacing, thus the WF wire represented in Figure 4.11 will have a scan file with 720 data rows, as it is a 5.32mm wire specimen.

Wire Profile	WF_630mm				
XIncrement	15				
X Location	0				
Total Sample Length	630				
Pts/rev	720				
XSmoothing	4				
XMedian	3				
YAveraging	8				
YMedian	3				
DataState	Trued				
TimeStamp	10/26/2018 13:47				
FileIndex	0				
Data					
2.7008	2.7033	2.7046	2.7057	2.7059	2.706
2.7007	2.7055	2.7048	2.7052	2.7049	2.7046
2.702	2.7009	2.6996	2.6979	2.6963	2.6957
2.6965	2.6969	2.6935	2.6919	2.6913	2.6922
2.703	2.7042	2.7016	2.6997	2.6984	2.6979
2.6912	2.6902	2.6883	2.6883	2.6903	2.694
2.6814	2.6789	2.6788	2.6794	2.6823	2.6869
2.6674	2.6661	2.6662	2.668	2.6718	2.676
2.6673	2.6672	2.6676	2.6682	2.6696	2.6712
2.668	2.6679	2.6666	2.6669	2.6687	2.6719
2.6711	2.6777	2.672	2.6681	2.6639	2.6608
2.6887	2.6884	2.6784	2.6718	2.6665	2.663
Encoder Index = 0,1,...,Pts/rev					
Scanner Index: j = 0,1,...,799 (800pts)					

Figure 4.11: Scan File Format

Chapter 5 - System Calibration

Non-contact laser based systems are capable of incredible accuracies, particularly once effective data filtering techniques are implemented. However, no mechanical system or measurement specimen is perfect and thus pose significant problems to measurement accuracy. Misalignments that are considered tiny have large ramifications when measurements are being conducted on the scale of microns. Mitigation of the effects caused by the natural cast “bow” of the wire along with sensor skew is the primary focus of this chapter. The reduction of sensor skew via the use of a correction map generated by a calibration cylinder will be the first topic of discussion, followed by the development of an effective process to correct for non-concentric specimen chucking and the bow that is inherent in indented steel wires. Later stages of this chapter will discuss measurement uncertainty and repeatability of the system after the scans have been corrected for sensor misalignment and wire bow. Finally, the measurement of indents that were machined with known indentation characteristics will be analyzed to verify the accuracy of the system.

5.1 The Necessity of System Calibration

Laser line-scan modules, or any laser based displacement measurement system for that matter, measures a displacement based on the reference point of the system. This reference point is often called the laser spot, also known as the point of greatest focus; coincidentally, it is also the location of which measurement uncertainty is minimized since the uncertainty is directly proportional to the spot size. For the Indent Profiling System, it is desirable to locate this reference point, or line in the case of the sheet laser, on the surface of the wire with the laser sheet coincident with the bore axis of the lathe assembly that applies the rotation to the wire being scanned. If this is accomplished, then the true height-map of the wire being scanned will be ascertained, neglecting wire bow. However, perfect alignment of a mechanical system is not realizable and generates error where misalignment exists. To put the importance of correcting for system misalignment into perspective, if the laser head is misaligned by 0.1° in the yaw rotation for a scan width of 16mm, an error of $28\mu\text{m}$ is induced across the scan length. Bear in mind that most wire indents are about $100\mu\text{m}$ deep. Alignment of the mechanical system can only go so far, even with the inclusion of precision linear translation stages and micrometers to assist with the alignment of the system. However, a majority of the alignment error can be mitigated by scanning a specimen with known physical dimensions and applying a correction map to the captured data to account for the misalignment of the system. This calibration procedure is summarized in the following section.

Wire cast “bow” is another problem that requires correction via mechanical wire guides and software processing. Indented steel wire has a natural cast and is stored in large wire spools; the natural cast of the wires can be a few inches over a 2-foot segment of wire after it is removed from the reel. This poses significant problems when it comes to accurate measurement of the wire surface as the centroid of the wire profile is no longer in alignment with the rotational axis of the scanning system due to the bow. As the wire is constrained by the mechanical alignment bushings on the carriage frame it forms a parabolic curve. Once scanned, this observation can be used to correct for the wire bow, thus straightening the wire and forming an ideal measurement; this procedure will be the primary focus of Section 5.3. When system misalignment and wire bow have been properly accounted for, the Indent Profiling System is capable of measuring profiles with micron levels of precision.

5.2 Correcting for Sensor Skew

5.2.1 Sensor Misalignment Leads to Distorted Data

For the sake of illustration, imagine the wire is suspended horizontally. Now envision being in the cockpit of a plane flying straight towards the wire with the wings parallel to the wire length. The plane represents the line-scan laser scanning the surface of the wire, casting a sheet of light that measures the surface. The visualization concerning the plane is a convenient way of describing the orientation of the scanner in the discussion to follow: pitch involves aiming the scanner sheet up or down, yaw rotates the sheet left and right, and roll rotates the laser sheet as if the plane was spinning about its axis from nose to tail. The rotational degrees of freedom of the laser sheet are shown in Figure 5.1.

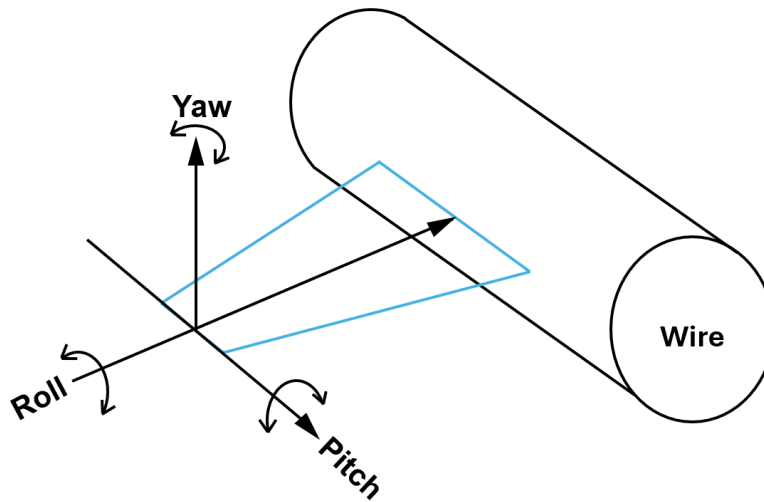


Figure 5.1: Laser Sheet Orientation

If the sheet laser is perfectly aligned with the wire (pitch, yaw, and roll all equal 0°) and the reference point is in the perfect position, then the ideal scan of the wire is obtained and the measured height-map perfectly matches the surface of the scanned wire. If the scanner is perfectly aligned, but too close to the surface then the object will appear too large since the scanner is measuring a larger displacement with respect to the reference point; conversely, being too far away makes the object too small. If the yaw error is introduced, then the resulting scan appears as a truncated cone. If pitch error is introduced, the size of the cylinder appears incorrect, slightly larger than the ideal case. If roll error is introduced, then the scan forms a hyperboloid. Any of these errors are cumulative and significantly affect the resulting scan profile. However, once it is understood that the alignment errors involved are small, the distortion caused by the misalignment of the sensor is predominately second order in nature. By scanning a specimen of known geometry, it is possible to apply a correction map to the captured data, placing the data points where they truly belong as if system misalignment did not exist in the first place.

5.2.2 Calibration Cylinder

For the calibration process, specimens with well-known geometrical properties are required; precision ground cylinders are ideal specimens to use for this purpose, since the nominal diameter

is constant about the length of the specimen. A scan of such precision ground cylinder is seen in Figure 5.2; in this case a 5mm (0.1970in) specimen from McMaster-Carr [2320A002].

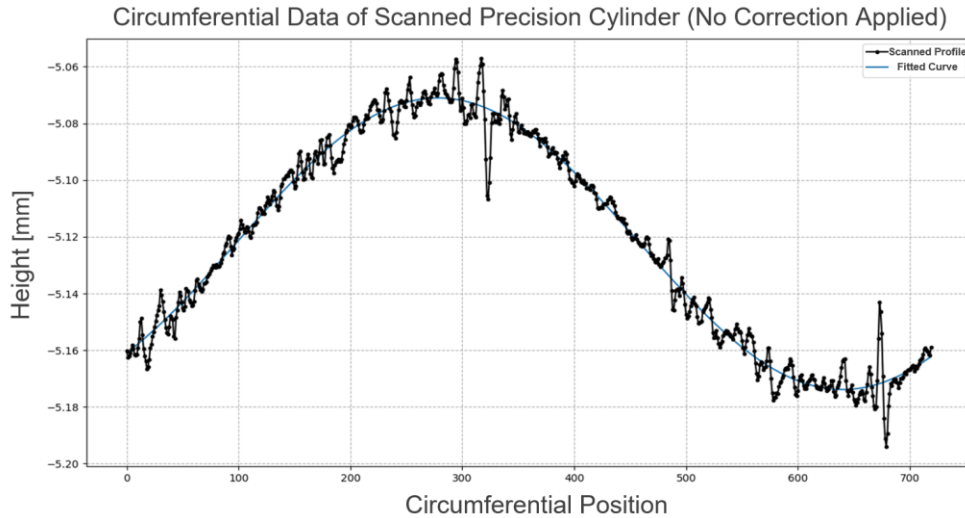


Figure 5.2: Calibration Cylinder Scan

Figure 5.2 represents the uncalibrated data obtained when a precision ground cylinder is scanned with the light sheet aligned approximately axially. The particular data shown in the figure is the height profile measurements along the circumference of the cylinder at a specific longitudinal position. Through this data, a line of best fit is obtained via a Fourier transform, the phase of which is locked to 360° . The runout measured, which is the amplitude of the fit, is the culmination of the non-concentric positioning of the precision ground cylinder in the lathe chuck, off axis rotations caused by slight angular misalignment of the specimen in the chuck, and finally, of primary interest, the distortion caused by the misalignment of the laser measurement system. By applying similar Fourier analysis on every scanned circumferential section, it is possible to isolate the error caused by specimen alignment and runout since the precision ground cylinder is approximately a perfect cylinder with a constant diameter. The remaining error is the byproduct of system sensor misalignment alone, neglecting thermal disturbances. This, as expected, generates a displacement correction map for a specimen of given size, in which the alignment errors are approximately second order. When a new scan is made, the calibration map is added to it, thus accounting for the misalignment error of the system and placing the measured data in the correct location. An example of the calibration results can be seen in Figure 5.4 in which the calibration cylinder has been corrected for system misalignment; the calibrated scanned diameter is within 1 micron of the nominal diameter specified by the precision ground cylinder.

5.3 Off-Bore Rotation (Wire Bow)

Indented wires, as stated previously, have an amount of cast “wire bow” for a given length of wire. The manufacturing process leaves a natural bow in the wire that is often not removed, some wires exhibit cast of multiple inches across a 2-foot length. The Indent Profiling System uses bushings on the carriage to center the wire for the line-scanner, support the length of the wire, and minimize wire bow; the bushings have an internal diameter that closely matches the maximum diameter of the particular wire specimen being scanned. One of the brass bushings can be seen in Figure 3.4. The cast of the wire is constrained by the two bushings, alleviating the severity of the inherent bow, but not completely eliminating it. This represents a problem, in that the off-axis rotation of

wire cross-sections due to the bow causes an unavoidable distortion in the scan. In this situation, the longitudinal axis of the wire is not in line with the bore-axis of the lathe.

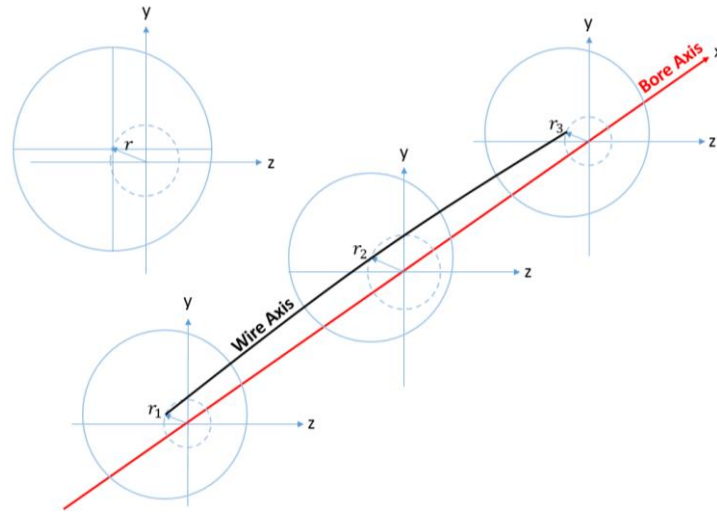


Figure 5.3: The Effect of Wire Bow on Off-Bore Rotations

Wire cast “bow” can be corrected through the use of certain processing steps. As the wire is constrained by the alignment bushings on the carriage frame it forms a parabolic curve; technically, this curve is circular in nature, but the small arc segment constrained by the bushings is considered parabolic. An illustration of the effect of wire-bow on off-bore rotations is given in Figure 5.3. Once it is understood that the wire bow centroid follows a parabolic arc, the procedure listed below can be used to manipulate the scan and correct the indented wire to a straight cylinder, free of bow distortions.

- (a) Determine locations of the wire ribs, the areas where indentations do not exist. Indent row locations, and conversely, rib locations, can be found using Fourier transforms on the average scan profiles (outlined in section 6.2.1). The method of using profile flatness can also be used (outlined in section 6.2.2) to programmatically assess where non indented profiles lie.
- (b) Identify bow direction. For each slice of the wire profile in the y-z plane, compute the axis offset, r , using the non-indented rows. This is accomplished by taking a circle fit of the points that lie on the wire rib locations and determining the displacement from the bore axis of the measurement system. This is done for each unique axial measurement location, 800 each per wire segment scan.
- (c) Fit the axis offsets to a parabolic equation, $r = f(x)$.
- (d) Using the parabolic equation and bow direction, remap the distorted data to an ideal cylinder with no bow. Since the displacement and angle of the scan profile from the bore axis of the system is calculated, it is possible to remap the data to the bore axis as if wire bow does not exist.

This method is effective at eliminating the bow inherent to the indented steel wires being scanned. After it is properly executed, little to no trace of the bow exists. After the calibration map has been applied and the wire bow has been removed the wire scan is in an ideal state and is ready for processing by the algorithms described in Chapter 6.

5.4 Measurement Uncertainty and Repeatability

Once sensor misalignment has been dealt with via the aforementioned calibration steps, and off-bore rotations caused by nonconcentric specimen chucking or inherent wire bow has been eliminated through software correction, an ideal trued scanned surface is obtained. The trued scan is largely error free from the distortions caused by sensor misalignment or cast of the specimen; accuracy to the true specimen dimensions is on the order of microns. By scanning a specimen of well-known geometrical properties, such as the precision ground cylinders used in the prior section and applying the necessary corrections, it is possible to obtain an assessment of the uncertainty and repeatability of the optical system in this case, a laser-line module. A scan was taken of such precision ground cylinders with a nominal diameter of 5.004mm [0.197in] and 10mm (0.3940”), with a tolerance of 0 to 0.005mm [0 to 0.0002in], and a maximum RMS surface roughness of 0.25 μ m [10 μ in]. These precision cylinders were obtained from McMaster-Carr as class ZZ go pins (item 2320A002). The resulting height-map of the 5.004mm [0.197in] precision ground cylinder, after calibrations and off-axis rotation corrections have been applied, can be viewed in Figure 5.4. In this figure, μ represents the average scan height, analogous to cylinder radius, implying almost perfect agreement between the corrected data and the measured precision ground cylinder. The bottom of the figure represents a height map of the corrected data, through which the red line corresponds to a corrected line-scan, seen directly above the heightmap. Note how the measured diameter is a fraction of an micron off from the nominal diameter of the calibration cylinder, this indicates that an ideal scan has been achieved; to put this in perspective, the width of a thick human hair is on the order of 100 μ m.

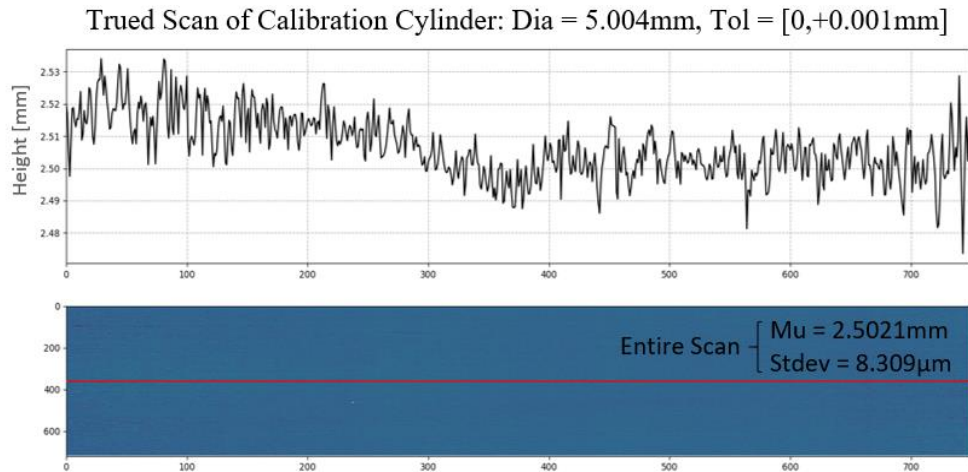


Figure 5.4: Trued Calibration Cylinder Height-Map

A histogram of the binned heights of the trued calibration cylinder height-map is provided in Figure 5.5, in which, the measured height is analogous to radius. From the histogram, it is clear that the scatter of the measurements from the optical system follows a Gaussian distribution as expected. However, the uncertainty is computed to be 8.3 μ m, greater than the theoretical uncertainty (<2 μ m) of a blue laser with spot width of 45 μ m. As an aside, the laser module can never hope to measure the surface roughness of the calibration cylinder in the first place since the RMS roughness is smaller than the resolution capability of the laser module. Thus, this is not the direct limiting factor in the measurement uncertainty.

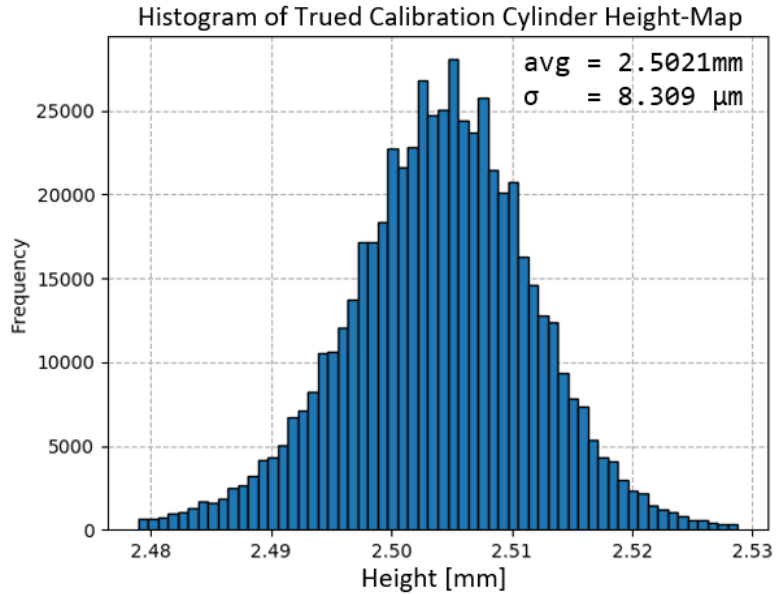


Figure 5.5: Trued Calibration Cylinder Histogram

By looking at adjacent laser scan profiles, the source of the higher than expected measurement uncertainty becomes apparent. Figure 5.6 shows five adjacent data lines from the measured of an indented wire rib. From this figure it is obvious that the low frequency and high frequency noise show significant similarities across adjacent profiles, separated just microns apart from one another and still being partially illuminated from the same laser light sheet. The same figure shows high system repeatability when the same location is scanned; on the order of less than two microns. The similarity of the low and high frequency content across adjacent profiles is indicative of broadband noise, and thus, implies that laser speckle interference (LSI) is the culprit of the higher than expected measurement uncertainty [47]. Laser Speckle Interference is a repeatable phenomenon and has been used to generate a transfer length measurement system for a previous FRA project [47].

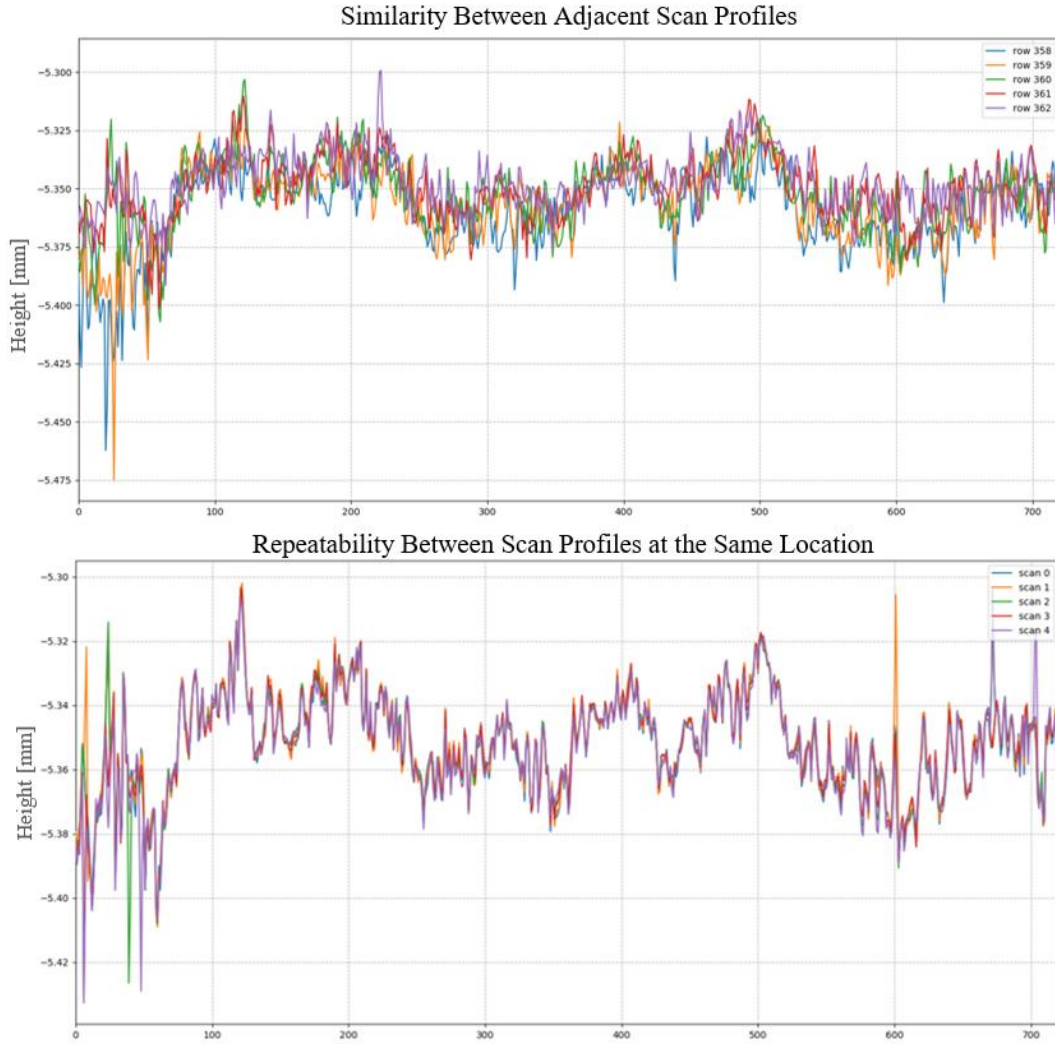


Figure 5.6: System Repeatability

Laser speckle interference is inherently broadband and is a mostly unavoidable phenomenon when a coherent light source illuminates a surface. This effect is illustrated in Figure 5.7, in which a coherent light source impinges upon a surface of given roughness and reflectivity. The scattered light generates constructive and destructive interference at a given distance away from the illuminated surface, such as at a location of an imaging array is located (or the eye of the observer).

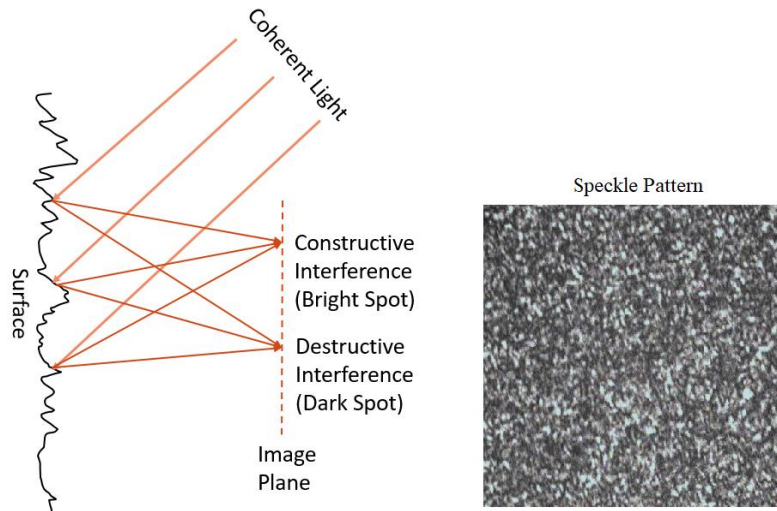


Figure 5.7: Laser Speckle Interference

This effect is generally undesirable from a measurement accuracy standpoint as it represents noise that cannot be filtered out because it is broadband. However, sometimes this effect can be used positively as a method to conduct displacement measurements. Figure 5.8 highlights such a system. The laser speckle interferometer was made for a prior FRA project to measure strain profiles of prestressed concrete railroad ties [7][47]. It used the displacement of the laser speckle pattern images to track and correlate displacements using a known gauge length between a dual camera imaging system. However, in the application of the Indent Profiling System such an effect is undesirable as it introduces a fixed biased profile shape in the measured displaced laser profile. This phenomena is characterized by broadband noise that cannot be filtered out, leaving the laser line scanner with a nominal radial measurement uncertainty of $8.3\mu\text{m}$.



Figure 5.8: Automated LSI System on Concrete Ties in Plant

This measurement uncertainty is significantly reduced by the filtering and averaging techniques applied in Chapter 4. The system is accurate enough to achieve reliable measurements on most indented wire geometry in practice since indent depths of 5.32mm wire are typically on the order of $100\mu\text{m}$, an order of magnitude above the measurement uncertainty of the system. Additionally, the system is not taking single measurements in either the basin of the indent or the crest of the

indent; it is taking hundreds of measurements. The blue line laser, a Keyence LJ-V7060, was used due to the high amount of data that it could acquire over the given area of interest and has a level of measurement uncertainty that is amenable to the measurement of most indent geometries in practice. The amount of data collected, coupled with the reasonable uncertainty of the measurements and the processing algorithms highlighted in Chapter 6, lead to reliable extraction of indent geometrical features.

5.5 Machined Indents

In this section the system was used to measure the characteristics of machined indents, which represent indent shapes of known geometry. A set of machined indented wires of known geometry was created for a different FRA research project prior to the involvement of the author [37]. For that project, the machined wires were created for a similar purpose, to provide a system checkout for the precursor to the Indent Profiling System described in section 2.3; this research leveraged these samples as well since they represent known geometry. This was done in order to verify the correction steps in the aforementioned sections and test out the algorithms that will be explained in great detail in the following chapter, Chapter 6. These indents were made by machining grooves with an end mill in the sides of wire similar to the wire used in the manufacturing of typical prestressed indented wire. A photograph of a resulting sample row of these indents is shown in Figure 5.9, which represents a groove made with an end mill having a 30° chamfer angle, with an equivalent machined indent orientation of 45° . The blue line shown in the Figure represents the scan path of the laser line scan at a single rotation angle position corresponding to the center of the indent row. It should be noted that these machined indents, unlike actual indents which are formed by deforming (indenting) the wire surface, are created by removing a small amount of material from the associated wire via an end mill. These fabricated indents provide an ideal test case for the checkout of indent feature extraction algorithms since they represent features of known geometry.

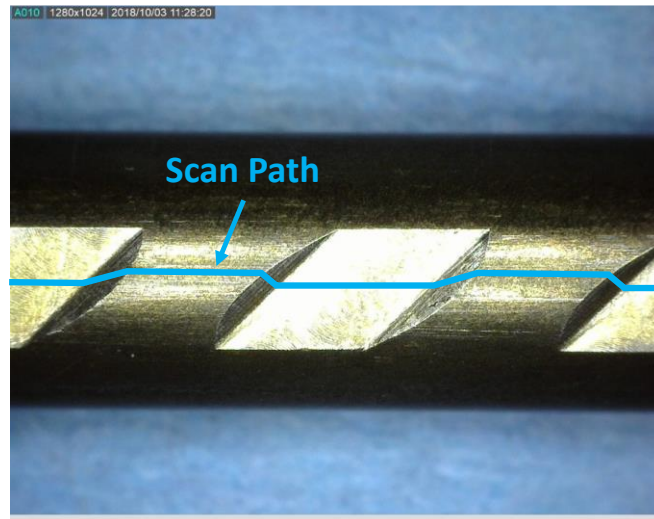


Figure 5.9: Sample Scan of Machined Indent (30°)

The basic concept behind the feature extraction algorithms in the Indent Profiling System is to reduce the indent shape to a series of slices that can be approximately represented by a curve fit, typically a trapezoidal shape for a chevron style of indent, as suggested in Figure 5.10. This

trapezoidal shape is well-suited for the basic Chevron indent profile, the indent most common in industry; however, the trapezoidal shape would not apply to a dot shaped indent.

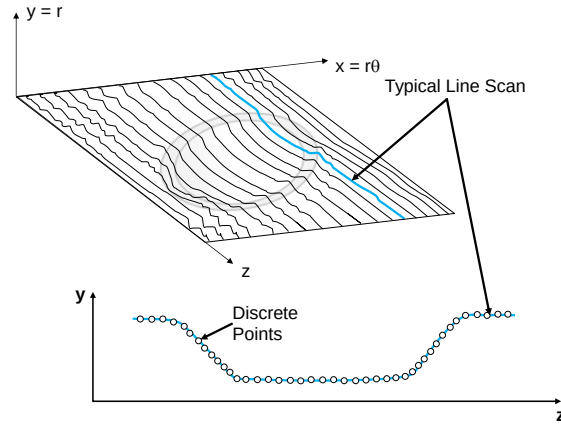


Figure 5.10: Basis for Feature Extraction (Trapezoid Slice)

This type of trapezoidal fit is shown applied to a longitudinal slice through the center of the machined indent shown in Figure 5.9, along with some characteristic measurements of the sidewall angles, is shown in Figure 5.11. While the machined indents represent the ideal indent geometry, having straight sidewalls, basins, and crests, the fit of a trapezoid to the indent profiles of manufactured indented wires is a fantastically close approximation to real wire geometry.

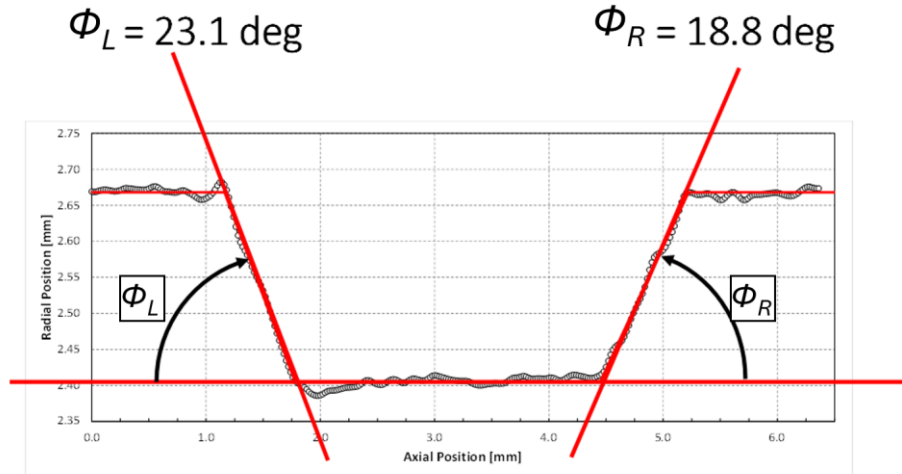


Figure 5.11: Trapezoidal Slice for a Machined Indent (30°)

Note that the measured sidewall angles do not correspond to the 30° end mill chamfer angle. The reason for this can be explained by considering the diagram shown in Figure 5.12, which compares the end mill chamfer angle, θ , to the actual measured indent sidewall angle, ϕ . The simple algebraic relationship shown in the Figure follows directly from the relationship between the blue line scan and the red end mill chamfer line. For a 30° chamfer angle and a 45° orientation angle, the resulting theoretically measured sidewall angle for the machined indent is

$$\tan \phi = \frac{1}{\sqrt{2}} \tan \theta = \frac{1}{\sqrt{2}} \tan(30 \text{ deg})$$

$$\phi = 22.2 \text{ deg}$$

which compares well to the values measured on the left and right sides of the machined indent, as shown in Figure 5.12. It is important to note that this relationship is valid for indent centerline geometry.

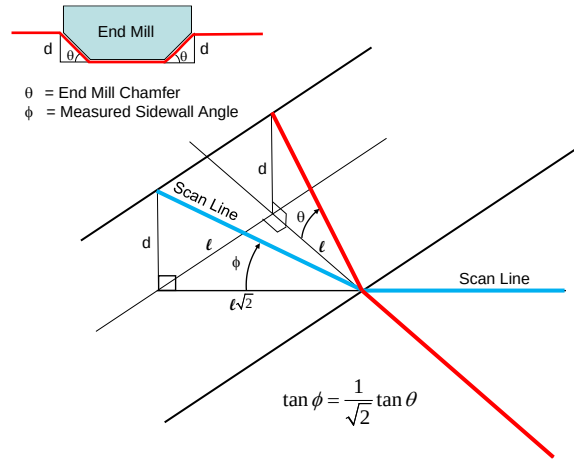


Figure 5.12: Measured Sidewall Angle Relationship

Furthermore, the data summarized in Figure 5.11 indicates an indent depth, measured along the centerline, of 270 μ m (0.0106in). Comparison with a mechanical dial indicator with a resolution of 0.001in yielded a measured indent centerline depth of 0.010in of the same indent, a reasonable agreement considering the resolution limitation of the dial indicator.

This measurement example highlights the effectiveness of the aforementioned correction steps, demonstrates how closely a trapezoidal shape approximates indents of known geometry (and later, formed geometry), and generates confidence in the reliability of the system at extracting accurate indent features. A multitude of machined wires from a prior FRA project [37], representing 12 specimens of varying sidewall angles and depths, were measured by the Indent Profiling System and will be the subject of further discussion in Section 7.3. Furthermore, multiple modern wires that have recently seen use in industry, as well as indented wires extracted from concrete crossties that have been in service spanning the course of years to multiple decades, will be subjected to processing as well. The discussion of the results generated by the Indent Profiling System will come after an explanation of the feature extraction algorithms is given in the section that immediately follows.

Chapter 6 - Process for Extracting Indent Geometry

The primary objective of the Indent Profiling System, above all else, is to accurately extract the geometrical features of the wires that have been scanned. Prior chapters have been dedicated to the acquisition of scan data, the refinement of the captured data, and the development of calibration techniques used to generate data that is ideal for processing. The following section will focus on the development of algorithms that will be used for the extraction of indent geometry.

The algorithms highlighted below will be well suited for analyzing chevron type indentations, by far the most common type of indentation seen in industry, seeing extensive use in smaller diameter wires. Other indentation types include wires with dotted or spiral shaped features; however, these indentation types are not as prevalent. The indent feature extraction process is generalized enough to work for any discrete indentation type that is formed into individual rows. The general process that indent feature extraction utilizes is described in the following steps. First, the individual, trued scans are spliced together to form one contiguous scan that will be subjected to feature recognition. Second, the locations of individual indents are determined by row position, indentation pitch, and the orientation of the indents; individual indents are then isolated for feature extraction. Third, each indent is processed by algorithms appropriate for the indentation style to obtain the important features of the indentation. Fundamentally, the algorithms used to extract the indent features of chevron type indents are implemented differently than those used for dotted or spiral indentations. While algorithms for extracting geometry of dotted or spiral style indentations are not covered in the scope of this dissertation, development would follow a similar path to the chevron type extraction. Finally, after all isolated indents have been subjected to processing, a report is generated summarizing the results. The final report includes: results summarized in ASTM A881 and ISO 10138-2 format, an example height-map of the scanned indented wire, and detailed statistics and histograms showing variations on a row-by-row basis, in addition to the primary results file.

It is important to note that the development and implementation of the extraction algorithms in this chapter were a collaboration between the author and John Bloomfield. The author generated the algorithms highlighted in this chapter based on the preliminary data from the Indent Profiling System; John Bloomfield later integrated these algorithms back into the system until it was fully featured. The author then developed a post-processing program that generated more data than the original Indent Profiling System initially provided; this additional data is represented in Chapter 7 and used in the correlations overviewed in Chapter 8. A detailed discussion of the results obtained using the algorithms below will be the subject of Chapter 7 - Overview of Collected Data, and the wire report summaries of wires relevant to the scope of this dissertation are detailed in Appendix C.

6.1 Scan Splicing

Up until the point of feature extraction, scans are contained as individual segments. However, for the purpose of indent isolation and feature extraction the scans must be joined into one continuous entity, as illustrated in Figure 6.1.

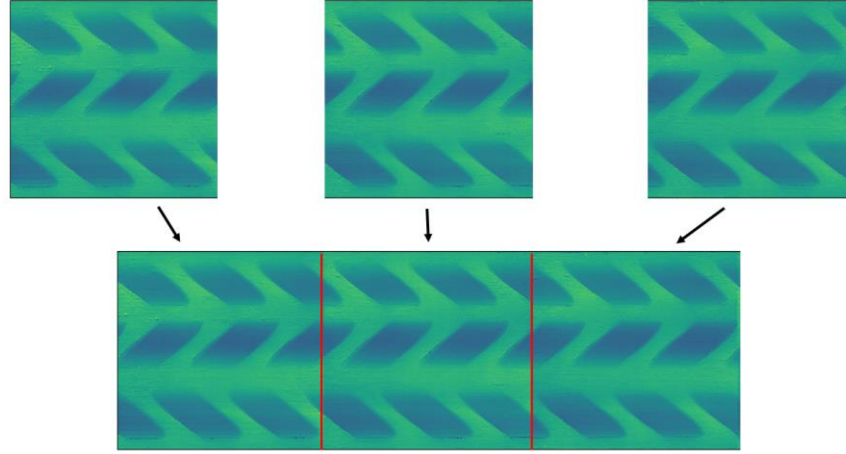


Figure 6.1: Scan Splicing

In order to obtain statistically relevant sample sizes, it is desired to capture the entire pattern formed by the indent rollers on the steel wire, as those indents represent statistically unique samples. As such, scans with a total length of 25 inches (630mm) are common in order to capture one full repetition of the wire pattern, corresponding to indent rollers of 8 inches in diameter commonly seen in industry. The line-scan module utilized by the Indent Profiling System captures the indent surface features across a 16mm length. However, it should be noted that line-scan lasers see increased measurement uncertainties at the extremities of the scanning width. This is an unavoidable byproduct of mathematics related to the processing of the edges of the imaged profile; however, the discussion of sensor binning and detailed Fourier analysis used to process the image profiles are outside of the scope of this dissertation. A visualization of the increased measurement uncertainty at the fringes of the full scan can be viewed in Figure 6.2 which highlights the undesirable effect on a scan that has not be subjected to the calibration procedure.

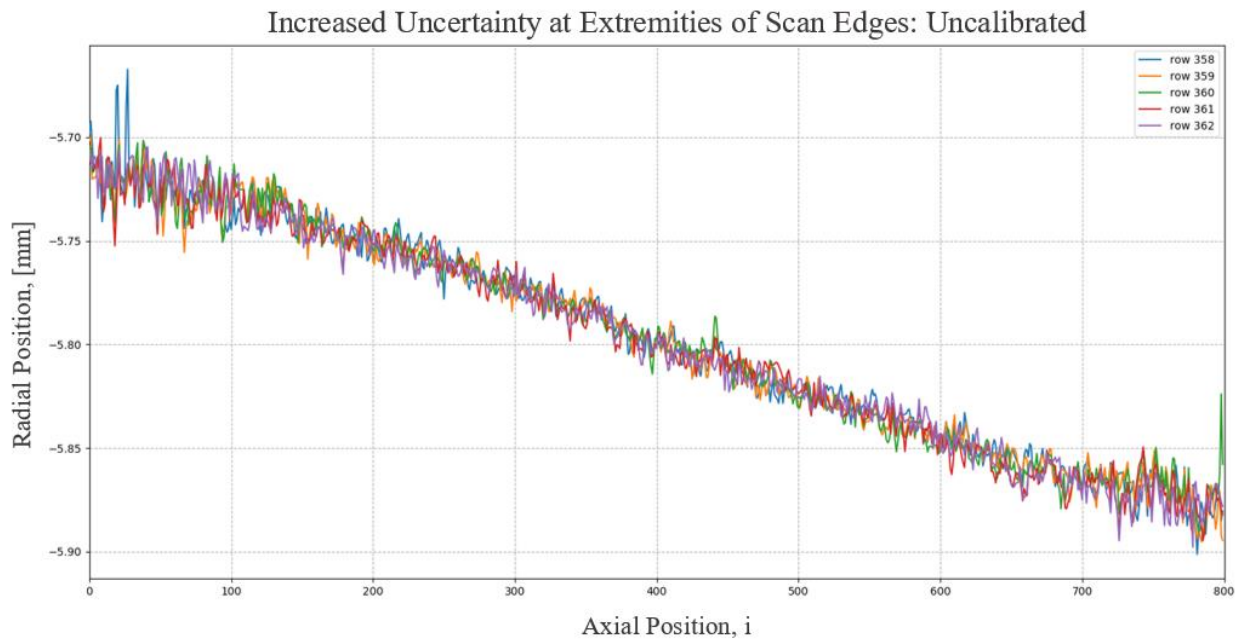


Figure 6.2: Increased Measurement Uncertainty at Edges of Line-Scan

From the standpoint of statistics collection, it is favorable to have measurement uncertainties that are consistent throughout the range of the data. Section 5.4 contains a detailed discussion of the measurement uncertainty of the system once calibration procedures were applied. A measurement uncertainty of 8.3 microns was determined for 90% of the scan in the center of the profile. Instead of inheriting the increased measurement uncertainty at the edges of the scans it is more reasonable to omit the edges of the scan. By settling with a scan width of 15mm instead of the initial 16mm, it was possible to ignore the effects of increased uncertainty at the edges of the scan. For a 630mm (24.80in) scan length, with a 15mm scan width, this corresponds to 42 scans of the wire specimen to be captured.

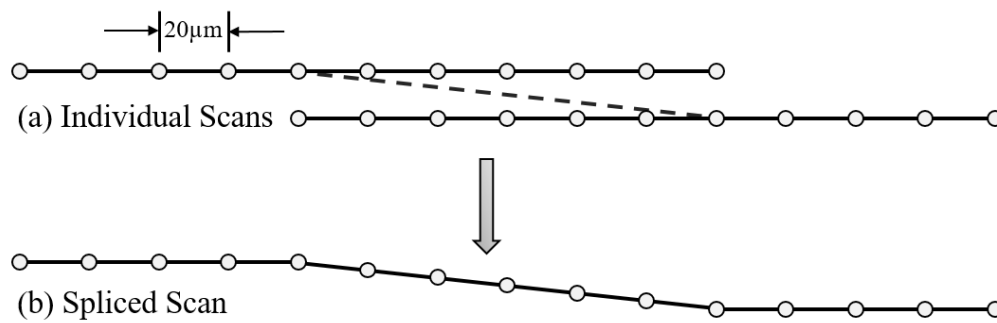


Figure 6.3: Method for Joining Overlapping Scan Segments

Due to the accuracy of the scanning procedure after calibrations and data correction steps have been applied, it is possible to simply align the scan profiles from end to end, illustrated as such in Figure 6.1. However, it is also possible to overlap the edges of the scans as seen in Figure 6.3(a), interpolate between the two overlapped sections, and obtain a smoothly spliced section as illustrated in Figure 6.3(b). From a feature extraction perspective, this interpolation step affects nothing, however, it does make the contiguous scan more attractive from a data visualization standpoint as it does not leave a step of a couple of microns at the transition created between the scan segments. Once a contiguous scan has been formed from its component scans, it is then possible to proceed with data visualization, feature recognition, and geometry extraction as highlighted in the subsections below.

6.2 Indent Row Detection

With the creation of a contiguous scan the procedure of feature recognition can begin. However, prior to isolating individual indents for analysis, it was necessary to determine the location of the indent rows that the indentations form. From the manufacturing process, the indent rollers form discrete indents, with a particular spacing (pitch), into rows separated at equal intervals about the circumference of the wire. Once the positions of the indent rows have been detected with respect to the scan, later processing steps were used to locate the individual indents that compose the row.

6.2.1 Averaged Trilobal Shape and Fourier Analysis

The majority of indented wires used in industry are manufactured with three indented rows, equally spaced about the circumference of the wire, with one of the rows having an orientation contrary to the other two. In practice, the indent rows are not equally spaced about the circumference of the wire due to imperfections in the manufacturing process, but the following method still stands. The observation of a finite number of equally spaced rows trivializes the detection of the indent row positions. Each longitudinal profile of the continuous scan can be averaged, yielding the average trilobal shape of the wire as a function of angular position. A trilobal shape is a mix between a circle and a triangle; as the indent rollers press the indents into the wire, the steel is deformed, and thus, forms a shape that is roughly trilobal in nature. The cross-sectional view of a wire shown in the bottom right corner of Figure 4.2 clearly illustrates the trilobal shape of a scanned indented wire.

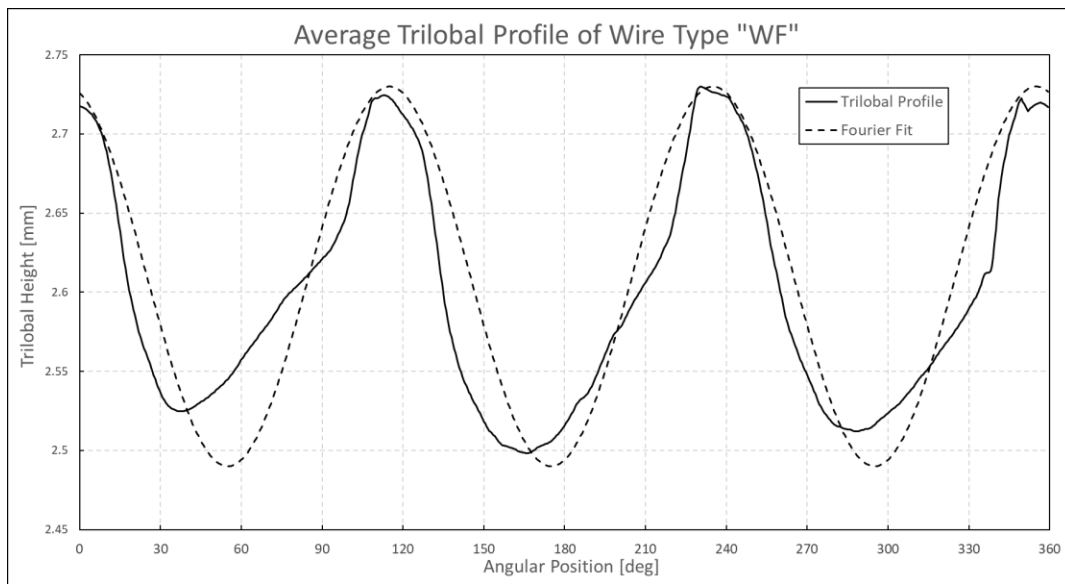


Figure 6.4: Obtaining Indent Rows From Average Trilobal Profile (Wire Type “WF”)

From the trilobal profile, it can be seen that there are three distinct peaks and troughs that represent where the indent rows are with respect to the scan, an example of which can be visualized in Figure 6.4. From Figure 6.4, it is clear that the indent ribs, the areas that are largely unaffected by the deformation process caused by the indent rollers, occur at positional increments of 115° , 235° , and 355° with respect to the scan origin. Note how those values are separated by increments of 120° , implying three equally spaced rows. By applying a Fourier transform of fixed frequency on the averaged trilobal profile data, it is possible to extract the points that separate the indent rows. The separation points are represented by the peaks of the fitted sinusoidal function illustrated in Figure 6.4. The method of using Fourier transforms to analyze the indent row locations based on the average trilobal profile of the scan yields accurate results and is applicable to any wire composed of an arbitrary number of equally spaced indents rows.

6.2.2 Alternative Method: Determining Profile Flatness

An alternative procedure can be used to automatically determine the locations of indent rows. This method can be applied to a wire with an arbitrary number of indented rows with equal spacing or, more interestingly, unequal spacing. Instead of using Fourier transforms to analyze the averaged

trilobal shape of the wire being scanned, this method assesses the relative flatness of the longitudinal profiles that the scan is composed of. Since the contiguous scan is composed of individual scans that have had calibration and wire-bow corrections applied, the space between the indented rows, the ribs, are mostly free from the deformations caused by the indent rollers. As such, the scanned profiles along the ribs of the wire are significantly flat. By assessing the flatness of the longitudinal profiles as a function of angular position, it is possible to ascertain the positions of the indented rows. This can be seen in Figure 6.5 which shows a depiction of the flatness of the longitudinal profiles of wire type “WF”.

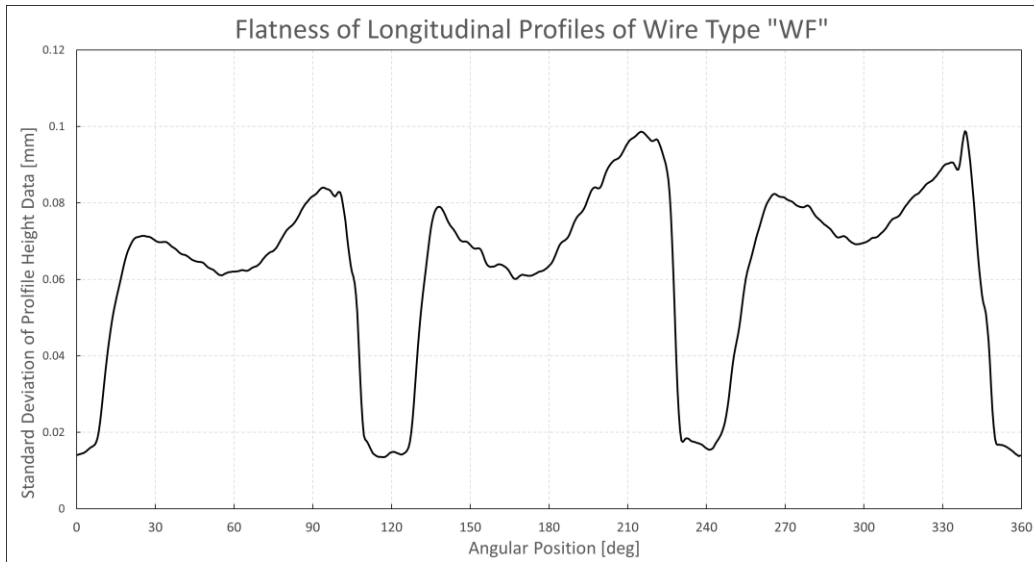


Figure 6.5: Location of Indent Rows From Profile Flatness (Wire Type “WF”)

Due to how the scans are aligned, flatness is analogous to the assessment of the standard deviations of the heights of the longitudinal profiles. From Figure 6.5 it is clear that the points of greatest flatness occur where the standard deviations of the profiles are lowest, thus, it can be determined from this particular example that the indent row transition points are located at 120°, 240°, and 360°. Figure 6.6 is a composite illustration of the previous figure with height-map of wire type “WF”. It clearly shows how profile flatness corresponds with indent row transitions. This methodology is a reliable way of extracting the points at which the transition between indent rows occurs. Furthermore, it works for any arbitrary number of indent rows, or indent rows with unequal circumferential spacing. When paired with robust basin detection algorithms, the flatness of the data as a function of angular position can be analyzed, and indent row transition points can be determined with acceptable precision.

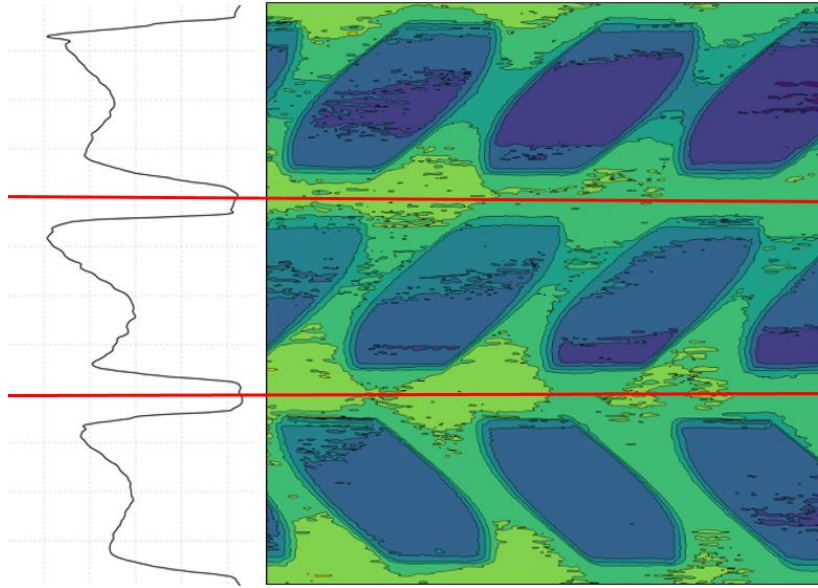


Figure 6.6: Indent Row Detection

6.3 Determining Indent Location and Orientation

Once the indent row locations have been identified by the algorithms detailed in the section above, the detection of individual indents can proceed. To successfully isolate indents, the topic of section 6.4, a determination of pitch and orientation for the indents contained by each row is required. Indent pitch is determined using the following process. First, the centerline of each indent row is selected, located directly in between the indent row transition points. Along the centerline profile are the depressions caused by the indents. Upon the centerline profile, Fourier analysis is once again performed, returning the pitch between the indents in the associated row. This can be visualized in Figure 6.7(a) which illustrates the pitch between neighboring indents, determined from the Fourier analysis.

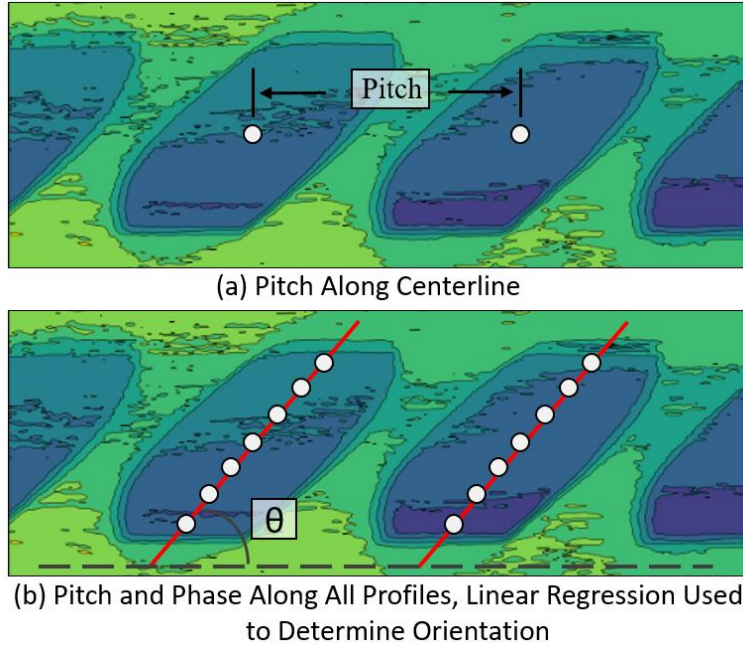


Figure 6.7: Determining Pitch and Orientation Angle

Next, the extraction of indent row orientation is necessary. Holding the previously calculated pitch constant, Fourier analysis is carried out on the rows adjacent to the centerline profile to obtain the phase offset of the adjacent profiles with respect to the centerline profile. This processing is carried out on all profiles contained by the width of the indents; the profiles that are contained by the indent width are determined by the flatness of the profiles, or the magnitude ratio of the Fourier analysis. As suggested by the prior section, indentations exist where the standard deviations of the longitudinal scan profiles are higher; conversely, the areas of greater flatness, the ribs, are characterized by lower standard deviations. Alternatively, profiles that have a magnitude ratio approaching zero after Fourier analysis has been performed lie on a rib; larger magnitude ratios imply the existence of indents. The obtained pitch and phase offset points are illustrated in Figure 6.7(b) as white dots representing the location of the trough of the Fourier transforms on the longitudinal profiles. Through these points, a line of best fit is calculated, seen as a red line in Figure 6.7(b), thus determining orientation of the indents in the row, θ , with respect to the x-axis of the scan, the dashed black line. This methodology is then applied to every indent row, calculating indent pitch and orientation to a high degree of accuracy. Because of how orientation angle was computed, each indent row is assigned one orientation angle associated with all of the indents contained by the row. The orientation angle is then used to isolate individual indents contained in each row.

6.4 Indent Isolation

The one hurdle remaining prior to geometrical feature extraction was the isolation of individual indents from the rest of the scan. In this process, the indent row locations along with indent pitch and orientation are used to determine the bounds of the individual indents. Figure 6.8 provides a depiction of the detected boundaries of the indents based on indentation orientation, indent pitch, and indent row width for wire type WF; this is applied on all three rows of wire.

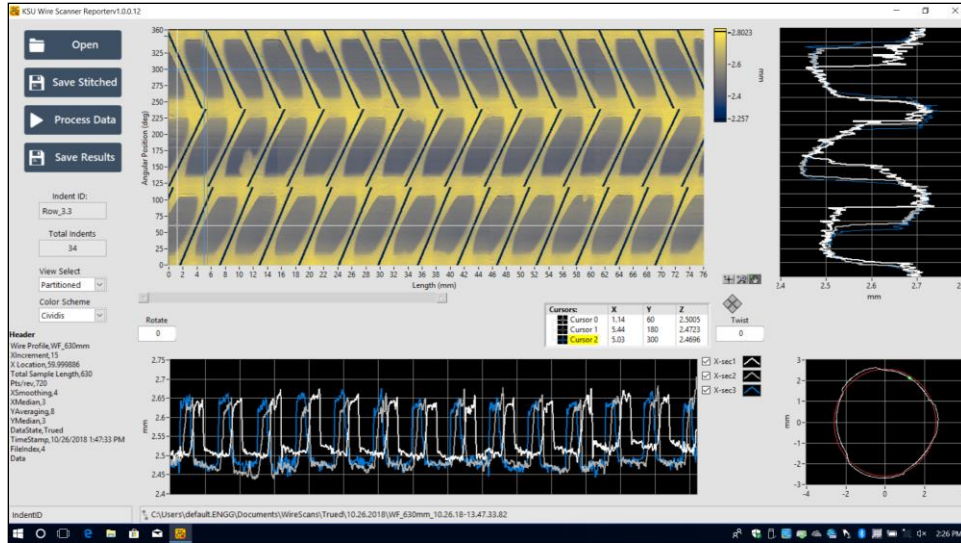


Figure 6.8: Wire Scan Reporter Indent Partitioning

The calculated boundaries of the individual indents are then compared with the limits of the contiguous scan. If an indent is not completely contained within the bounds of the scan, it is classified as a “partial” indent, and thus, is omitted since complete data does not exist for it. The picture contained in Figure 6.9 shows the “complete” indents that fall within the confines of the acquired data. Once the indents have been successfully isolated, they can be subjected to the feature extraction process summarized in the following subsections.

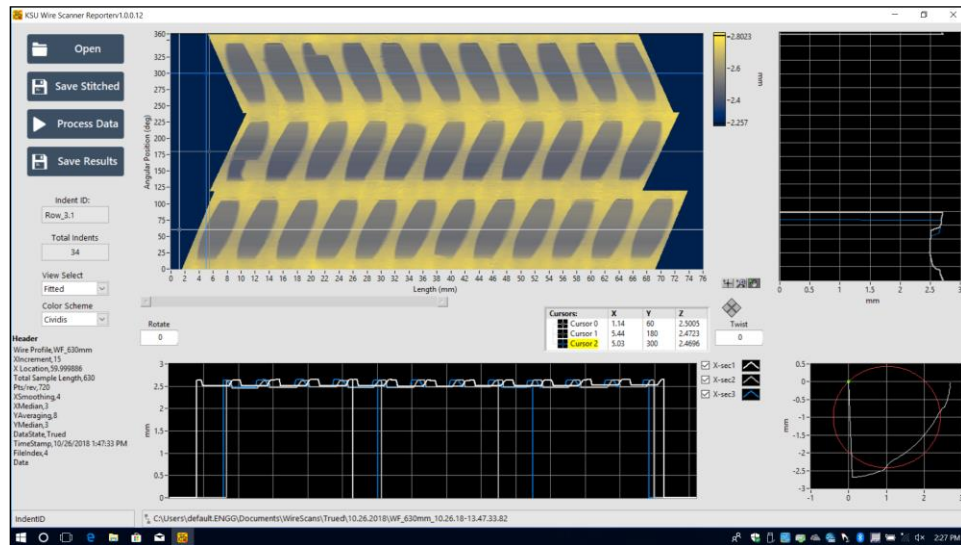


Figure 6.9: Wire Scan Reporter Indent Isolation

6.5 Trapezoid Fit of Least Squares

The majority of the processing procedures up until this point, from data collection to indent isolation, have been generalized enough to work for most indentation styles. However, there is a

departure in the universal aspect of the processing, as individual indent styles must be processed in fundamentally different ways depending on the features that they possess. As stated previously, one cannot use the same set of feature extraction algorithms used for a chevron type indentation on a different wire that utilizes a dotted pattern. A majority of small diameter indented wires used in industry rely on chevron style indents to increase the bond characteristics between the wire and concrete. Thus, the processing algorithms highlighted in this section and the remaining subsections will be focused on the feature extraction of chevron style indents. Furthermore, the results summarized in Chapter 7 will exclusively detail the chevron style indents that were included within the scope of this research project. It should be emphasized that the generalization of the steps leading up to this point would allow the further development of feature extraction algorithms for indentations of different geometry, namely, dotted or spiral patterns.

The data contained by the isolated indents is well behaved, being thoroughly conditioned by the filtering and corrections highlighted in the previous sections. The primary task remaining was to determine a suitable curve fitting algorithm to identify the critical indent features contained by the data profiles, turning otherwise random data into usable results. Chevron style indents are known for having predictable profile characteristics, featuring flat indent crests and basins, along with straight transitions between these points. Scans were taken of various 5.32mm chevron wires by utilizing the Indent Profiling System. The centerline profiles of a sampling of these wires are illustrated in Figure 6.10(a). Note the striking similarity between the longitudinal profiles. While the magnitude of the relative depths and sidewall angles differ, all of these profiles can be described under one category, trapezoidal.

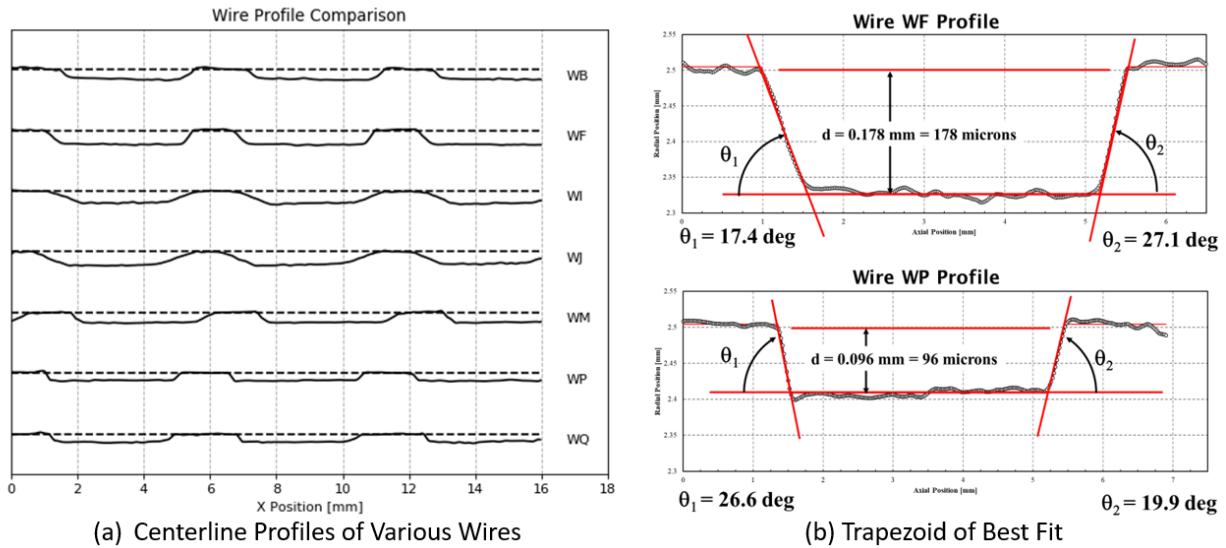


Figure 6.10: Applicability of Trapezoidal Curve Fit

Initial manual processing attempts of the longitudinal profiles are depicted in Figure 6.10(b), clearly showing the applicability of the trapezoidal curve fit to the data profiles. This was repeated across multiple chevron indents and the same success was universally observed. Therefore, a trapezoidal curve fitting algorithm was developed in order to extract useful geometrical features from the profiles of chevron style indents.

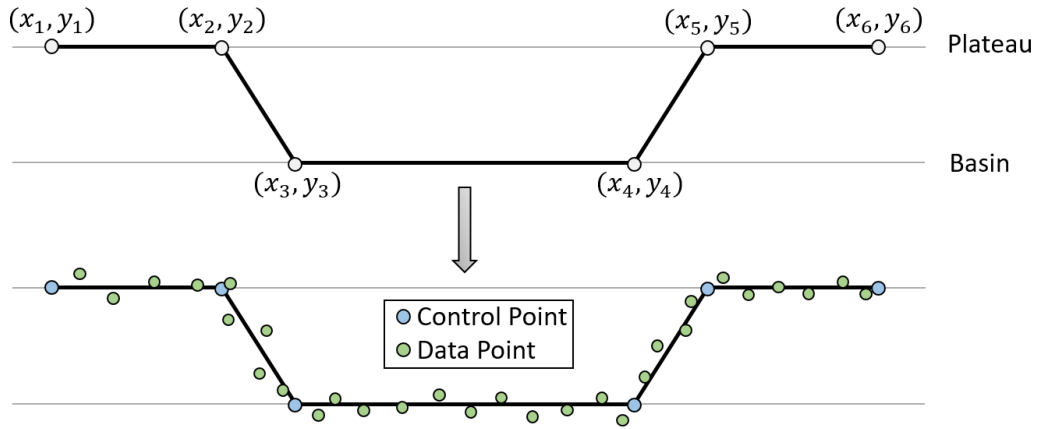


Figure 6.11: Trapezoid Fit of Least Squares

The algorithm is summarized graphically in Figure 6.11, in which, a trapezoid fit of least squares is used to apply a line of best fit to the selected data. The purpose of a least squares algorithm is to minimize the difference between the fitted lines, or lines in the case of a trapezoid fit, and the data visualized as green dots in the figure above. When the minimization of the error between the target profile and the data is achieved, the control points represent the idealized profile fitting the data.

For the case of the trapezoid fit applied to chevron style indents, only two possibilities for the measured heights exists: the top of the indent, and the bottom of the indent. This means that for the aforementioned curve fit, the following must hold true,

$$y_{top} = y_1 = y_2 = y_5 = y_6$$

with the additional requirement,

$$y_{bottom} = y_3 = y_4$$

Further restrictions are applied to limit the curve fitting algorithms, limiting the cases of mathematical degeneracy that prevent realistic solutions,

$$y_{top} > y_{bottom}$$

In addition to,

$$x_1 < x_2 < x_3 < x_4 < x_5 < x_6$$

6.6 Obtaining Primary Geometric Features

The general guideline for the extraction of the geometrical features of an isolated indent are as follows. A trapezoidal fit of least squares is applied on every eligible longitudinal profile of the indent. An eligible profile is defined as falling within the “width” of the detected indent. From these idealized two-dimensional profiles the following critical geometry parameters for a chevron type indent are obtained for the particular profile: depth, indent length, basin length, sidewall angles, sidewall lengths, and profile area. The two-dimensional results for each profile are then recorded. It is possible to have a centerline depth, an average depth (across all observed profiles),

and a maximum/minimum depth (also observed across all profiles). This can also be applied to any other two-dimensional parameter obtained from analysis.

Three-dimensional indent features are constructed from the 2-dimensional profile results. The integration of profile areas across the width of the indent yields volume, the integration of indent lengths across the width gives planform area, and the integration of sidewall lengths across the indent width obtains sidewall area, and so on and so forth. The integration interval is small, on the order of $20\mu\text{m}$, thus the results obtained via numerical integration are accurate. A more detailed explanation of the extracted variables and how these variables relate to the captured profiles are the subject of the subsections to follow.

6.6.1 Analyzing Width

An assessment of indent width is necessary prior to obtaining other geometrical features. Indent width, in addition to being a reportable geometrical parameter, is used to determine regions of the isolated indent that are eligible for feature extraction. The slant profile of the indent, which represents the measured height profile along the orientation angle of the indent and is visualized as the red lines in Figure 6.7(b), is also trapezoidal in nature. By applying a trapezoid fit on the isolated indent slant profile, it is possible to acquire the width of the indent. Figure 6.12 highlights the applicability of using trapezoid fits on the slant profile; the line of best fit overlaps the measured data, indicating excellent agreement. However, it would significantly degrade the quality of the data extraction process if extremely shallow profiles were allowed to be included within the width of the indent. Therefore, the width of the indent is defined as where the average profiles exceed a depth of $20\mu\text{m}$ based on the trapezoidal profile fit.

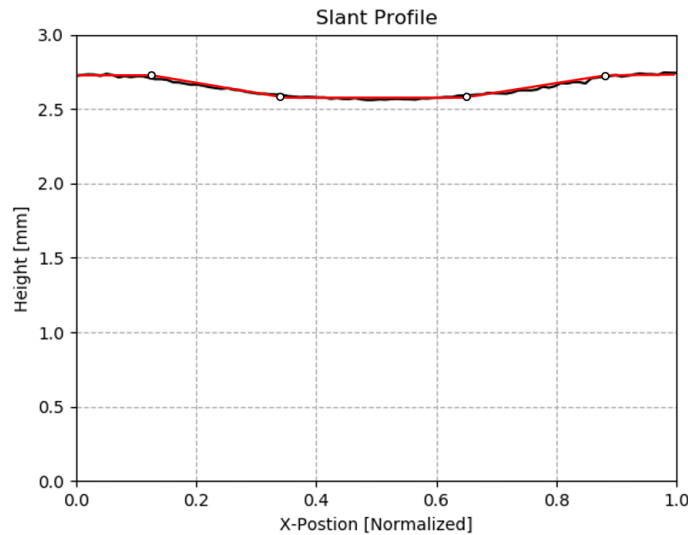


Figure 6.12: Trapezoid Fit of Indent Slant Profile (Wire WM)

6.6.2 2-D Geometry

The two-dimensional geometry is summarized by the features extracted directly through the use of the trapezoidal fit of least squares. These two-dimensional features are illustrated below in Figure 6.13, which overviews the primary 2D characteristics; the only 2D feature omitted from the illustration is basin length, which is length of the bottom horizontal line of the curve fit. The observation of pitch in the two-dimensional context is redundant since it has already been

ascertained in a previous section and was used to determine the bounds of the indent isolation. An important observation is made that two geometrical features obtained from the curve fit have values that are dependent on the side of the indent in which they are measured. Sidewall angle and sidewall length are these values. Sidewall angle for example, will have a separate value related to the left and right side of the profile. All of these two-dimensional values are obtained from every longitudinal profile that is contained by the width of the indent, and thus, all of these 2D values vary as a function of location along the width of the indent. These values are recorded in the results file generated by the Indent Profiling System and are integral to the calculation of the three-dimensional geometry in the section that immediately follows. An example entry of extracted two-dimensional parameters for an indent can be seen in Figure 6.16.

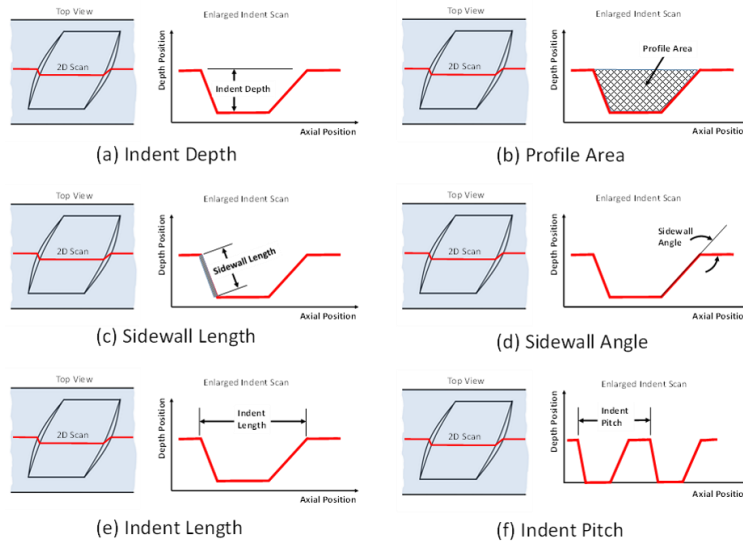


Figure 6.13: 2D Wire Indent Geometrical Features

6.6.3 3-D Geometry

The three-dimensional geometry extracted by the Indent Profiling System relies on the integration of two-dimensional parameters, or observations that rely on the conglomeration of sets of two-dimensional data (such as average depth). To put it simply, parameters characterizing the three-dimensional geometry represent data that cannot be computed from two-dimensional data acquired for a single profile alone. The key 3D features to be measured by the Indent Profiling System are illustrated in Figure 6.14; this is the same illustration from Chapter 3 but is reproduced here for convenience. A brief description is given in the following paragraph for how each 3D parameter highlighted by the figure below is calculated. Note that every 3D parameter is computed as a scalar value and does not vary as a function of indent width, in contrast with the 2D parameters.

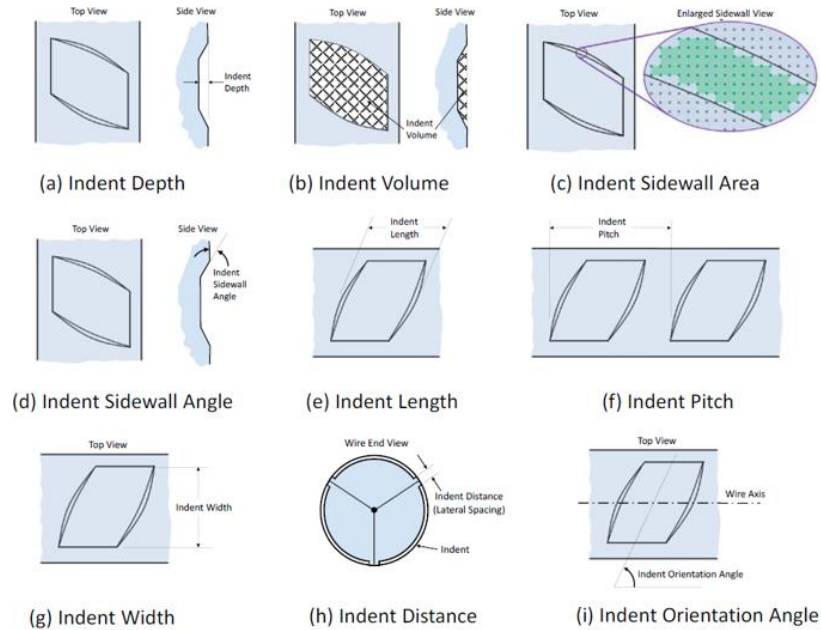


Figure 6.14: 3D Wire Indent Geometrical Features

Indent depth is computed as the average depth of all of the accumulated two-dimensional profiles. Indent volume is the integration of all profile areas across the width of the indent. Likewise, sidewall area is the integration of the 2D sidewall lengths across the width of the indent; two sidewall areas exist, left and right. Indent sidewall angle (3D) is the average sidewall angle of the two-dimensional parameters; two sidewall angles exist, left and right. Indent length (3D) is the average indent length of the two-dimensional parameters. Pitch is classified as a 3D parameter since it is computed based on all of the indents contained by a single indent row, rather than a single isolated indent. Pitch has the same value that is obtained by the algorithms in Section 6.3; each row has a separate pitch value. Indent width for each isolated indent is obtained using the method elucidated in Section 6.6.1 prior to 2D feature extraction. Indent distance is the average rib spacing determined by the profile flatness procedure listed in Section 6.2.2. Finally, indent orientation angle is computed per row in Section 6.3. One additional three-dimensional indent feature not illustrated in Figure 6.14 is planform area, which involves the integration of all indent lengths across the width of the indent.

The geometric features listed in this section and the prior section play a crucial role in quality control. A selection of chevron type wires from modern industry, historical concrete crossies, and fabricated specimens were processed by the Indent Profiling System; the results of which will be the main source of discussion in Chapter 7. Furthermore, the three-dimensional data was shown to correlate favorably with certain performance criteria, particularly transfer length and splitting propensity. The significance of the two-dimensional and three-dimensional data on wire-concrete performance characteristics will be the primary subject of Chapter 8.

6.7 File Report Format

The discussion of this brief section will encompass the layout of the processing results file format now that the data acquisition and feature extraction processes have been explained. The processing results file details the 2D and 3D geometrical features extracted from each scanned wire;

additionally, it records the trapezoidal curve fit data of all longitudinal profiles that were processed for each individual indent. The file can be divided into two main components: the global data block and the indent data blocks associated with the individual isolated indents.

A depiction of the global data block can be visualized in Figure 6.15. Similar to the wire scan report, a short header is provided prior to the data, in which the basic characteristics of the scan subjected to processing are recorded. Below the header, a high-level overview of the processing results is given, most notably, the nominal diameter of the scanned wire, the number of isolated indents that were subjected to processing, and the IDs of any isolated indents that were manually omitted from the report by the operator. Next, variables that are unique per indent row are tabulated. These variables include the orientation angle of the indents in the row, the average width of the indents per row, and the physical spacing between the indent rows that the rib occupies (the region in which no indentations occur along the length of the wire). Below that, an array is listed: the global data block. The global data block contains any variable that represents a single value for an isolated indent. Each indent is specified by the row that it occupies and its position within the row, providing a unique identifier for the isolated indent. The following scalar 3D values are recorded per indent: volume, pitch, width, sidewall area (left and right), average depth, and average sidewall angle (left and right). Further post-processing of the results file by a separate program generates a more exhaustive list of 2D and 3D parameters, 38 overall, far too many to conveniently name in this short section.

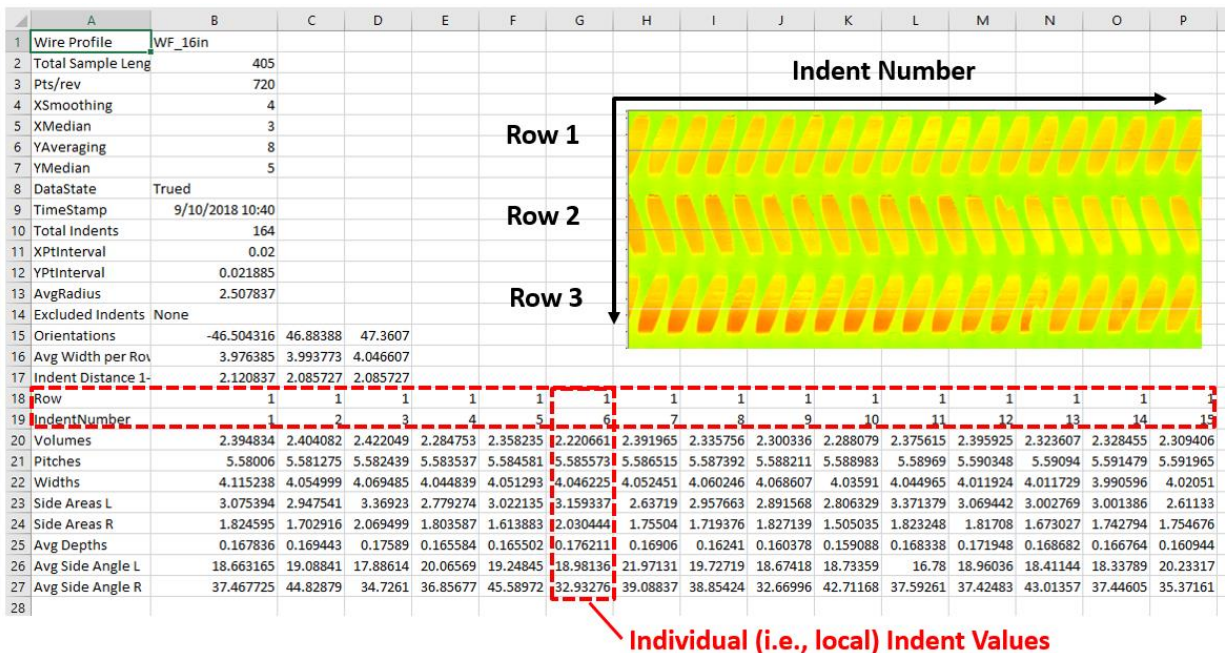


Figure 6.15: Indent Profiling System Initial Report (Global Block)

The second component of the processing report results file contains the indent data blocks associated with the individual isolated indents. Figure 6.16 provides an overview of the layout of a typical indent data block, which contains the information for a single indent. Each indent data block contains a header, the top of which highlights the ID of the isolated indent, along with information related to the coordinate system of the indent. Unique scalar values for the indent directly follow, such as orientation, volume, pitch, width, and sidewall areas of the indent. These values are also seen in the global data block. Finally, an array can be seen that summarizes the

[illegible]

6.8 Post-Processing, Statistics Generation, Histograms

```
graph LR; RawScans([Raw Scans]) -- "Data Filtering  
Truncation  
Calibration Maps  
Splicing" --> TruedScan([Trued Scan]); TruedScan --> HeightMapRenders[Height-Map Renders]; TruedScan --> Results[Results]; Results --> Reports[Reports:  
ASTM A881  
ISO 10138-2]; Results --> PostProcessedResults[Post-Processed Results]; PostProcessedResults --> Statistics[Statistics]; PostProcessedResults --> Histograms[Histograms];
```

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From the calibrated and trued scans, images of the height-maps and three-dimensional views of the wires can be rendered to show the physical surface features. By utilizing the initial processing results file, reports can be created for common measurement standards, namely ASTM A881 and ISO 10138-2 as discussed in Chapter 2. Further post-processing of the initial report yields additional 2D and 3D parameters that prove to be useful in characterizing the manufacturing process of the indented wires or are related to wire-concrete performance criteria. By analyzing the post-processed results, detailed statistics can be ascertained, along with histograms that visualize variations in the measured features. A potentially limitless ability exists to envision and process the captured data, but these represent the results that are of immediate interest to the scope of this research.

Chapter 7 - Overview of Collected Data

With respect to the development of the non-contact Indent Profiling System, the research was divided into two primary phases. During the first phase of this research the key objective was to design and implement an automated Indent Profiling System to produce unbiased, statistically relevant sample sizes. After motion control and data acquisition of the system was implemented, calibration techniques and data manipulation steps were developed to enhance the quality of the data being received, and algorithms were implemented for feature extraction. It is important to note that John Bloomfield performed the mechanical design and assembly of the system, provided automation of the system by implementing motion control and a user interface to facilitate interaction with the unit, and integrated the data processing and extraction algorithms developed by the author to extract the indentation geometry of the wires from the prior chapter. The author developed the algorithms highlighted in the previous chapter based on the preliminary data from the Indent Profiling System; John Bloomfield later integrated these algorithms back into the system until it was fully featured. The author then developed a post-processing program that generated more data than the original Indent Profiling System initially provided; this additional data is represented in Chapter 7 and used in the correlations overviewed in Chapter 8. After the development, the system was applied to measure specimens of known geometry to verify the correct and reliable operation of the system and quantify expected measurement uncertainties as described in the prior sections.

The second phase of the project involved the application of the Indent Profiling System to measure the indent characteristics of a multitude of indented wires; the discussion of the geometric feature data extracted by the Indent Profiling System will be the primary subject of this chapter. A sampling of these wires were from those used in recent industry. Ten unique wire types in this category were used to make concrete prisms to evaluate cover testing and transfer lengths; this group will frequently be referred to as “Cover Testing” wires. Another group were wires that were extracted from historical crossties that had been in track for upwards of multiple decades; these will be referenced as “Crosstie Wires” and represent wires that had good wire-concrete performance. The last set of wires were created with known “machined indents” for use with system checkout and were available from a prior project [37][48]. In conjunction with the transfer length and splitting propensity testing of concrete prisms for the larger FRA project [41], the Indent Profiling System results were then used to extensively investigate which geometrical parameters of indented wires contribute most significantly, or detrimentally, to prestressed member performance criteria. The correlation of the Indent Profiling System results with performance criteria will be extensively discussed in Chapter 8.

Table 7.1: Wires Included in Study

Processed Wires		
Cover Testing	Crosstie Wires	Machined Wires
WB	E-1	15
WD	F-1	15-.16-T1
WF	H-1	30-.16-T1
WG	J-1	45-.16-T2
WH	K-1	60-.16-T1
WI	L-1	75-.16-T1
WJ	M-1	90-.16-T3
WM		X1
WP		X2
WQ		X3
		X4
		X5

The first set of wires, those commonly used in modern industry, represent a wide variety of indent depths and indentation shapes, additionally, the wires feature considerable differences in sidewall angles used in practice. These selected wires share a common “chevron” pattern and are nominally 5.32mm in diameter. The geometrical results obtained from these modern wires were used to analyze the variations of the individual parameters on a row-by-row basis and across the entire specimen. Furthermore, prestressed concrete prisms were created using the same wires [51] to evaluate the effects of reduced concrete cover, indent geometry, release strength, and aggregate mix on wire-concrete performance metrics such as splitting propensity and transfer length. Adrijana Savic and other researchers constructed these prisms; the author evaluated transfer length of the prisms using an automated measurement system [47] and, along with the assistance undergraduate researchers, assessed splitting propensity when cracking occurred. The geometric features of the indents could then be correlated against measured performance criteria of the test prisms, thus determining which geometrical characteristics have the most significant influence on wire-concrete performance.

Wires extracted from pre-existing concrete railroad ties in service represent the second set of wires. James Scott, along with other researchers, performed the saw cuts on the crossties and extracted the wires and tendons [43] allowing for the evaluation of remaining prestress force. The author performed 3D scans of these ties [50] and the evaluation of the extracted wires with the Indent Profiling System. These wires form the basis for wire geometry that tends to work well in practice, as many of the crossties that the wires were extracted from performed favorably over the course of decades. Some of the concrete ties were subjected to an estimated 4 billion gross axle tons of loading during the service life of the tie, indicating favorable wire-concrete performance. The third group of wires, those with fabricated “machined” indents, were used for system calibration and verification of feature extraction algorithms. A list of the wires included in the study is provided in Table 7.1; the first wire group corresponds to “Cover Testing” wires. A detailed

discussion of the indentation features of all three wire groups subjected to processing by the Indent Profiling System will occur in the following sections.

7.1 Cover Testing Wires

A large subset of the wires subjected to testing included wires that are frequently used in modern industry. These wires represent a wide variety of indent depths and indentation shapes, additionally, the wires feature considerable differences in sidewall angles used in practice. Most of these wires were amassed through prior FRA research projects [37][42][45] in addition to wires provided by Nucor-LMP [51], a commercial partner in the FRA research project outlined by this dissertation. The wires contained by this group, representing ten unique chevron type wires, were used to satisfy a critical component of the second phase of this research. First, the geometric features of these 10 unique wires were extracted by the Indent Profiling System. Second, the captured indented wire geometry was then used in conjunction with empirical data obtained from prestressed concrete prisms created using the same ten wires. Adrijana Savic and other researchers created these pretensioned prisms; whereas the author evaluated transfer length of the prisms using an automated measurement system and, along with the assistance undergraduate researchers, assessed splitting propensity when cracking occurred. The concrete prisms were constructed with the purpose of measuring the effect of reduced concrete cover on wire-concrete performance criteria, thus, the wires in this group are named the “cover testing” wires. From this combined information, indentation geometry was then correlated with wire-concrete performance criteria such as transfer length and splitting propensity to quantitatively determine which indent features contribute most significantly, or detrimentally, to desirable performance characteristics. The subject of correlations will be the source of extensive discussion in Chapter 8.

Furthermore, a large sample of concrete prism data, including numerous sample lengths of wires exist for this group. Thus, statistically relevant sample sizes were obtained, allowing the Indent Profiling System to analyze the manufacturing intricacies of the wires on a row-by-row basis as hundreds of indents can be sampled per wire specimen. No manufacturing process is perfect; the information extracted by the Indent Profiling System is used to highlight the significant manufacturing variations that can be seen in individual wires. The Indent Profiling System was used on the wires in this group to capture a full revolution of the indent rollers, representing the capture of all statistically unique indents formed by the manufacturing process. Discussion of the wire pattern repetition that this system is capable of detecting makes use of the data captured for this group of wires and is covered in Chapter 9.

7.1.1 Cover Testing Wire Specimens

Ten unique chevron type indented wires from industry were included in this area of research. These wires were subjected to scanning by the Indent Profiling System. The extracted geometry was then used to investigate the statistical significance of the captured data, investigate the manufacturing differences of indent geometry on a row-by-row basis, and provide the information necessary to assist with the correlation of wire features with wire-concrete performance criteria. The ten cover testing wire specimens were cut to 36-inch lengths; the specimens were stored in sealed PVC tubes prior to use, and thus, were free from any signs of corrosion that would impair wire scanning. Digital microscope images of the ten cover test wires are provided in Figure 7.1; this composite image covering all of the cover testing wires demonstrates the diversity of

geometric features that this wire group possesses. The wire naming conventions were adopted from prior FRA research projects [42][45][51]; the naming identifiers protect the identities of the wire manufacturers of each specimen.

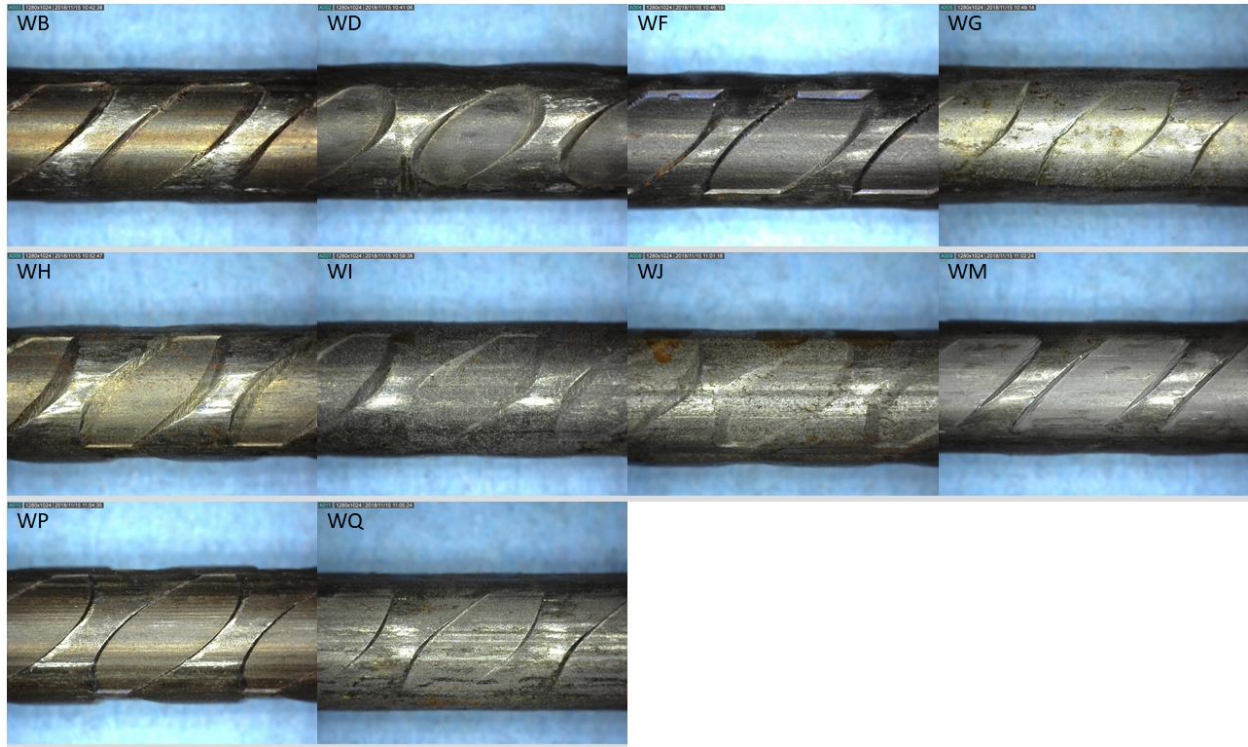


Figure 7.1: Digital Microscope Images of Cover Testing Wires

From the figure above, it is clear that all of the wires conform to a general chevron pattern; WD may appear to be elliptical in nature, but closer observation reveals that the top and bottom of the indent, from the perspective of the image, form horizontal lines. Some notable observations of the digital microscope images of the cover testing wires are as follows. Wire types WF and WH appear to be the deepest indentations of the lot, this assessment arises from the fact that the indentations are deep enough to have a sidewall angle present at the top and bottom of the indent rather than just the right and left side. This observation, coupled with the generous planform area, would indicate that these indents will have the largest volumes in comparison to the rest. Furthermore, the shallowest indents appear to be WG and WQ, both are unlikely to have an average depth that exceeds $70\text{-}80\mu\text{m}$, or volumes that are larger than 1mm^3 .

Additionally, it appears that WH, WI and WJ have similar sidewall angles of around 10° and contain the shallowest sidewall angles out of the entire cover testing wire group. Furthering this observation, wires WH and WJ should have the largest sidewall areas once indentation depth has been considered along with the shallow sidewall angles. All indentations appear to have an orientation angle that comfortably exceeds 45° by visual inspection. The steepest sidewall angles observable by the microscope images are associated with wires WF, WM, and WP; these indents feature crisp sidewall angles that are 20° or larger. Finally, wire WF appears to have the highest manufacturing quality out of any of the wires in the group, exhibiting minor imperfections caused by the occasional damaged indent roller tooth, cleanly made indents, and created from a wire with

no inherent cast. A contour plot of a scanned segment of wire type WF, which clearly demonstrates the crispness of the indentation pattern, is illustrated in Figure 7.2.

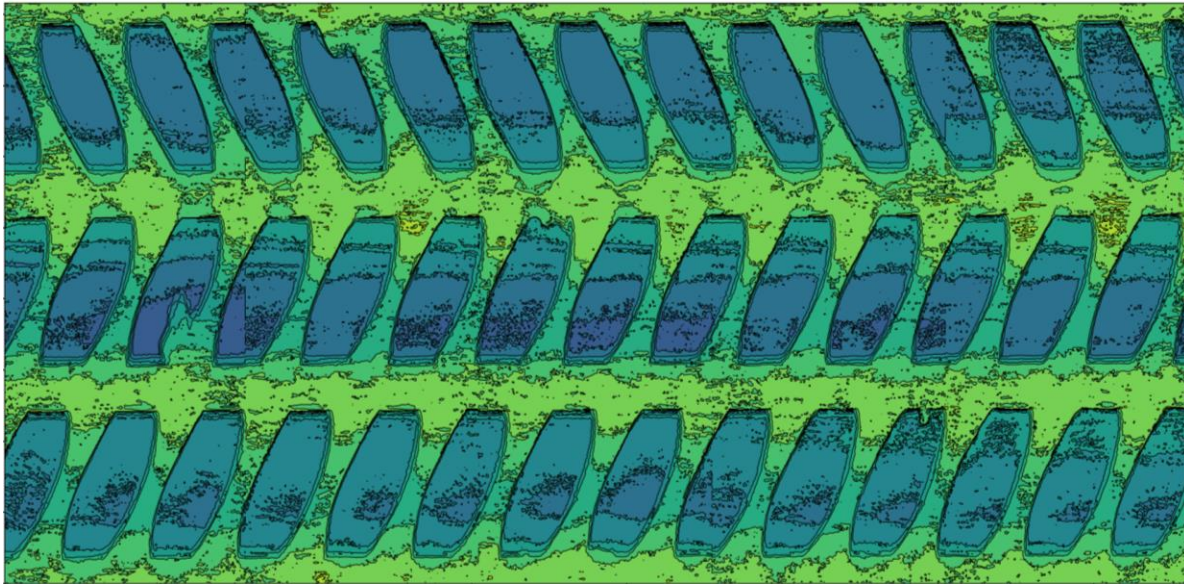


Figure 7.2: Scan Segment of Wire Type WF

7.1.2 General Data

The ten chevron type indented wires used for cover testing were subjected to processing by the Indent Profiling System. Each specimen in the group was successfully scanned; 25 inches (630mm) of each wire was scanned, capturing enough data to characterize a complete repetition of the indent rollers. By capturing the indentation pattern caused by one full revolution of the indent rollers, all statistically unique indents formed by the manufacturing process can be evaluated, leading to statistically significant sample sizes. On average, over 300 unique indents were scanned per wire specimen, representing over 100 indents per row. This allows for the visualization of manufacturing variations over the span of the entire wire, or on a row-by-row basis. The data captured by the Indent Profiling System on the ten cover testing wire specimens is summarized in Table 7.2, in which the mean values of all scanned indents are tabulated. Table 7.3 follows shortly thereafter, which summarizes the standard deviations of the same data set.

Table 7.2: Cover Testing Wire Indentation Data (Means)

Indent Data (Cover Testing Wires)										
	ID	Nominal Dia [mm]	Orientat-ion [deg]	Total Indents	Volume [mm ³]	S.W. Area [mm ²]	Avg Depth [mm]	S.W. Angle [deg]	Avg Length [mm]	Pitch [mm]
Mean	WB	5.153	47.7	302	1.696	2.922	0.119	20.24	4.060	5.580
	WD	5.257	57.8	337	1.600	2.744	0.141	18.62	3.512	5.548
	WF	5.195	48.4	333	2.446	2.452	0.163	24.33	4.014	5.604
	WG	5.324	56.1	332	0.760	2.317	0.066	16.07	3.885	5.644
	WH	5.107	51.0	332	2.154	3.961	0.164	9.83	3.676	5.599
	WI	5.208	50.1	335	1.102	2.850	0.094	9.69	3.436	5.593
	WJ	5.211	50.8	333	1.428	3.638	0.123	9.75	3.411	5.609
	WM	5.175	47.3	334	1.252	2.062	0.101	18.98	4.085	5.564
	WP	5.283	50.3	315	1.745	1.803	0.117	33.96	3.444	5.581
	WQ	5.288	55.8	332	0.776	2.149	0.067	17.75	3.878	5.645
S.W. Area: The average sidewall area of the left and right side of the indents.										
S.W. Angle: The average sidewall angle of the left and right side of the indents.										

Table 7.3: Cover Testing Wire Indentation Data (Standard Deviations)

Indent Data (Cover Testing Wires)										
	ID	Nominal Dia [mm]	Orientat-ion [deg]	Total Indents	Volume [mm ³]	S.W. Area [mm ²]	Avg Depth [mm]	S.W. Angle [deg]	Avg Length [mm]	Pitch [mm]
Standard Deviation	WB			302	0.219	0.679	0.009	9.15	0.149	0.015
	WD			337	0.109	0.568	0.010	5.12	0.158	0.013
	WF			333	0.145	0.829	0.011	11.91	0.098	0.020
	WG			332	0.059	0.573	0.006	6.32	0.113	0.003
	WH			332	0.193	0.468	0.015	2.14	0.068	0.004
	WI			335	0.104	0.420	0.006	2.94	0.093	0.010
	WJ			333	0.080	0.767	0.008	2.36	0.087	0.004
	WM			334	0.100	0.562	0.005	8.48	0.049	0.006
	WP			315	0.132	0.413	0.012	17.53	0.101	0.005
	WQ			332	0.069	0.469	0.006	7.59	0.100	0.003
S.W. Area: The average sidewall area of the left and right side of the indents.										
S.W. Angle: The average sidewall angle of the left and right side of the indents.										

It should be noted that the parameters contained in the tables listed above come directly from the requirements of the two main indented wire measurement standards, as well as parameters that were found to correlate favorably with wire-concrete performance criteria. Many more geometric parameters are computed by the Indent Profiling System and the post processing software written by the author, but the tabulated information represents a sampling of the most important ones.

From the tabulated information above, several important observations can be made. The wires would be classified as 5.32mm wires under ASTM A881 due to the listed nominal wire diameter. As predicted by the inspection of the digital microscope images, all wire types comfortably exceed an orientation angle of 45°. Furthermore, the smallest indents by volume are WG and WQ, not exceeding 1mm³, while the largest indents are WF and WH; the tabulated data matches the previous observations of the digital microscope images. It was predicted that the indents with the

shallowest sidewall angles would be wires WH, WI, and WJ, being less than 10°; this is supported by the data tables. Unsurprisingly, the indentations of wire types WF, WM, and WP encompassed some of the steepest sidewall angles of the group, being joined by WB and WD in exceeding sidewall angles of 18°. Furthermore, a majority of these wire types would pass the measurement requirements set out by ASTM A881 [38], highlighted in section 2.1.

The most important takeaway from the tables listed above, is the inherently high standard deviation of some of the parameters, namely sidewall angle and sidewall area. It will be discussed in the subsection that immediately follows that the standard deviations of parameters for each individual row can be significantly lower than the standard deviations of the entire sample, this implies that each row is statistically different from its companions. It is often insufficient to trust mean values that represent the entire sample (namely, all rows combined) when significant manufacturing variations exist on a row-by-row basis. The manufacturing variations of the measured cover testing wires scanned by the Indent Profiling System are highlighted in the next subsection.

7.1.3 Statistical Variation

The ability of the Indent Profiling System to collect statistically relevant sample sizes, in which all unique indents formed by one complete repetition of the indent rollers are captured, allows for the analysis of geometric parameters on a row-by-row basis. No manufacturing process is perfect, and thus, it is expected that variations exist between neighboring rows, and within the individual rows themselves. These variations can be the byproduct of a multitude of things: unequal indent roller pressure, damaged roller teeth of individual rollers, improper geometry of the roller teeth, and many more factors. This subsection highlights the importance of using statistically relevant sample sizes to analyze the intricacies of the manufacturing process of the resulting indentation geometry and the ability of the Indent Profiling System to provide the necessary data.

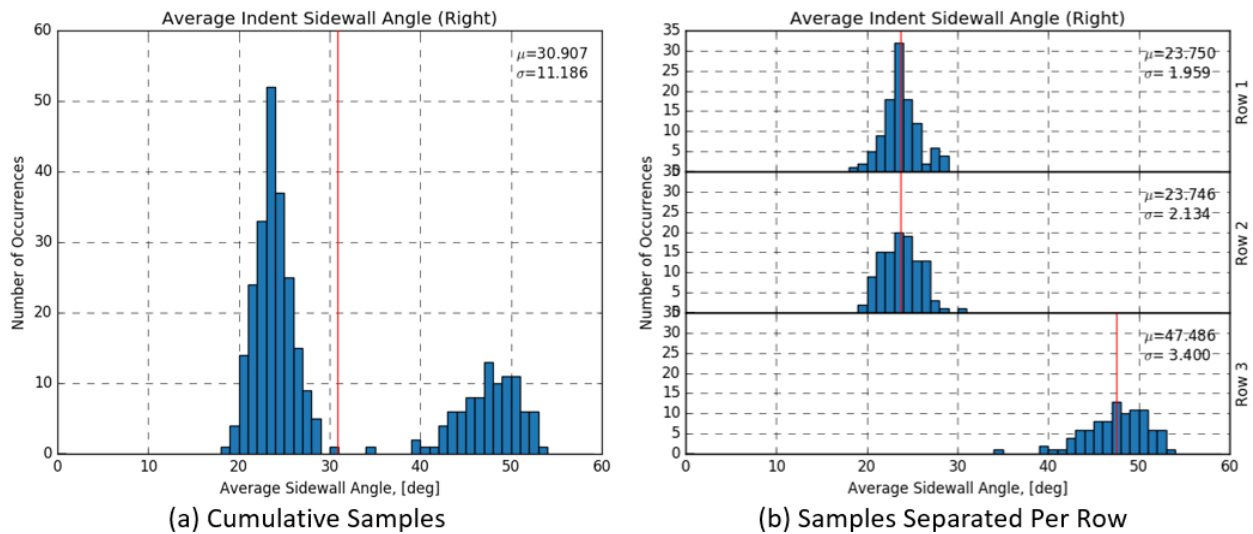


Figure 7.3: Variation of Sidewall Angles on the Right Side (Wire WP)

The previous subsection noted the presence of unusually high standard deviations for some of the parameters listed in Table 7.3. The deviations of the sidewall angles and sidewall areas of wire types WF and WP represented a large percentage of the mean measured values in Table 7.2. For example, the standard deviations of the average indent sidewall angles (right side) of all observed samples for wire type WP is 11.19°, whereas the standard deviations of the same parameter per

row do not exceed 3.40° ; this information is visualized in Figure 7.3. Note that these values do not correspond directly to the data tabulated in Table 7.2 and Table 7.3 since those tables specifically list the average sidewall angles of the combined left and right sides. Since the standard deviations of parameters for each individual row can be significantly lower than the standard deviations of the entire sample, it implies that each row is statistically different from its companions. This is clearly illustrated in Figure 7.3, in which histograms of the average sidewall angle of the right side of the indent are provided for the cumulative samples, and on a row-by-row basis. Figure 7.3(a) represents a bimodal distribution, with the peak on the left side rising significantly above the peak on the right. This implies that the two rows on the right side of the indent contain shallower sidewall angles than the third row. This is confirmed by Figure 7.3(b), which indeed shows that one indent row has sidewall angles that are twice as steep as the other two rows on the right side.

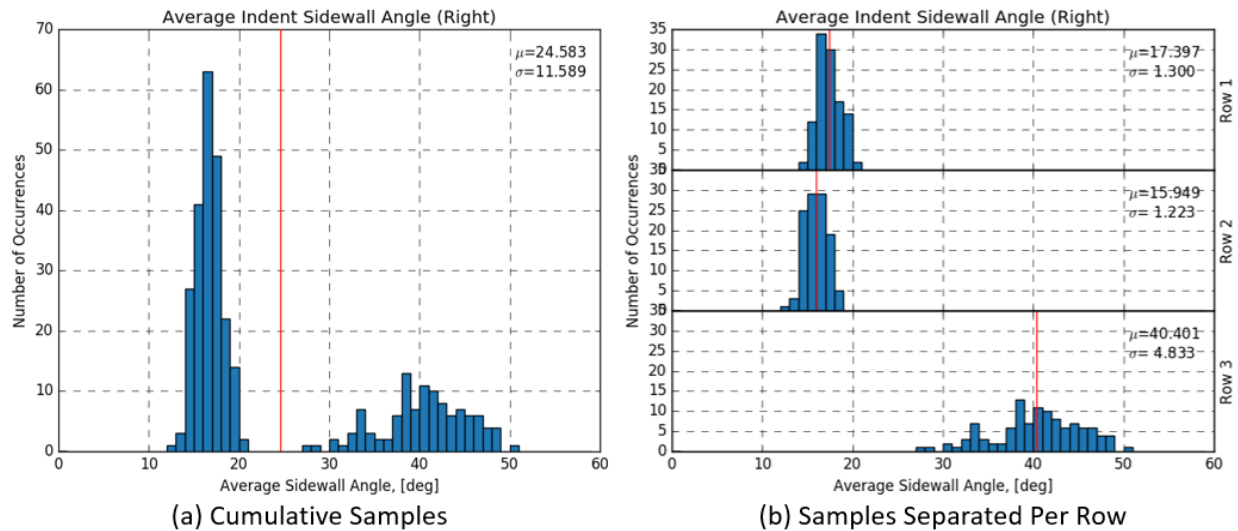


Figure 7.4: Variation of Sidewall Angles on the Right Side (Wire WF)

From the data contained by Table 7.3, it is obvious that wire type WF suffers from the same problems that WP has in regards to inconsistent sidewall angles on a row-by-row basis. Figure 7.4, which shows data pertaining to wire type WF, shares the same story and observation that Figure 7.3 does. It is worthy to note that the statistical distribution of the row containing the steeper sidewall angles is so far away from its shallower counterparts that the independent statistical distributions do not overlap at any point.

Furthermore, the severity in the differences of the parameters on a row-by-row basis are not isolated to a single side of the indent. In the case of average sidewall angles, the disparity between rows can persist on both the right and left side of the indentations. This is illustrated by the histograms provided in Figure 7.5, which display the variations of sidewall angles per side and per row. Note how the two rows with steeper sidewall angles on the left side of the indent switch to being shallow on the right side of the indent; the third row, shows the opposite trend. It is unlikely that the large variations in sidewall angles are desirable, or even intended, from a manufacturing standpoint. However, up until this point it has not been possible to capture statistically significant sample sizes of sidewall angle per row; thus, the manufacturer is likely unaware that this disparity even exists.

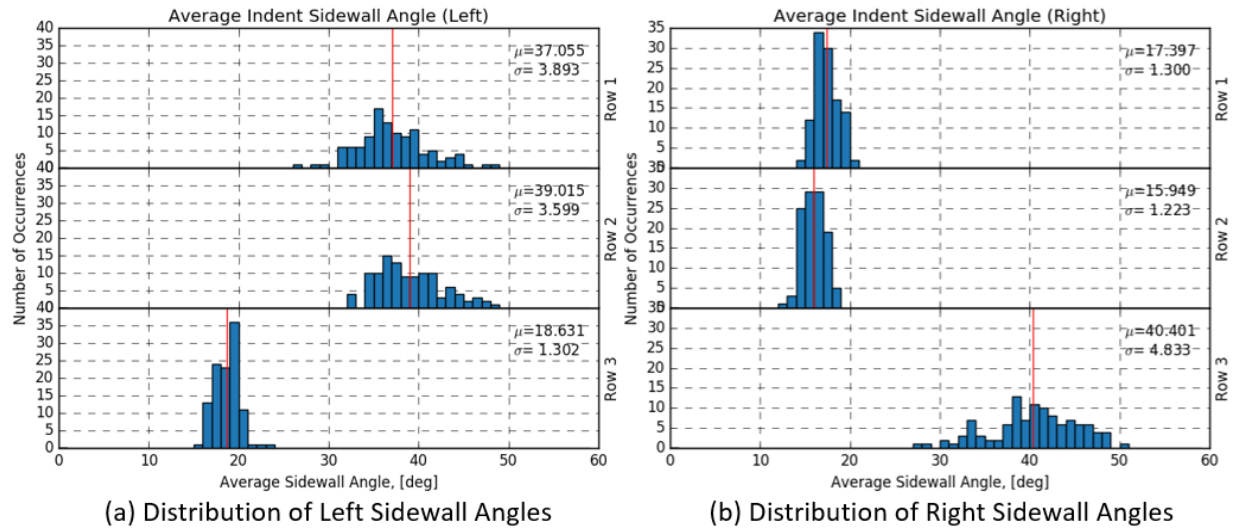


Figure 7.5: Variation of Sidewall Angles Between Sides (Wire WF)

For each cover testing wire, a length of 25 inches (630mm) was scanned and subjected to processing, thus, over 300 total intents per specimen were analyzed, representing over 100 indentations per row. Enough data is captured per scan to be statistically relevant; this can be seen by the histograms shown in the aforementioned figures in this section that clearly show the statistical distributions of the indent parameters on a cumulative and row-by-row basis. Thus, it is useful to bound the collected data with confidence intervals that describe the range that a certain percentage of the data can be found in. A confidence interval of 95% was applied to some of the critical geometric parameters listed in Table 7.2 per indentation row to help visualize the measured variations of the collected data. Confidence intervals of 95% are favored by statisticians to provide bounds on where 95% of the measured values are expected to be observed.

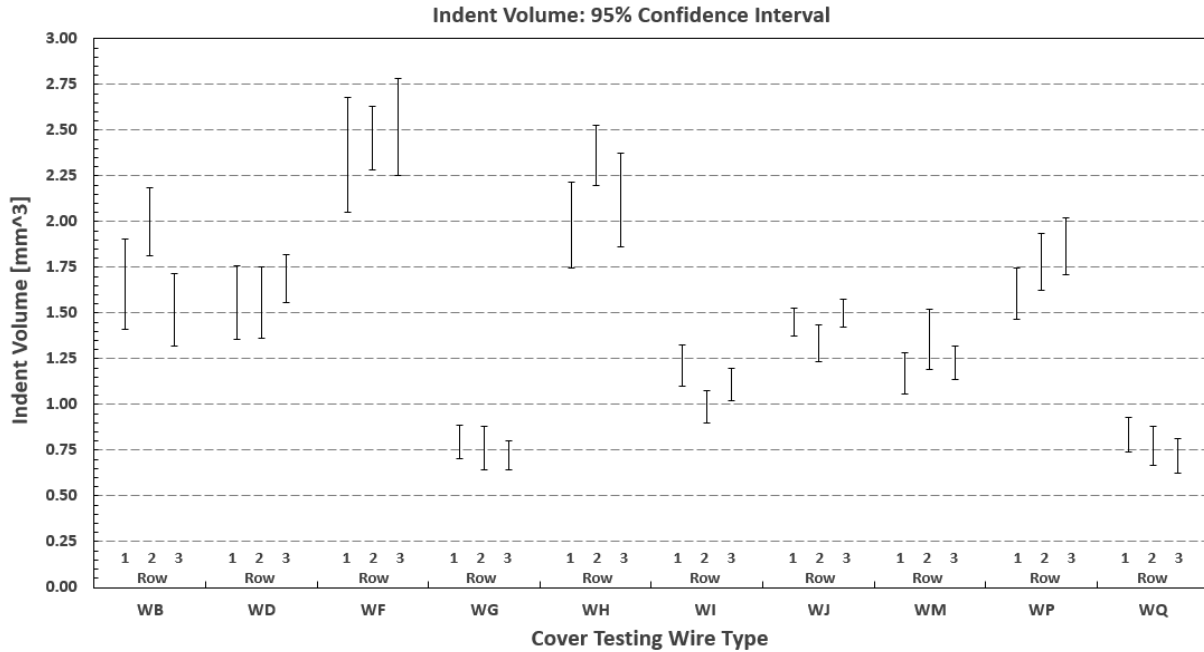


Figure 7.6: Measured Variations of Indent Volume

The plot provided above in Figure 7.6 details the measured variations of indentation volume per row and per wire type. Once again, the error bars show where 95% of the data is expected to reside within the particular data pool. For example, 95% of the measured indent volumes for row 1 for wire type WB are expected to fall in the range of 1.41mm^3 to 1.91mm^3 . Specimens in which the confidence bars significantly overlap one another across all three indent rows implies that every row shares similar manufacturing variations. Wire specimens WG and WQ are prime examples of this, visualized in Figure 7.6, and consequently have exceptionally low standard deviations for indent volumes, measured across all indents, summarized in Table 7.3. In contrast, wire types WB and WH have widely different measured indent volumes per row; some of the data per row hardly overlaps the data of neighboring rows, implying large manufacturing variations exist.

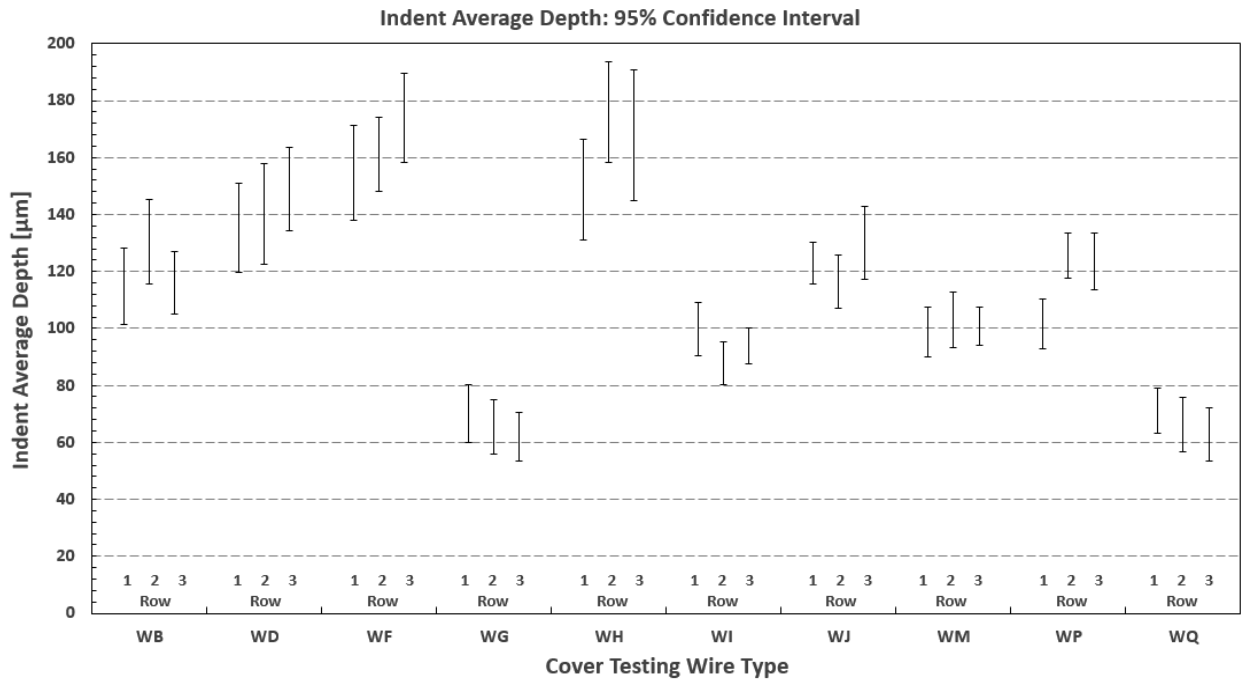


Figure 7.7: Measured Variations of Indent Average Depth

Figure 7.7 depicts the variations of average measured indentation depths and shows similar trends to the previous volume plot. Wire types WD, WG, WM, and WQ have confidence intervals that closely match across rows, resulting in standard deviations that constitute a low percentage of the mean values tabulated in the prior subsection. Furthermore, wires WH and WP have rows with significantly different manufacturing characteristics when it comes to average indentation depth. Figure 7.7 also visually indicates that WH possesses some of the deepest indentions, whereas WG and WQ are the shallowest. It is worthy to note that Figure 7.6 and Figure 7.7 share significant similarities in the overall shape of the plot. This is due to the fact that indentation volume and indentation depth are highly correlated with one another and will be discussed more thoroughly in Chapter 8.

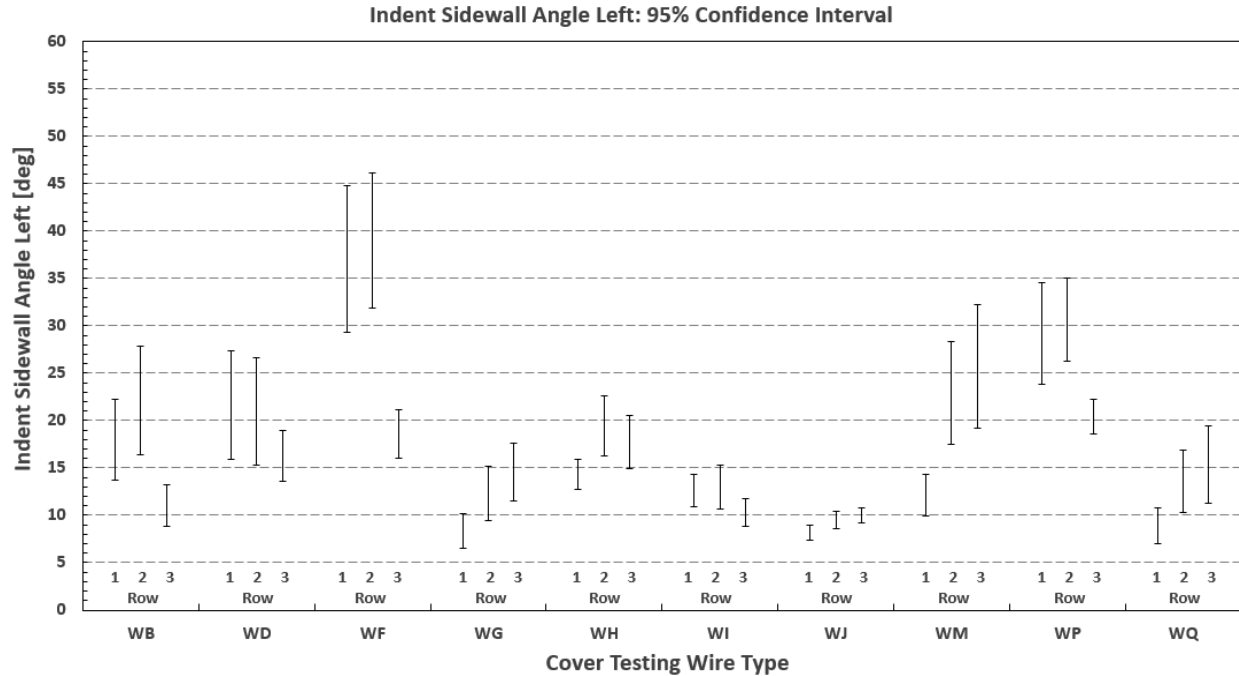


Figure 7.8: Measured Variations of Average Indent Sidewall Angle (Left Side)

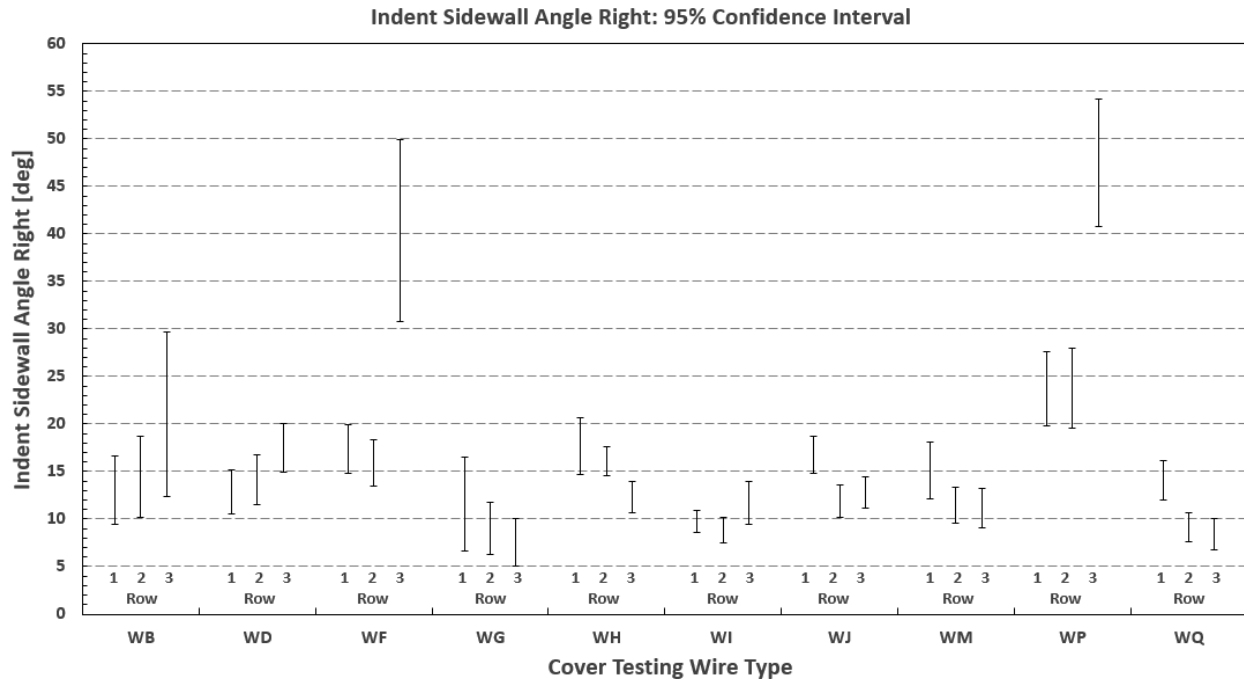


Figure 7.9: Measured Variations of Average Indent Sidewall Angle (Right Side)

Figure 7.8 and Figure 7.9 portray the measured variations of the average indent sidewall angles of the left and right side of the indentations respectively, per row. These plots are in clear agreement with the manufacturing variations highlighted in histograms contained by Figure 7.3, Figure 7.4, and Figure 7.5. Wire types WF and WP have vastly different indentation angles per row as

indicated by the confidence interval plots. Both Figure 7.8 and Figure 7.9 imply that indentation sidewall angle is exceptionally challenging to manufacture consistently in comparison to other parameters. Sidewall angle is highly sensitive to slight variations in indentation depth and the span over which the sidewall occurs; this can be seen from the result of the sensitivity analysis of this parameter contained in Appendix B.

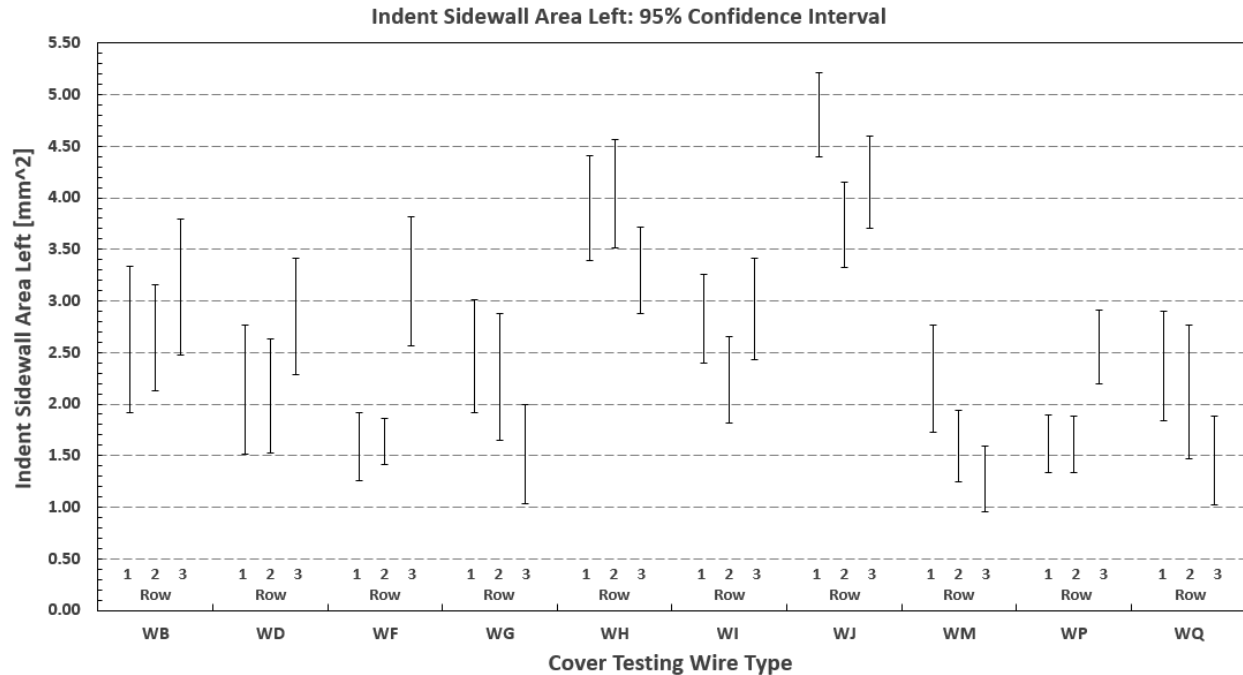


Figure 7.10: Measured Variations of Indent Sidewall Area (Left Side)

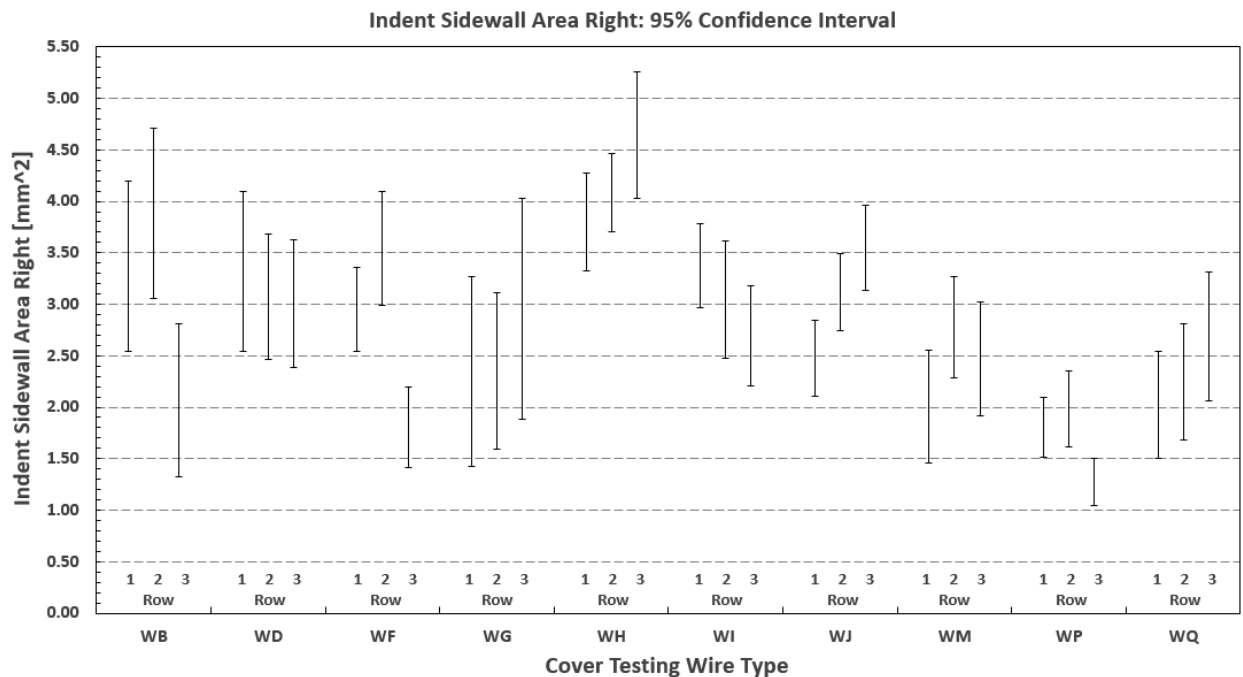


Figure 7.11: Measured Variations of Indent Sidewall Area (Right Side)

Figure 7.10 and Figure 7.11 show the measured variations of the indent sidewall area per row. The most notable takeaway from this set of plots is that sidewall area is challenging to maintain consistently as well; this is evident from the fact that many of the confidence intervals across rows of the same wire type do not overlap. Furthermore, the standard errors of the computed confidence intervals are a large percentage of the measured mean values. This indicates that not only are the rows significantly different, but measured values of sidewall area in individual rows can vary drastically. This is due to the fact that sidewall area is a fundamentally three-dimensional parameter that is heavily influenced by many other variables, namely, indent width, average indent depth, and the sidewall angle of the particular side in which the sidewall area is being measured. Any variations of those statistics correspond to a change in sidewall area, and thus, the manufacturing uncertainty of sidewall area is higher since it is a product of its base parameters. The sensitivity of this parameter is also summarized in Appendix B.

The Indent Profiling System has demonstrated the ability to capture statistically relevant sample sizes of many critical indentation characteristics. By scanning the wire pattern that is the result of one complete revolution of the indent rollers, all statistically unique indentations from the manufacturing process are accurately represented. This allows the Indent Profiling System to analyze the manufacturing intricacies of the wires on a row-by-row basis as hundreds of indents can be sampled per wire specimen. No manufacturing process is perfect, and the information extracted by the Indent Profiling System has been successfully used to highlight the significant manufacturing variations seen in individual wires.

7.2 Crosstie Wires (Extracted)

A subset of the wires selected for analysis by the Indent Profiling System were extracted from preexisting concrete railroad ties that saw many years of service. These concrete railroad ties were subjected to extensive measurements for other categories of the primary FRA research project [43][51]. Predominately, these historical ties were used to assess remaining residual prestress force of ties that had favorable long-term performance in track. However, it was of particular interest to scan the indented wire geometry of these ties since they represented specimens that worked well in practice. These areas of the project collected detailed three-dimensional crosstie geometry data through the use of a separate laser scanning system [50] and great effort was taken to determine the residual prestress force that remained in the concrete railroad ties after years of service.

Table 7.4: Concrete Crosstie Types

ID	Quantity	Manufacturer	Alternate ID	Wire #	Length
A	6	Itisa	136 RE	4	8'3"
B	6	Unknown	N/A	7	8'6"
C	6	FLORIDA EAST COAST	N/A	6	9'0"
D	6	SAN-VEL	Sante Fe	8	8'6"
E	6	CXT GRAND ISLAND	CXT497S	18	8'6"
F	6	CONFORCE COSTAIN	CN 60A	26	8'3"
G	6	KOPPERS	CSX	8	8'6"
H	6	ROCLA	N/A	24	8'6"
J	6	ROCLA	N/A	24	8'3"
K	6	COSTAIN GENSTAR	CP RAIL	24	8'6"
L	6	CXT	BN100	28	8'3"
M	6	ROCLA	BN100	28	8'3"

Twelve unique crosstie types were included in this component of the research, detailed in Table 7.4. 3D scans of these twelve concrete crossties are illustrated in Figure 7.12; these scans are used

to emphasize the significant physical differences between the specimens. After preliminary testing was completed a subset of the ties were cut along the cross-section where the rail seat is located, the section upon which the steel rail sits, in order to verify the geometry of the section. As a result of this saw-cut operation, the last 22 inches of the crossties were cut off, allowing for extraction of the indented wires and strands from the crossties. James Scott and research assistants performed the saw cuts and extraction of wires from the historical cross ties [43], whereas the author performed the 3D scans of the crossties [50]. These crosstie wires provide a unique historical basis to which the modern wires can be compared to.

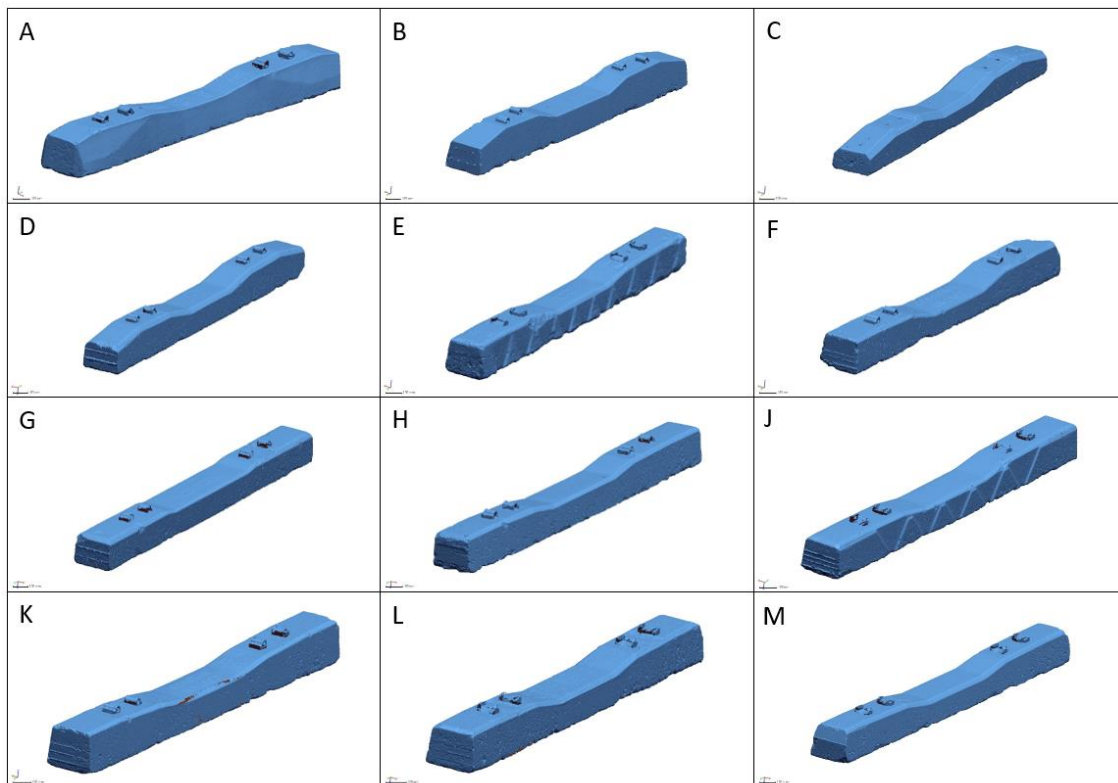


Figure 7.12: Concrete Crosstie Scans

7.2.1 Crosstie Wire Specimens

Twelve unique concrete crossties types were included within the scope of the main FRA research project [51], each group contained six individual crossties. One crosstie from each group was cut along the rail seat cross-section, yielding 22-inch lengths of wire or strand depending on the crosstie. The wires and strands associated with each unique crosstie type are illustrated in Table 7.5. One of the ties, type A, was a post-tensioned design, and thus, used non-indented wire/rod that exceeded 3/8 inches in diameter. Four of the ties featured strands, comprised of a central wire with six wires twisted around the central member in a spiral pattern; each of these ties contained between 6-8 strands. The remaining seven ties utilized indented wires with nominal wire diameters falling in the 5.00mm range. Thus, the indented wires of these seven unique ties could be subjected to measurement by the indent profile system.

Table 7.5: Concrete Crosstie Extracted Wire Types

	Layout				
	# of Wires	Wire Type	Indentations	Dia. Wire	Pattern
A	4	Wire	Non-indented	0.415"	2-2
B	7	Strand	Non-indented	0.375"	3-4
C	6	Strand	Indented	0.375"	2-4
D	8	Strand	Indented	0.375"	4-4
E	18	Wire	Indented	5.30mm	4-4-4-6
F	26	Wire	Indented	4.86mm	10-6-10
G	8	Strand	Indented	0.385"	4-4
H	24	Wire	Indented	4.97mm	6-6-6-6
J	24	Wire	Indented	4.94mm	6-6-6-6
K	24	Wire	Indented	4.95mm	8-8-8
L	28	Wire	Indented	4.97mm	8-10-10
M	28	Wire	Indented	5.02mm	8-6-6-8

The seven wires extracted from concrete railroad ties encompassed in this section of the study are E-1, F-1, H-1, J-1, K-1, L-1, and M-1. The first letter designates the tie type that the wire originated from and the following number dictates which tie in the group that the wire was extracted from. In all cases, the first tie in a group was subjected to saw cutting and subsequent wire extraction, and thus all wires receive the same trailing designation. Note that the letter “I” is skipped in the tie type designation, this is to prevent confusion between the number “1” that immediately follows. Digital microscope images of the extracted wires are provided in Figure 7.13.

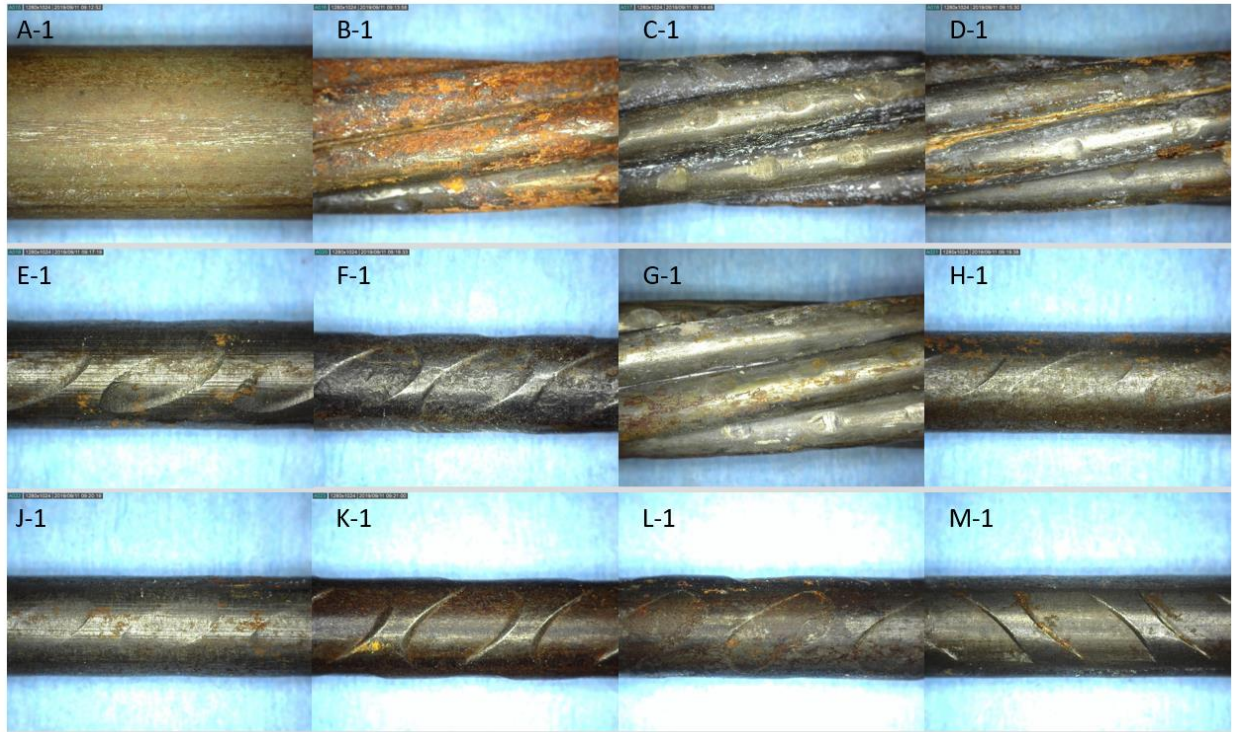


Figure 7.13: Digital Microscope Images of Extracted Crosstie Wires

From the digital microscope images, some notable observations for the indented wires can be made. E-1 has dish shaped ellipsoidal indentation profile, in which, a shallow sidewall angle exists across the entirety of the perimeter. For this wire, a 10-degree sidewall angle at a depth of 100-

120 microns is common. F-1 is highly corroded, with a thoroughly pitted surface which led to complications with the laser scanner. This wire has steep, crisp sidewall angles exceeding 20 degrees, coupled with a moderate depth; once again this indentation follows an ellipsoidal profile, but is still reasonably close to a chevron. Wire H-1 has an exceptionally shallow sidewall angle, estimated to be in the range of 5-8 degrees. This observation, in addition to the depth being on the order of 60-80microns, will ensure that this indentation has a tiny indent volume in comparison to a majority of the other specimens; indent volumes exceeding 1mm^3 are unlikely for an individual indent. Furthermore, the indent profile is an extremely elongated ellipse, but caused no difficulties with the processing algorithms. J-1 has a profile that is similar to E-1, but shares significant similarities to H-1 in regards to indentation depth. However, the sidewall of J-1 is slightly steeper, but not by a considerable margin.

The deepest indent of all is K-1, paired with a crisp, relatively steep sidewall that is estimated to be 15-20 degrees; average indent depths are on the order of 100-130 microns. Indent L-1 has a moderate sidewall angle in the range of 8-13 degrees, with a shallow depth, falling within the bounds of 60-80microns. Its profile differs from the rest of the specimens, forming a shape that more closely resembles a pill rather than an ellipse. Indent volumes for this specimen are unlikely to exceed 0.8mm^3 for an individual indent. Wire type M-1 coincidentally shares significantly similar features to wire WM discussed in the previous section. It is a true chevron type indent, in which the depth of the indent decays asymptotically to zero at the extremities of the indent width. Furthermore, it has steep, crisp sidewalls on the order of 15-20 degrees and has a depth on the order of 100-120microns. Wire M-1 appears to have the highest manufacturing quality out of any of the wires in the group, exhibiting no imperfections, cleanly made indents, and created from a wire with no inherent cast.

7.2.2 Crosstie Wire Results

The seven different chevron type indented wires extracted from concrete crossties were subjected to processing by the Indent Profiling System. Six of the scans were successful, however, the severe corrosive pitting on wire F-1 prevented a usable scan from being captured; laser-based systems can either be tuned to capture accurate scans of diffuse or reflective surfaces, but often struggle to image surfaces that are a combination of both. Thus, six of the wires extracted from the concrete railroad ties will serve as the historical comparison to their modern counterparts highlighted in the previous section. The data captured by the Indent Profiling System on the six crosstie wire specimens is summarized in Table 7.6, in which, the mean and standard deviations are listed for parameters of particular interest. It should be noted that the parameters contained by the following table stem directly from the requirements of the two main indented wire measurement standards, as well as parameters that were found to correlate favorably with wire-concrete performance criteria. Many more geometric parameters were computed by the Indent Profiling System, but the information contained below represents a sampling of the most important ones.

Table 7.6: Crosstie Wire Indentation Data

Indent Data (Crosstie Wires)										
	ID	Nominal Dia [mm]	Orientat-ion [deg]	Total Indents	Volume [mm ³]	S.W. Area [mm ²]	Avg Depth [mm]	S.W. Angle [deg]	Avg Length [mm]	Pitch [mm]
Mean	E-1	5.216	49.1	207	1.142	3.408	0.107	9.46	4.133	6.129
	H-1	4.981	44.9	208	0.742	3.079	0.073	7.18	4.470	6.103
	J-1	4.960	55.9	207	0.800	3.032	0.088	7.26	3.969	6.101
	K-1	5.124	60.1	209	1.832	2.443	0.117	15.79	4.391	6.136
	L-1	4.936	56.3	47	0.736	3.167	0.075	9.22	3.559	6.065
	M-1	4.954	47.2	199	1.237	1.937	0.099	16.36	4.302	5.965
Standard Deviation	E-1			207	0.131	0.480	0.015	1.20	0.151	0.025
	H-1			208	0.106	0.616	0.011	1.75	0.124	0.003
	J-1			207	0.076	0.480	0.012	1.53	0.148	0.007
	K-1			209	0.141	0.568	0.011	3.55	0.160	0.026
	L-1			47	0.120	1.374	0.015	3.19	0.343	0.088
	M-1			199	0.156	0.520	0.016	5.48	0.077	0.022
S.W. Area: The average sidewall area of the left and right side of the indents.										
S.W. Angle: The average sidewall angle of the left and right side of the indents.										

The scanned crosstie wires had nominal diameters of around 5mm, with E-1 being slightly larger than the rest. Five of the wires exhibited orientation angles exceeding 45°, apart from wire type H-1 which missed the cut-off by a narrow margin. Many orientation angles are considerably larger than 45° as many of the indentations form highly tilted ellipses. Statistically relevant sample sizes were obtained for a majority of the wires, neglecting L-1, which suffered from severe indent deformations caused by damaged indent rollers. A full-length scan was successfully captured for crosstie wire L-1, but the malformations of a majority of the indents required a shorter segment to be processed. The damage to specimen L-1 is visualized in Figure 7.14 which depicts the damage of the wire with a digital microscope image in addition to a contour plot of the wire scan; severe damage can be seen on two of the three rows. Furthermore, the damage caused by the chipped roller teeth can be seen as increased scatter in the measurements of certain geometric parameters for wire type L-1, notably average sidewall length and average sidewall area.

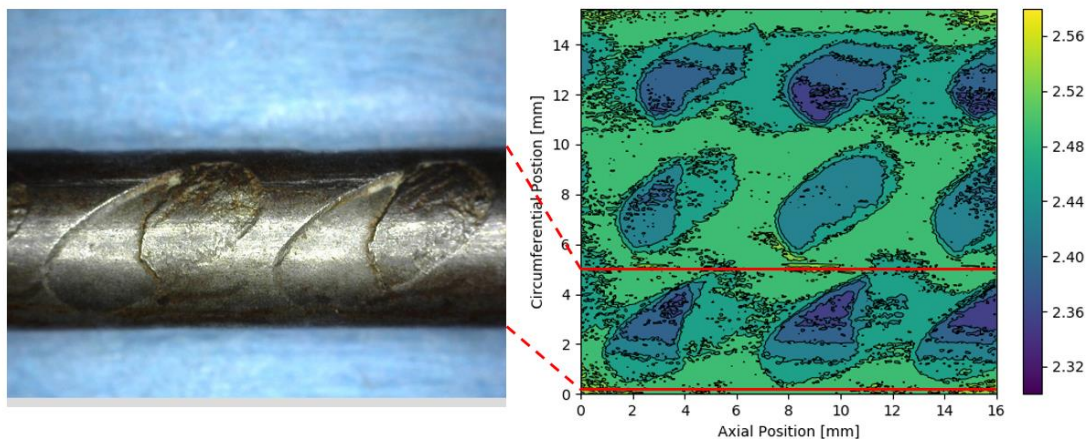


Figure 7.14: Severely Malformed Indents (Crosstie Wire L-1)

Observations of the digital microscope images earlier led to a prediction that indent volumes would likely not exceed 1mm^3 on average for wire types H-1, J-1, and L-1; this is clearly confirmed by the data summarized in Table 7.6. It was also predicted that K-1 would be the deepest indent of all, based on the microscope images, and have steep sidewall angles in comparison to other wires in the group; this is also confirmed by the results given in Table 7.6. Overall, the sidewall angles represented by the crosstie wire group are consistent and shallow. On a separate note, many of these wires would fail to pass the requirements of ASTM A881 based on the measured indent lengths and allowable indent pitch. This can be seen in the ASTM A881 requirements for 5.00mm and 5.32mm indented wires outlined in Table 1.1 [38].

The most striking difference between the historical crosstie wires and the modern wires is that the sidewall angles of the crosstie wires are considerably shallower on average in comparison to their more modern counterparts. Additionally, the orientation angles of the historical wires were much more inclined and many of the indentations resembled highly stretched ellipses. However, some of the wires bore significant similarities, namely crosstie wire M-1 and cover testing wire WM from the prior section. A comparison between the height-maps of the aforementioned wires is illustrated in Figure 7.15, which highlights how similar the overall shapes are.

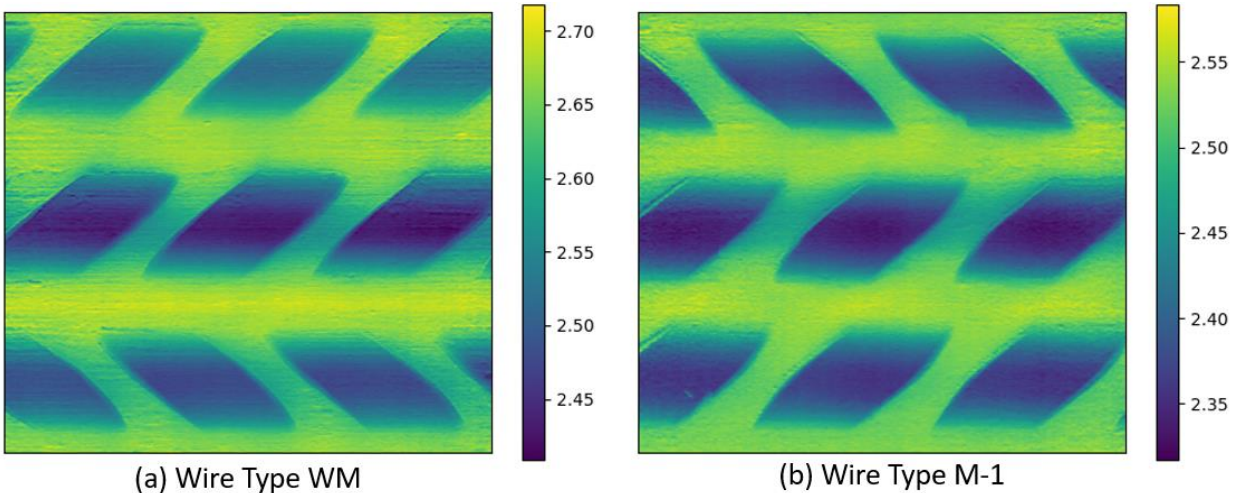


Figure 7.15: Similarities Between Wire WM and Wire M-1

7.3 Machined Indent Wires

The third group of wires, those with fabricated “machined” indents, were used for system calibration and verification of feature extraction algorithms. A set of machined indented wires of known geometry was created for a different FRA research project prior to the involvement of the author [37]. For that project, the machined wires were created for a similar purpose, to provide a system checkout for the precursor to the Indent Profiling System described in section 2.3; this research leveraged these samples as well since they represent known geometry. The indent geometry was formed by using custom made carbide endmills to remove material from a smooth wire with a nominal diameter of 5.32mm, analogous to wire type WA. Six separate tungsten-carbide endmills were custom made, each capable of generating “indentations” with a specific sidewall angle due to the chamfer built into the nose of the endmill. Figure 7.16, provided below, details a schematic of the endmill geometries used to form the indentations [37].

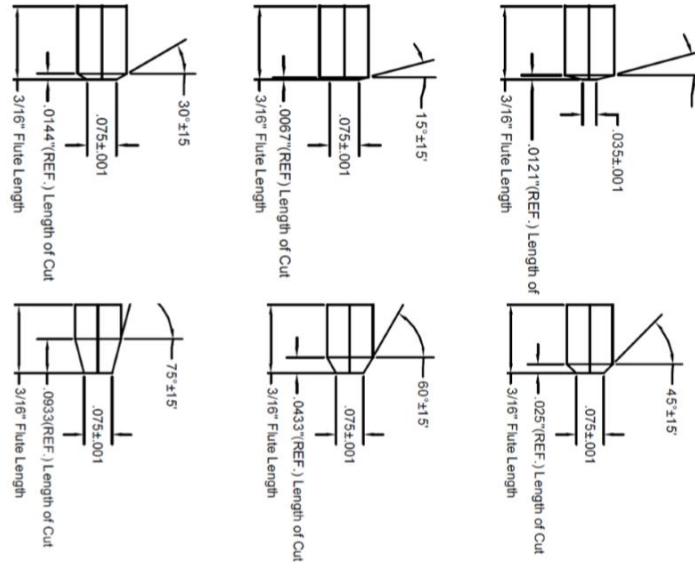


Figure 7.16: Endmill Geometry Used to Create Machined Indents

These six endmills were capable of machining indents with sidewall angles in increments of 15°, thus, indentations could be formed that varied from 15° to 90°, the most severe sidewall angle possible. Furthermore, two separate wires were fabricated for each sidewall angle, but with two separate indentation depths: shallow and deep. The tool depth was varied 0.004" ($\approx 100\mu\text{m}$) to generate the transition from shallow indentations to deep indentations; in practice, this proved challenging to achieve uniformly. Thus, 12 machined wires were fabricated with six separate sidewall angles each with two unique indentation depths; a picture of the machined wires can be visualized in Figure 7.17. The indentations were machined with an indentation orientation of 45° with respect to the longitudinal axis of the wire by keeping the tool height constant and moving the milling bed appropriately. These machined wires provide indents of known geometry that prove to be helpful with system verification.



Figure 7.17: Picture of Wires With Machined Indents

7.3.1 Machined Wire Specimens

Twelve unique machined wires were subjected to scanning by the Indent Profiling System to assist with system checkout. The group contained six sets of indentation sidewall angles formed by the cutting tools in increments of 15° , with two separate indentation depths apiece. The indentations were formed with an orientation of 45° . Furthermore, the fabricated specimens featured machined indents on a roughly 5.5" length of wire. Each row included 18 indents, thus, an entire specimen contained 54 indents since 3 rows were used. Digital microscope images of the fabricated wires are provided in Figure 7.18.

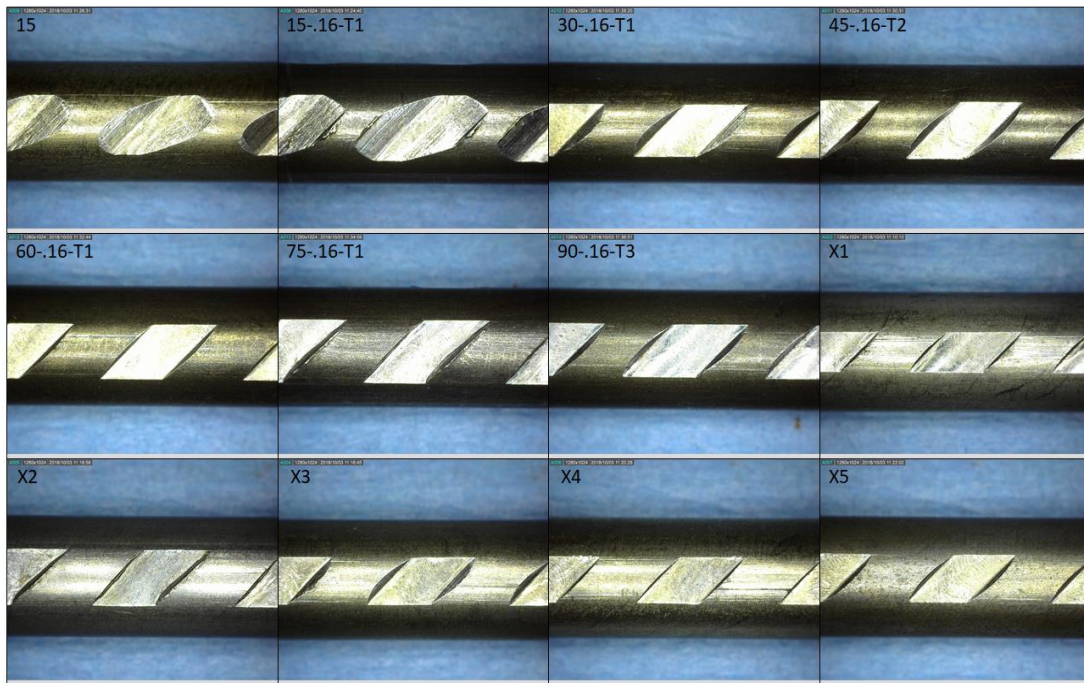


Figure 7.18: Digital Microscope Images of Machined Wires

The machined wires listed in Figure 7.18 above inherited a naming convention from the previous project, with many of the wires being labeled with the prefix of “X”; this convention likely originated when the wire labels were lost at some point. However, the Indent Profiling System makes wire identification trivial since it can obtain sidewall angles and indentation depths with ease. The Indent Profiling System results were used in addition to a shadowgraph imaging system to aid with the proper identification of the wires.

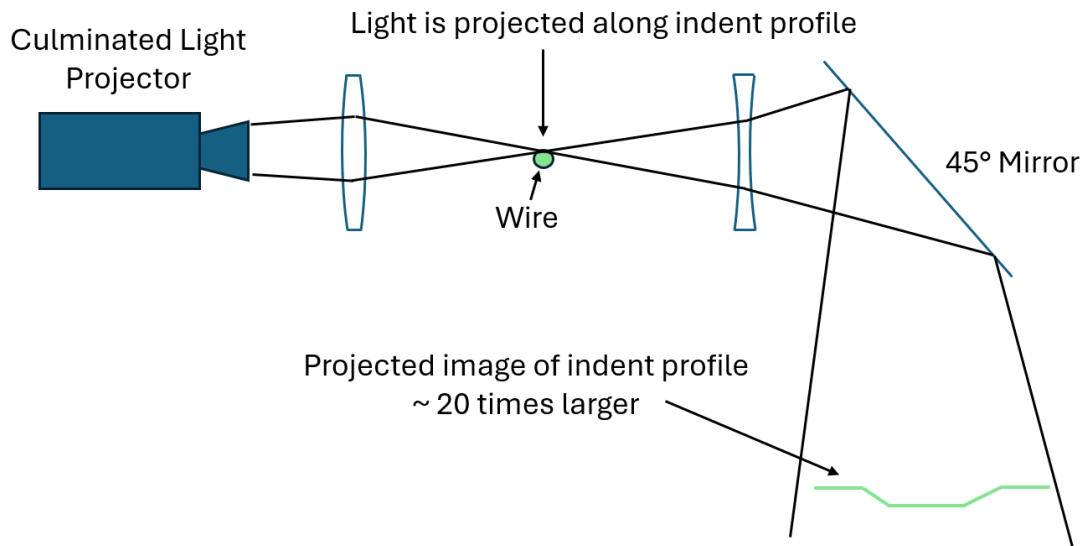


Figure 7.19: Shadowgraph Imaging System

The shadowgraph imaging system works by projecting light across the machined track of the indent, and enlarging the resulting shadow, much like a projector would. A simplified depiction of the shadowgraph imaging system setup can be seen in Figure 7.19. This shadowgraph system provided a magnification increase by a factor of 20. An example of the shadowgraph imaging system results can be seen below in Figure 7.20 being used to identify an indent formed by an endmill that featured a 15° chamfer angle.

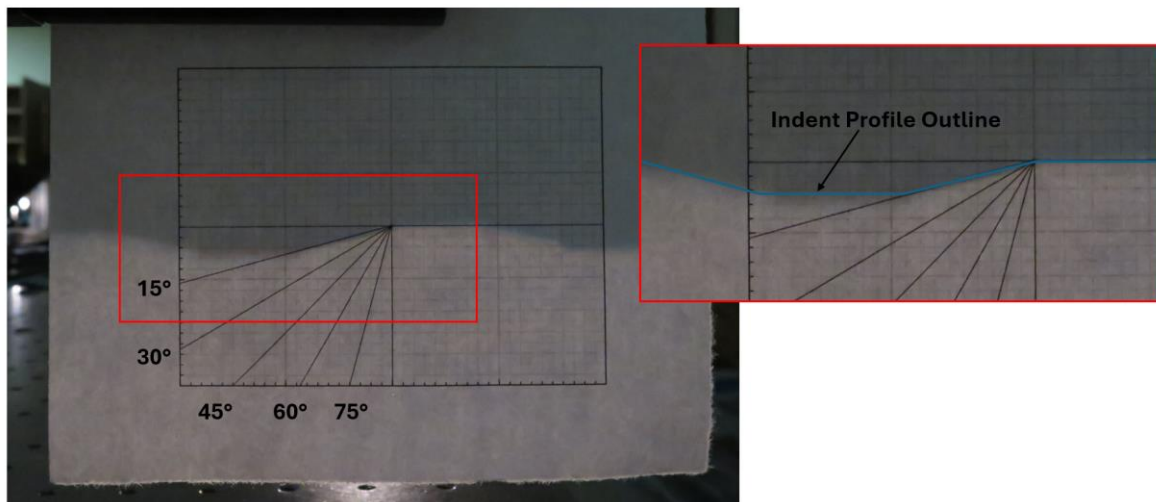


Figure 7.20: Shadowgraph Imaging of Machined Indent

The shadowgraph imaging system, in conjunction with the Indent Profiling System were used to properly identify the machined wires. Table 7.7 overviews the proper identification of the machined wires alongside the original alternate IDs to be used as a reference. The first number in the corrected ID intuitively represents the chamfer angle of the endmill used to form the indentation, whereas the letter that follows designates the intended relative depth of the wire: “S”

for shallow, and “D” for deep. Note that the targeted depth difference between the shallow and deep indents with the same indent angle geometry was 0.004” ($\approx 100\mu\text{m}$). The measured centerline depth results confirm this general observation, however, the relative depths between wires of different indentation angles vary significantly. For example, the centerline depth of 15-S, is vastly different than the one measured for 30-S.

Table 7.7: Machined Wire Identification

ID	Alternate ID	Centerline Depth [mm]	Δdepth [μm]
15-S	15	0.304	92
15-D	15-.16-T1	0.396	
30-S	X3	0.151	99
30-D	30-.16-T1	0.250	
45-S	X5	0.148	86
45-D	45-.16-T2	0.234	
60-S	X4	0.136	106
60-D	60-.16-T1	0.242	
75-S	X2	0.287	95
75-D	75-.16-T1	0.382	
90-S	X1	0.138	76
90-D	90-.16-T3	0.213	

Some critical observations from the digital microscope images along with the endmill geometry used to form the machined indentations are addressed next. The indentation with the 15° sidewall angle is the deepest indentation of all. The magnitude of the centerline depth, coupled with the shallow sidewall angle, ensures that 15-D has the largest volume out of any of the indents. In fact, it is so deep that the carbide endmill left a burr along the transition between the sidewall and the crest of the indent. The smallest indents, confirmed visually by the digital microscope images are 60-S and 90-S; this observation is due to the fact that both of these indent geometries have the shallowest centerline depth overall, in the range of 130-140 μm . Furthermore, all indentations formed by endmills with 30° and 45° chamfers left cleanly fabricated indents, whereas the 60° endmill suffered from a chipped cutting face and left an imperfect indent geometry for the shallower indentation. Both of the 75° specimens were impacted by imperfect tool pathing, seen by the marring on the right side of the indentation; the tool started to turn at the end of the cut rather than continue along the orientation angle. This significantly impacted the measured sidewall angles. Finally, the 90° endmill was not a straight-fluted endmill, instead it had a 45° cutting edge chamfer. Additionally, the “90°” endmill has a wider base diameter than the rest of the cutters, this can be seen in the digital microscope images since 90-.16-T3 and X1 have wider tracks at the base of the indent than the rest.

7.3.2 Machined Wire Results

By scanning and processing the machined wire specimens a verification of the accuracy of the system could be obtained since the machined indents represent geometry of known dimensions.

The data captured by the Indent Profiling System on all 12 machined wire specimens is summarized below in Table 7.8.

Table 7.8: Machined Wire Indentation Data

Indent Data (Machined Wires)								
ID	Alt. ID	Total Indents	Volume [mm ³]	S.W. Area [mm ²]	Avg Depth [mm]	S.W. Angle [deg]	Avg Length [mm]	Pitch [mm]
15-S	15	45	1.327	3.686	0.223	12.67	3.645	6.344
15-D	15-.16-T1	45	2.149	5.046	0.290	13.18	4.190	6.344
30-S	X3	45	0.595	1.050	0.105	19.93	3.599	6.345
30-D	30-.16-T1	45	1.249	1.582	0.184	21.84	3.730	6.343
45-S	X5	45	0.545	0.951	0.103	23.95	3.311	6.345
45-D	45-.16-T2	45	1.009	1.066	0.172	30.19	3.255	6.354
60-S	X4	45	0.493	1.390	0.082	22.42	3.641	6.347
60-D	60-.16-T1	45	1.082	0.872	0.178	43.14	3.205	6.343
75-S	X2	31	1.317	1.365	0.215	34.93	3.125	6.343
75-D	75-.16-T1	36	2.025	1.408	0.290	49.27	3.128	6.346
90-S	X1	45	0.600	1.437	0.088	22.96	3.968	6.342
90-D	90-.16-T3	45	1.091	1.030	0.156	32.43	3.817	6.343
S.W. Area: The average sidewall area of the left and right side of the indents.								
S.W. Angle: The average sidewall angle of the left and right side of the indents.								

The primary three-dimensional geometry of interest is indent volume and sidewall area, as these parameters pertain to wire-concrete criteria such as bond, transfer length, and splitting propensity. The two-dimensional characteristics used to compute these metrics correspond to average depth, average indent length, and average sidewall angle. Note that these two-dimensional parameters, particularly average depth and average sidewall angle, do not compare directly to the chamfer of the endmill used to form the indents. This arises from the fact that the scan plane is coincident with the bore axis of the wire, and thus is not perpendicular to the machined track of the indent except at the centerline location.

Observations of the data contained in Table 7.8 match the physical observations of the digital microscope images of the wires listed in the previous subsection. As noted previously from the microscope images, 60-S and 90-S have the shallowest depth, and thus the smallest indentation volume, this is confirmed by the tabulated data. Additionally, it was observed from the images that 15-D appeared to be the largest due to the shallow sidewall angle and deepest machined depth, this is also confirmed by the tabulated data. Earlier it was noted that the 90° endmill did not appear to be a straight-fluted endmill, instead it had a 45° chamfer and a wider nose track than the other endmills as observed by shadowgraph images and images obtained from the digital microscope. This is validated by the sidewall angle data, which is exceedingly far off from the steep angle expected from a true 90° cutting tool. The average basin length data from the Indent Profiling System (not listed in the table above) indicated that 90-S and 90-D had wider ground tracks than the geometry formed by other endmills. Furthermore, the pitch between indents across all specimens is consistent, the average indentation pitch is 6.345mm, varying only 0.012mm (12µm) across all machined wires; this consistency is inherent to the machining process used to form the wires.

Table 7.9: Verification of Sidewall Angle Extraction Algorithm

Indent Data (Machined Wires)							
ID	Alt. ID	Total Indents	Volume [mm ³]	S.W. Area [mm ²]	Centerline Depth [mm]	Centerline Angle [deg]	Chamfer Angle [Deg]
15-S	15	45	1.327	3.686	0.304	10.65	14.89
30-S	X3	45	0.595	1.050	0.151	22.11	29.87
45-S	X5	45	0.545	0.951	0.148	35.88	45.64
Centerline Angle: Centerline Sidewall Angle							
Chamfer Angle: The equivalent chamfer angle that the centerline sidewall angle forms							

Verification of the reliability of the feature extraction algorithms can be provided by comparing the captured geometric features with indents of known physical shape. The indentations of these machined wires were formed by using endmills with known chamfer angles, following machined tracks that formed an indent orientation angle of 45°. Thus, the sidewall angle information extracted by the Indent Profiling System can be compared with the known geometry of the endmills used to form the indents. A majority of the indented wires seen in industry have sidewall angles that vary from 5-45° and indentation depths that vary from 50-200µm for wires with a 5.32mm nominal diameter. Therefore, the following indents were selected to verify the accuracy of the sidewall angle feature extraction algorithm: 15-S, 30-S, and 45-S. The results of these particular wires are highlighted in Table 7.9, in which the critical parameter used to obtain equivalent chamfer angle is listed, the centerline sidewall angle. The centerline sidewall angle is the only location on the machined indent in which the sheet-laser plane is guaranteed to be perpendicular with the machined indent track. However, the centerline angle does not measure the chamfer angle of the endmill used to form the indents, since the orientation angle of the machined track is at a 45° angle. This is illustrated in Figure 5.12, which shows the relationship between the true machined sidewall angle and the measured centerline sidewall angle.

$$\theta_{chamfer} = \tan^{-1}(\sqrt{2} \tan(\theta_{centerline})) \quad (6.1)$$

By applying the simple algebraic relation above, a direct assessment of the equivalent measured chamfer angle can be obtained. Thus, it can be seen that the equivalent chamfer angles listed in Table 7.9 agree quite closely with the endmill chamfer angles used to form the indentations. The angles fall within a fraction of a degree of the expected values in all circumstances. This confirms the validity of the data extraction algorithms by using indents of known, fabricated geometry.

Chapter 8 - Correlations

The second phase of this research involved the application of the Indent Profiling System to measure the indent characteristics of a multitude of indented wires. A large subset of the wires subjected to testing included wires that are used in modern industry. These wires represent a diverse selection of indent depths, indentation shapes, and sidewall angles used in practice. The wires contained by this group, representing ten unique chevron type wires, were subjected to processing by the Indent Profiling System, the results of which were highlighted in section 7.1. The extracted geometric features provided statistically valid sample sizes as the entire wire pattern formed by a complete revolution of the indent rollers was captured for all wire specimens.

The captured indented wire geometry was then used in conjunction with empirical data obtained from prestressed concrete prisms created using the same ten wires. The concrete prisms were constructed for the purpose of measuring the effects of reduced concrete cover, aggregates, release strength, and wire type on wire-concrete performance criteria. Adrijana Savic and other researchers constructed these prisms; the author evaluated transfer length of the prisms using an automated measurement system [47] and, along with the assistance undergraduate researchers, assessed splitting propensity when cracking occurred. From this combined information, the detailed indentation geometry was correlated with wire-concrete performance criteria such as transfer length and splitting propensity to quantitatively determine which indent features contribute most significantly, or detrimentally, to desirable performance characteristics. Furthermore, it was possible to investigate which 3D geometric parameters can be reasonably approximated by 2D features extracted along the indent centerline. If the 2D parameters can be shown to correlate against already established 3D parameters that characterize wire-concrete performance criteria such as transfer length and splitting propensity, the potential for on-line production quality control in real-time may be realizable. The subject of correlations will be the source of extensive discussion in the sections that follow.

8.1 Correlation of 2D Parameters to 3D Parameters

The Indent Profiling System has proven to be a valuable research tool to extract indentation geometry. The statistically relevant sample sizes that the system is capable of collecting for scores of wire features can be used to determine which geometric features, or combination of features, have the most significant contributions to wire-concrete performance. However, it would prove to be valuable from a quality control perspective if an Indent Profiling System could be placed in the production line of an indented wire manufacturing facility to give real-time feedback on wire quality. The current Indent Profiling System requires a segment of wire to be cut from the end of a wire spool and is therefore not amenable to being placed in the production line as indented wire is being formed. Thus, it would be desirable to implement a non-contact laser-based scanning system capable of collecting profile data along the indent centerlines so that the wire quality could be monitored in real-time in a plant environment.

The implementation of such a system would require the understanding of how the two-dimensional centerline wire characteristics correlate against critical three-dimensional wire parameters that were found to be sufficient in predicting performance criteria such as transfer length, bond, and splitting propensity. The extensive data collected by the Indent Profiling System on a multitude of indented wires can be used to ascertain such correlations.

Table 8.1: Potential Correlations of 2D and 3D Parameters

	2D Feature	3D Feature
Single	Centerline Depth	Average Depth
	Centerline SW Length	Sidewall Area
	Centerline SW Angle	Average SW Angle
	Centerline Profile Area	Volume
	Centerline Length	Average Length
Multivariate	Centerline Profile Area	Volume
	Indent Width	
	Centerline SW Length	Sidewall Area
	Indent Width	
	SW : Sidewall	

Certain two-dimensional wire features summarized in Figure 6.13 are found to be analogous to their three-dimension counterparts illustrated in Figure 6.14. The table listed above, Table 8.1, lists sets of two-dimensional and three-dimensional parameters that are highly likely to correlate well with one another. For example, since most of the 3D parameters are integrations of 2D components across the width of the indent, it is intuitive that any parameter related to the average of the 2D parameters will correlate strongly with its 3D counterpart. Centerline sidewall length (the average of the left and right side) can be shown to exhibit a very strong relationship with average sidewall area of the indent, since the centerline sidewall length is a close approximation of the average sidewall length. The list of the 2D parameters provided in the table above were predicted to have a direct relationship with the 3D geometry.

The cover testing wire features extracted by the Indent Profiling System can be found in Table 7.2, which summarizes the most critical geometry. However, the aforementioned table only lists a sampling of extracted features. The Indent Profiling System currently extracts 38 wire features (after using the post-processing program) that encompass centerline geometry, two-dimensional profile averages, minimum and maximum values, as well as the three-dimensional wire geometry, far too extensive to tabulate in the context of this dissertation. These parameters exist per indent, or as the average of all indents for a particular wire specimen as Table 7.2 implies. The data collected for a set of wires, the cover testing wires for example, can then be used with commercially available statistics processing software to determine the correlations between the parameters outlined in Table 8.1.

Figure 8.1 highlights the correlation between centerline depth, a fundamentally 2D parameter, and average indent depth, a 3D parameter. The plot shows values of average indent depth that were predicted by the developed correlation against the measured values of average depth. If a perfect correlation existed, all of the data points would fall along the red line, which would imply a 1:1 mapping between the predicted and measured results. However, it is often not possible to choose correlation parameters in which the predicted value is completely dependent on the independent parameters chosen for the correlation, thus scatter exists; this is also exacerbated by imperfect measurements. This scatter can be described by the coefficient of determination, or R^2 -value of the correlation; this relates how far the data points deviate from the line of best fit. An R^2 -value of one implies a perfect correlation and a R^2 -value of zero implies no correlation. Unsurprisingly, a reasonable correlation exists between centerline depth and average indent depth, with a majority of the points clustering around the prediction line.

A perfect correlation is not expected to exist, however, because the centerline depth does not always reflect the average depth of the entire indent. Wire type WM for example has a basin that is shaped like a bowl, in which, it is deepest in the middle and asymptotically approaches a depth of zero at the extreme width of the indent. In this case, the centerline depth is clearly not indicative of the average depth of the indent. Overall, the correlation is favorable since a majority of the indents have consistent depths across the basin of the indent. The correlations that follow in this subsection were developed using the mean values of the processed cover testing wire specimens.

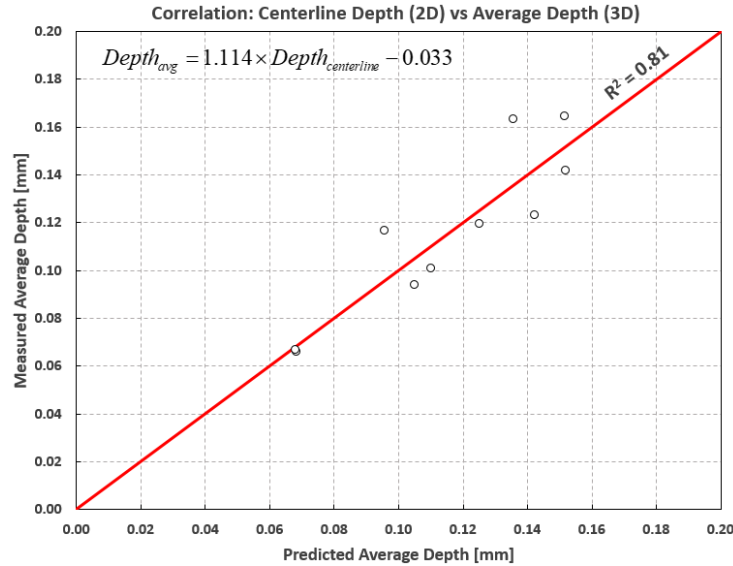


Figure 8.1: Centerline Depth (2D) vs. Average Depth (3D)

The plot listed below in Figure 8.2 clearly demonstrates a strong relationship between centerline sidewall length and the three-dimensional parameter of sidewall area. By simply measuring the centerline sidewall length it is possible to get a reasonable approximation of sidewall area.

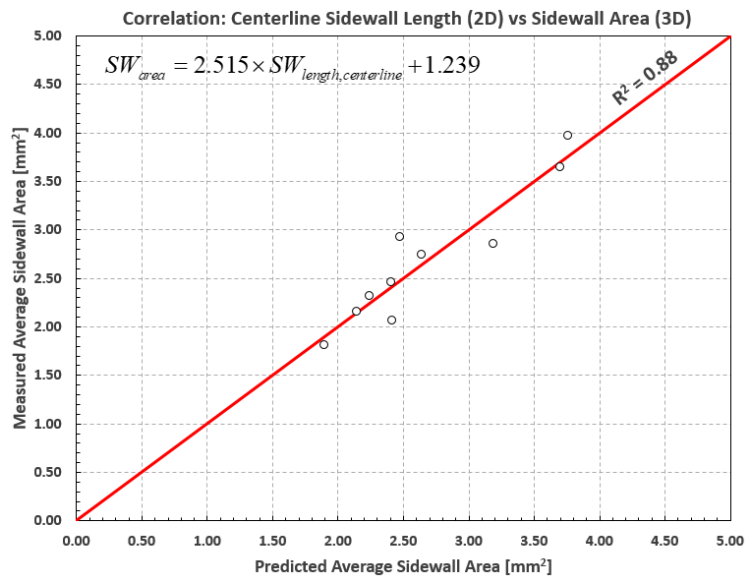


Figure 8.2: Centerline Sidewall Length (2D) vs. Sidewall Area (3D)

The correlation between centerline sidewall angle and average sidewall angle can be visualized in Figure 8.3. From this relation, it is apparent that the centerline sidewall angle is a relatively poor way to predict the average sidewall angle of the indent. This is due in part to the fact that sidewall angle can vary significantly as a function of location along the indent, additionally, it is a parameter that is notoriously challenging to measure accurately.

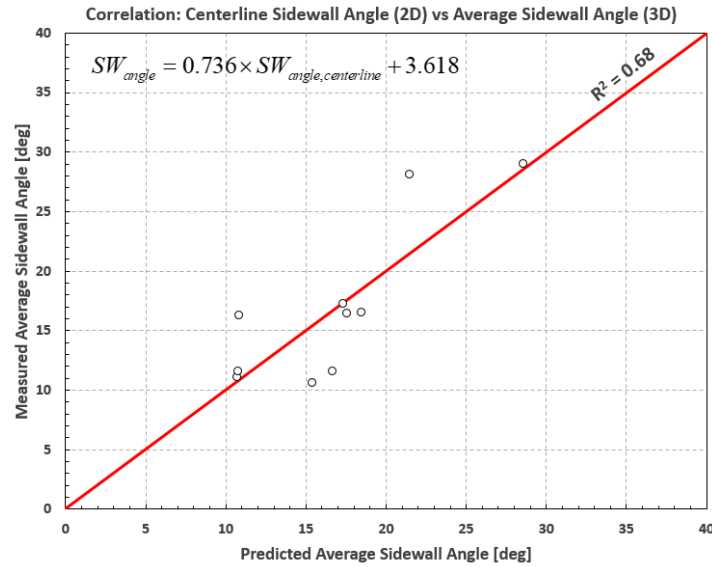


Figure 8.3: Centerline Sidewall Angle (2D) vs. Average Sidewall Angle (3D)

Likewise, centerline profile area roughly correlates with indentation volume as illustrated in Figure 8.4. Volume, fundamentally, is the integration of profile areas across the width of the indent. Volume is inherently three-dimensional and requires the additional knowledge of indent width to be accurately predicted. Since indentation widths can vary from wire to wire, it should come as no surprise as to why the correlation listed below is only approximate.

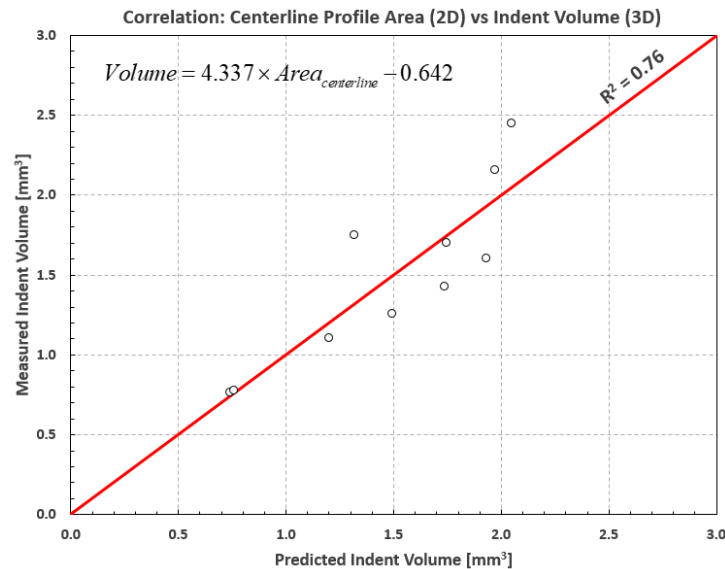


Figure 8.4: Centerline Profile Area (2D) vs. Indent Volume (3D)

Centerline indent length was shown to have no appreciable relationship with the average length of the indent, resulting in a R^2 value of 0.0002. The reason for the non-existent correlation is that indent length varies drastically depending on where it is measured along the width of the indent. This parameter is strongly influenced by the overall shape and size of the indentation geometry. Although all of the wires included in the cover testing group exhibited a chevron style indentation, the overall shapes of the indentations remained sufficiently diverse. Thus, average indent length is a function of indentation shape, and centerline length is not capable of predicting it without additional knowledge of the indentation shape.

A majority of the three-dimensional indent features rely on the integration of two-dimensional parameters to be obtained. Thus, features such as indent volume and indent sidewall area are not only dependent on average values of the 2D parameters, but are also reliant on the width of the indent to be accurately computed.

This can be seen in the following correlation, in which, both centerline profile area and indent width are used to determine indent volume, a fundamentally three-dimensional parameter; this correlation is illustrated in Figure 8.5. The predicted volume is much more faithful to the measured values once indent width is considered in the correlation, improving the R^2 value to 0.88; the previous value was 0.76 when indent width was not included. Thus, if the nominal width of the indents is measured or previously known from the manufacturing process, it is possible to reasonably predict indent volume. While indent width is not measured along the centerline of the indent profile, it is an exceptionally easy and accurate measurement to take without the need of a complex indent measurement system.

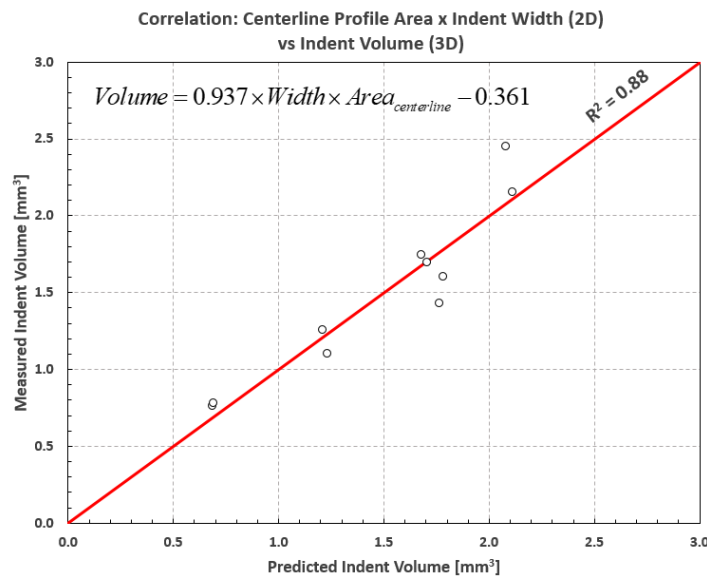


Figure 8.5: Multiple 2D Parameters Used to Evaluate Indent Volume

Indent sidewall area also receives a slight benefit to the correlation by using the centerline sidewall length in addition to the width of the indent. This improvement can be seen in Figure 8.6. However, sidewall area does not experience same amount of improvement that indent volume had when indent width was included.

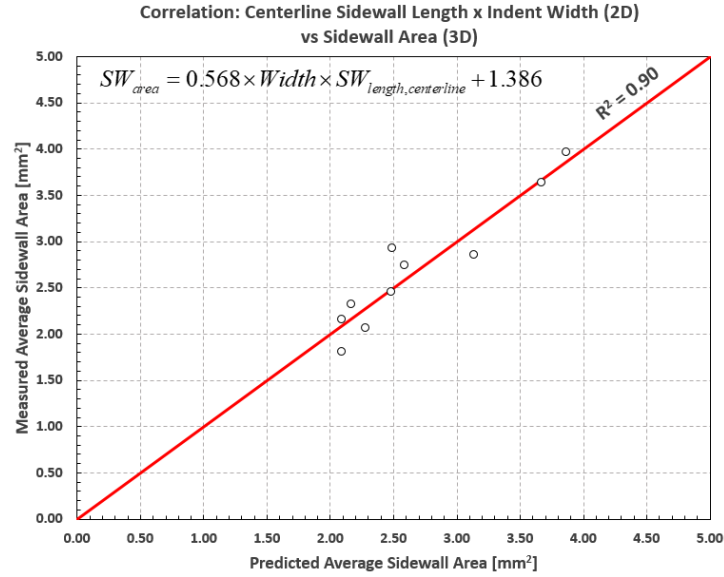


Figure 8.6: Multiple 2D Parameters Used to Evaluate Sidewall Area

The correlations in the section above demonstrate how a majority of the relationships hypothesized by Table 8.1 can be used to reasonably predict critical three-dimensional geometry. The information evaluated along the centerline of the indents, in conjunction with knowledge of the indentation width, is generally sufficient to obtain a prediction of the 3D geometry that has been shown to correlate well with performance parameters such as transfer length and splitting propensity. Armed with this knowledge, the potential for on-line production quality control in real-time may indeed be realizable.

8.2 Empirical Concrete Prism Data

A critical component of the second phase of this research is evaluating which indented wire geometric features, or combinations of features, contribute most significantly to desirable wire-concrete performance criteria. Prior sections of this dissertation were dedicated to the acquisition of accurate wire scans and the extraction of statistically significant quantities of detailed geometric features of a multitude of indented wires. As a result, a plethora of measured wire geometry is available to be correlated against parameters that can be used to indicate favorable wire-concrete performance.

In conjunction with the Indent Profiling System, sets of prestressed concrete prisms were made for the overall FRA research project [51]. These concrete prisms were constructed using the same ten cover testing wires that were subjected to extensive evaluation by the Indent Profiling System, the results of which, are summarized in Chapter 7. The concrete prisms were constructed with the purpose of measuring the effect of reduced concrete cover, aggregates, release strength, and wire type on wire-concrete performance criteria, namely, transfer length and splitting propensity. Adrijana Savic and other researchers constructed these prisms; the author evaluated transfer length of the prisms using an automated measurement system [47] and, along with the assistance undergraduate researchers, assessed splitting propensity when cracking occurred. From this combined information, the detailed indentation geometry can be correlated with wire-concrete performance criteria to quantitatively determine which indent features contribute most significantly, or detrimentally, to desirable performance characteristics.

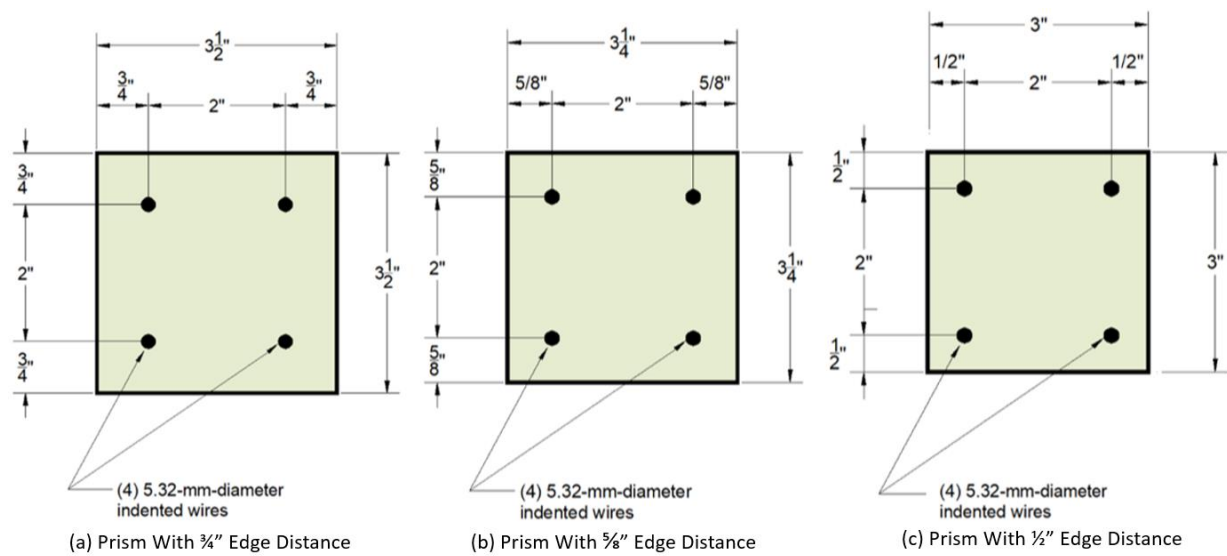


Figure 8.7: Concrete Prism Schematics

Three separate sizes of prisms were constructed for the larger FRA project [51] to evaluate the effect of reduced concrete cover, aggregates, and release strength on transfer lengths and splitting propensity for ten unique chevron wires. The wire patterns of the prisms were comprised of 4 wires with equal spacing, forming a square grid with 2" spacing between wires. The overall external sizes of the prisms were then chosen to provide the desired concrete covers for the tests, the distance between the center of a wire to the nearest free surface, resulting in the following concrete covers: $\frac{3}{4}$ ", $\frac{5}{8}$ ", and $\frac{1}{2}$ ". A schematic representation of the constructed prisms as seen in the overall report titled *Developing a Prism Qualification Test to Ensure Adequate Splitting Resistance in Pretensioned Concrete Railroad Ties* [51] can be visualized in Figure 8.7.

The prisms were cast with three separate mix designs utilizing different aggregates: Tucson, granite, and pea gravel. Furthermore, multiple concrete release strengths were tested, namely 4500psi and 6000psi for the prisms applicable to this portion of the research. The prestress force for the fabricated prisms was targeted at 28000lbs, each wire being tensioned to 7000lbf prior to de-tensioning. The prisms were cast in metal forms to ensure high geometrical tolerances; each prism was 69 inches in length so that a unique transfer length could be assessed on each side, provided no cracking occurred.

Overall, 161 prisms were created with ten unique chevron wires, three different concrete covers, three different aggregates, and two separate release strengths that could be used in the correlations in the sections that follow. To evaluate the transfer length measurements of the test prisms, an automated non-contact strain measurement system was utilized, a photograph of which, can be visualized in Figure 5.8. To accomplish this, a set of reference images were taken along the length of the prism ends prior to de-tensioning, after de-tensioning another set of images were taken and a strain profile was obtained. From the strain profile, the transfer lengths on each end of a prism could be determined, provided that no cracking occurred. The transfer length is a valuable quality control parameter used in determining wire-concrete performance, it is the length over which the prestress force from the wires is completely transferred to the concrete. An illustration of what the transfer length represents is provided in Figure 8.8; this illustration is a favorite of the FRA

team at KSU to elucidate what transfer length physically represents. From a design standpoint, it is required for the transfer length to be shorter than the distance from the edge of the tie to the rail seat. Transfer length is influenced by concrete release strength, but is also heavily dependent on wire indentation geometry.

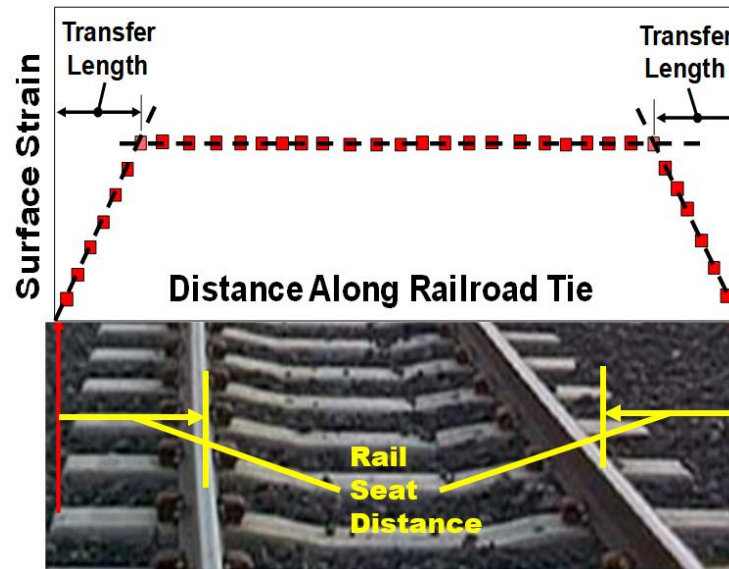


Figure 8.8: Transfer Length

In addition to the transfer length, the concrete prisms were used to assess splitting propensity. Splitting propensity is the amount of cracking that occurs after the de-tensioning process. For obvious reasons, it is desirable for this parameter to be zero, and preferable to have a significant margin of safety to guard against it. Splitting is primarily a function of prestress force, release strength, concrete cover, and can be heavily influenced by wire geometry. By reducing concrete cover to critical levels, cracking can be observed, allowing for the relationship between splitting propensity and wire geometry to be understood.

The majority of the prisms experienced cracking after the de-tensioning process; this was intentionally done based on the covers chosen to fabricate the prestressed prisms with. Each prism was subjected to manual assessment by the author and research assistants, in which, the cracks were drawn out for each end of the prism. This formed a “crack-map”, which tabulated the observed crack lengths and crack widths present on each prism. An example of a crack-map is illustrated in Figure 8.9.

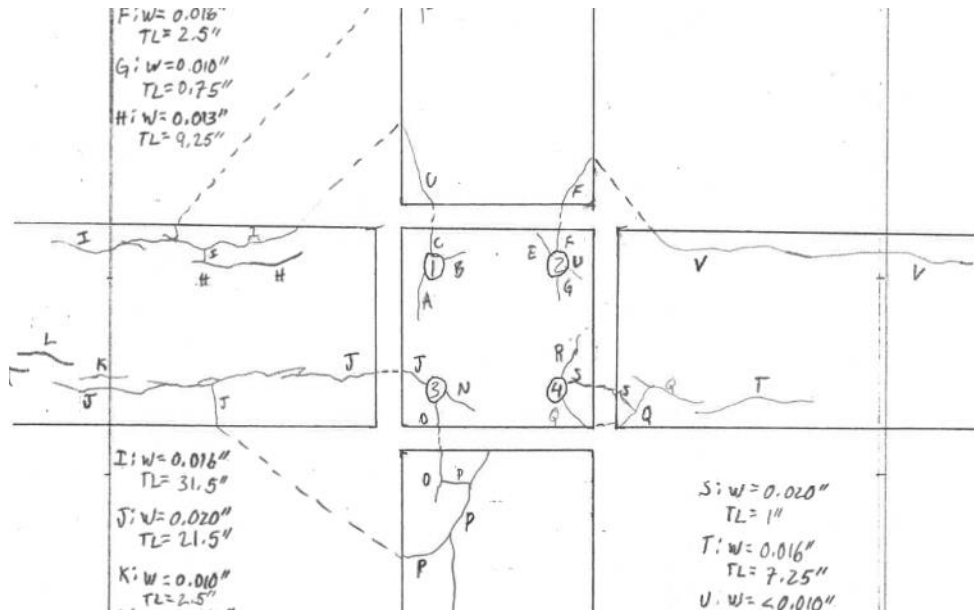


Figure 8.9: Concrete Prism Crack Map

Overall, 135 prisms (84% of specimens) had visible cracks after the de-tensioning process for prisms composed of the ten different cover testing wires. Of those prisms, 58 were made with Tucson aggregates, 53 were made with granite aggregates, and 24 were constructed with pea gravel. It is important to note that fewer prisms were constructed with pea gravel than the other two aggregates, and that only one unique release strength was tested for the prisms made of pea gravel.

Furthermore, prior FRA projects involved the creation of similar concrete prisms utilizing the same cover testing wires [18]. Those prisms were included in the correlation process in addition to the data captured by the cover testing prisms. The previous prisms were constructed with 1" concrete cover, and thus, infrequently experience splitting failures. As such, that set of prisms represented a consistent source of transfer length data since a vast majority of the prisms received valid transfer length measurements since no cracking was observed.

The transfer length and splitting propensity measurements on the test prisms resulted in an expansive amount of empirical data. This data covered ten unique chevron wires, three different concrete covers, three different aggregates, and two separate release strengths. The addition of the transfer length data obtained from prior FRA projects also provided a substantial amount of quality transfer length information [18] which the author assisted in measuring. The collected performance metrics of transfer length and splitting propensity could then be correlated with the extensive amount of data collected by the Indent Profiling System. The resulting correlations are the primary topic of discussion in the sections to follow.

8.3 Transfer Length Correlations

Transfer length describes an important performance characteristic in prestressed concrete members. Transfer length is the length over which the prestress force from the wires is completely transferred to the concrete, an illustration of what transfer length physically represents is provided in Figure 8.8. Prior research has shown that this parameter is influenced by concrete release

strength, but is also heavily dependent on wire indentation geometry. The results obtained by the Indent Profiling System, coupled with empirical measurements of transfer lengths of concrete prisms constructed using the same wire specimens, have been used to correlate the relationship between certain indent geometrical features and the resulting transfer length.

Transfer length measurements from a prior FRA project were used extensively in conjunction with results from the Indent Profiling System [18]. Fifteen separate sets of prisms were created with 1” concrete cover, utilizing nine different wires. Eight of these wires were identical to those highlighted in section 7.1 (WP and WQ were not available). The remaining wire, type WA, was a smooth 5.32mm wire with no indentation characteristics. Each test set included three prestressed concrete prisms, resulting in six separate transfer length measurements; these six measurements were averaged together to represent a single transfer length for the set. Additionally, three separate release strengths were tested: 3500psi, 4500psi, and 6000psi. A majority of the tests, 9 out of 15, were performed at 4500psi.

The first transfer length correlation was carried out on test sets that shared a common release strength in order to isolate the effects of wire indentation geometry on bond, and thus, transfer length. The 4500psi release strength data representing the nine unique wires was used in this case. Prior research has shown that multivariate linear regression with two select geometric parameters is sufficient to accurately predict transfer length [37]. Indentation volume and indent sidewall area were used to develop a correlation that resulted in a R^2 -value of 0.94, indicating an exceptionally strong correlation. As indentation volumes and sidewall area increase, the transfer length sees a corresponding decrease. This makes intuitive sense as the increase in indentation volume and sidewall area allows for more interlocking with the surrounding concrete and provides additional bearing area. The correlation showing the relationship between indent volume and sidewall area on transfer length is plotted below in Figure 8.10.

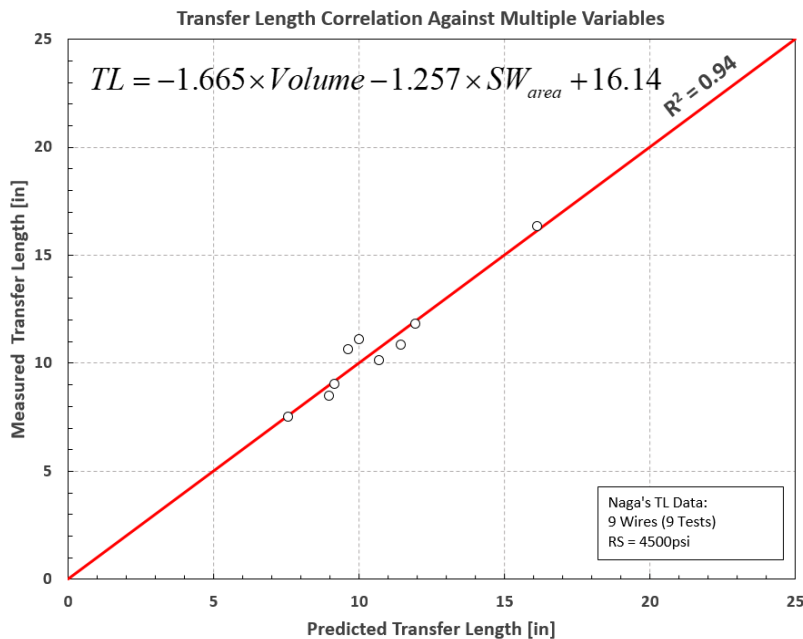


Figure 8.10: Transfer Length vs. 3D Indent Parameters (Constant Release Strength)

The second transfer length correlation that was carried out included all fifteen tests, involving three unique release strengths. Release strength has a direct influence on the transfer length, and thus, by maintaining the same geometric features, the effect of release strength on transfer length can be quantified. Furthermore, the compressive and tensile strength of concrete is directly related to the square root of release strength, therefore, the square root of release strength is included as a variable in the regression. The correlation involving the square root of release strength, indentation volume, and indent sidewall area to predict transfer length is provided in Figure 8.11. Once again, a strong correlation is observed, resulting in a R^2 -value of 0.88 with most of the points clustered next to the line of best regression. Similar to the previous correlation, increases in volume and sidewall area correspond to a decrease in transfer length. An increase in release strength has the effect of decreasing the transfer length, an observation that is matched by reality.

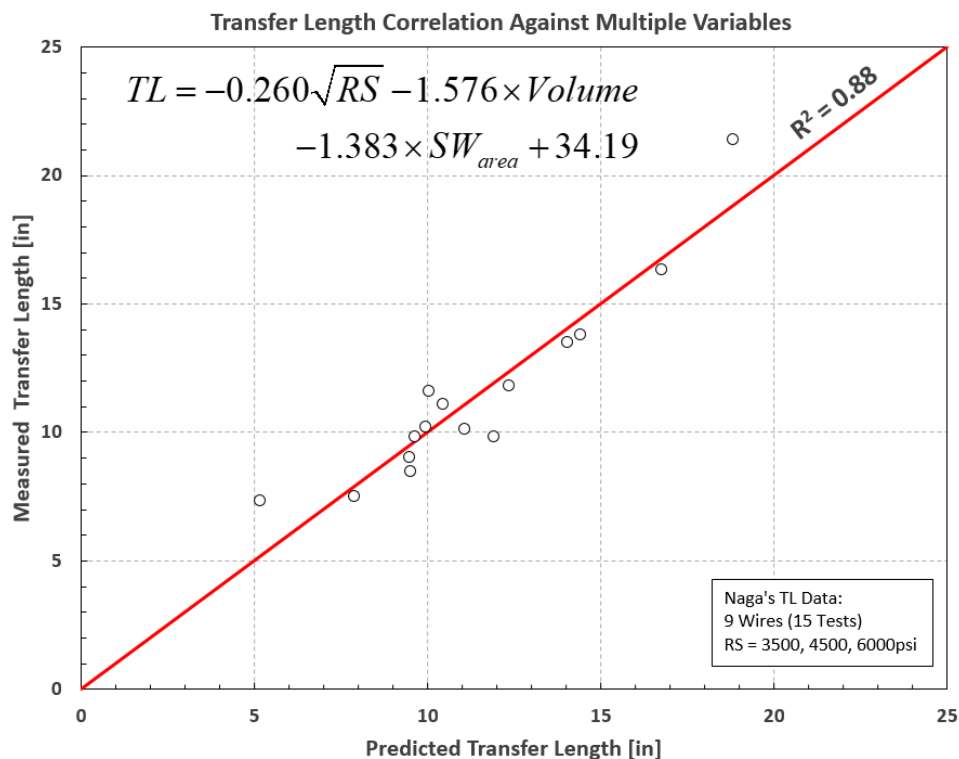


Figure 8.11: Transfer Length vs. 3D Indent Parameters (Variable Release Strength)

In section 8.1 it was shown that volume and sidewall area, fundamentally three-dimensional values, could be adequately represented by indentation geometry described by the centerline data alone. Indentation volume and sidewall area prove challenging to measure by manual means. Therefore, it is a desirable alternative to develop a correlation that relates the two-dimensional centerline geometry data to transfer length. Such a correlation is summarized by Figure 8.12. In this third correlation, centerline profile area is substituted for indent volume, furthermore, centerline sidewall length is used to replace sidewall area. The resulting correlation provides a reasonable prediction of transfer length, exhibiting a R^2 -value of 0.90.

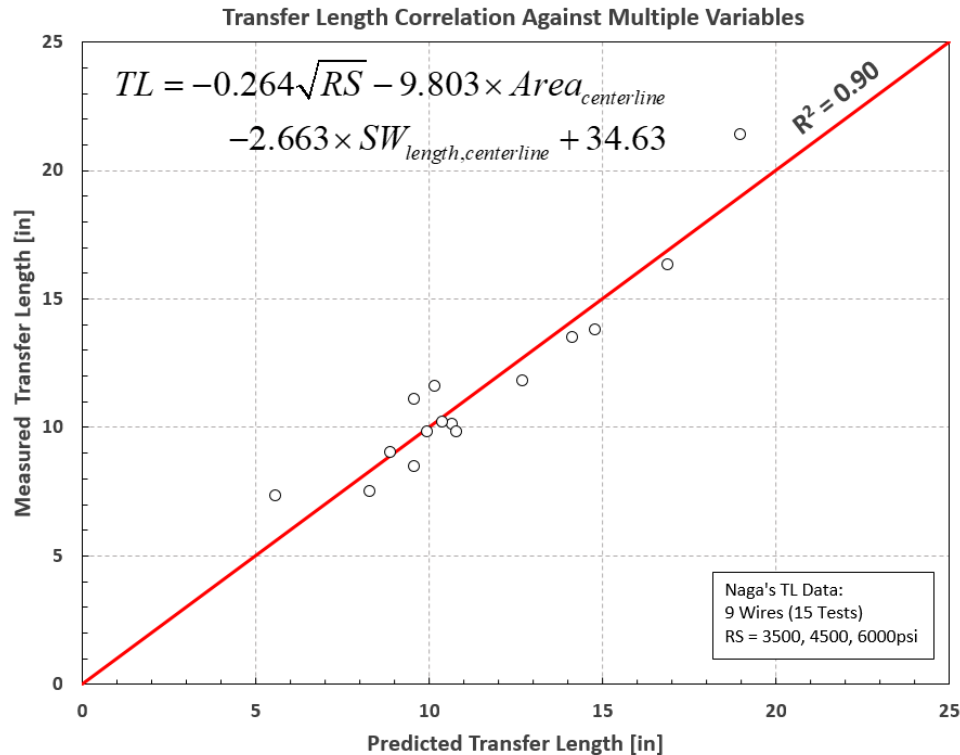


Figure 8.12: Transfer Length vs. 2D Indent Parameters (Variable Release Strength)

It has been demonstrated by this section that it is sufficient to describe transfer length with a three parameter regression model. One parameter, the square root of release strength, is a property of the concrete used to create the prestressed member, whereas the other two parameters quantify the effects of wire geometry on transfer length. Note that, release strength is in units of psi, whereas the parameters representing indent geometry are in dimensions of millimeters. The correlations, developed from measurements of nine different wires in addition to transfer lengths from 45 unique prisms, appear to predict transfer length to an accuracy of ± 2 inches.

8.4 Crack Length Correlations (Splitting Propensity)

Splitting propensity is another important performance characteristic that is a result of the interaction between the indented wires and the concrete of the prestressed member. As the wire is de-tensioned to provide prestressing force into the concrete, the wire pulls into the member as the wire becomes slightly shorter. During this process, a certain volume of the concrete must be displaced by the indentations in the wires, resulting in potentially significant splitting forces being applied to the ends of the concrete member. This perpetuates as cracking if the radial force is sufficiently high. As a side note, smooth wires with no indentations also displace a certain amount of concrete since the wire expands due to Poisson's effect as the wire is released. Cracking is particularly prevalent at reduced concrete covers as there is less confinement provided around the wire-concrete interface. Splitting propensity (cracking) is also influenced by wire geometry as the threshold for splitting is reached. The results obtained by the Indent Profiling System, coupled with empirical measurements of crack lengths observed on concrete prisms constructed using the same wire specimens, have been used to correlate the relationship between certain indent geometrical features and splitting propensity.

Section 8.2 overviewed the concrete prisms that were fabricated in order to collect detailed information on splitting propensity and transfer length [51]. 161 concrete prisms were created related to this section of the project; 135 of the prisms showed visible signs of cracking. These prisms were created with three separate concrete mixes utilizing a diverse set of aggregates, two separate release strengths, three separate concrete covers, and were constructed using the ten unique chevron type cover testing wires. Of the 135 prisms that experience cracking, 58 were made with Tucson aggregates, 53 were made with granite aggregates, and 24 were constructed with pea gravel. It is important to note that fewer prisms were constructed with pea gravel than the other two aggregates, and that only one unique release strength was tested for the prisms made of pea gravel. In every case that cracking was observed the prism was evaluated with a manual crack-map and given a total "crack length", also denoted as "CL" in many of the correlation formulas outlined in this section. An example of a typical splitting failure is illustrated in Figure 8.13.



Figure 8.13: Cracked Prism

The first correlation between crack length and indentation geometry pertains to test specimens that were constructed with Tucson aggregates. Similar to the transfer length correlations, critical indentation features and concrete test specimen parameters were selected and then subjected to multivariate linear regression. Due to the complexity of the interactions between the wire and concrete in terms of crack length, additional geometric parameters had to be applied to get reasonable correlations. The variables chosen had to not only be strongly correlated with crack length, but also had to have very little correlation with other chosen parameters. Thus, the following wire geometric parameters were selected: average indent planform area (volume divided by average depth), sidewall area, and sidewall angle. Furthermore, concrete cover must be included since it determines the confinement of the wire-concrete interface. The resulting correlation can be seen in the following formula and Figure 8.14. It should be observed that the wire parameters that most significantly influence bond, volume and sidewall area, also have the tendency to increase the amount of observed cracking. This makes intuitive sense as a wire that has high bond, ergo a short transfer length, is also accompanied by higher splitting forces. Additionally, cover has a large effect on crack length; significantly reducing cover also reduces confinement of the prestressing wire, thus, more cracking is observed. The correlation has a R^2 -value of 0.80, and thus, is a reasonable predictor of cracking for prisms made with similar aggregates. The provided 95% confidence interval provides bands in which a majority of the crack length data will fall using the formula listed below.

$$CL = 149.1\left(\frac{Volume}{Depth_{avg}}\right) + 93.3 \times SW_{area} - 22.55 \times SW_{angle} - 1075 \times Cover - 966.7$$

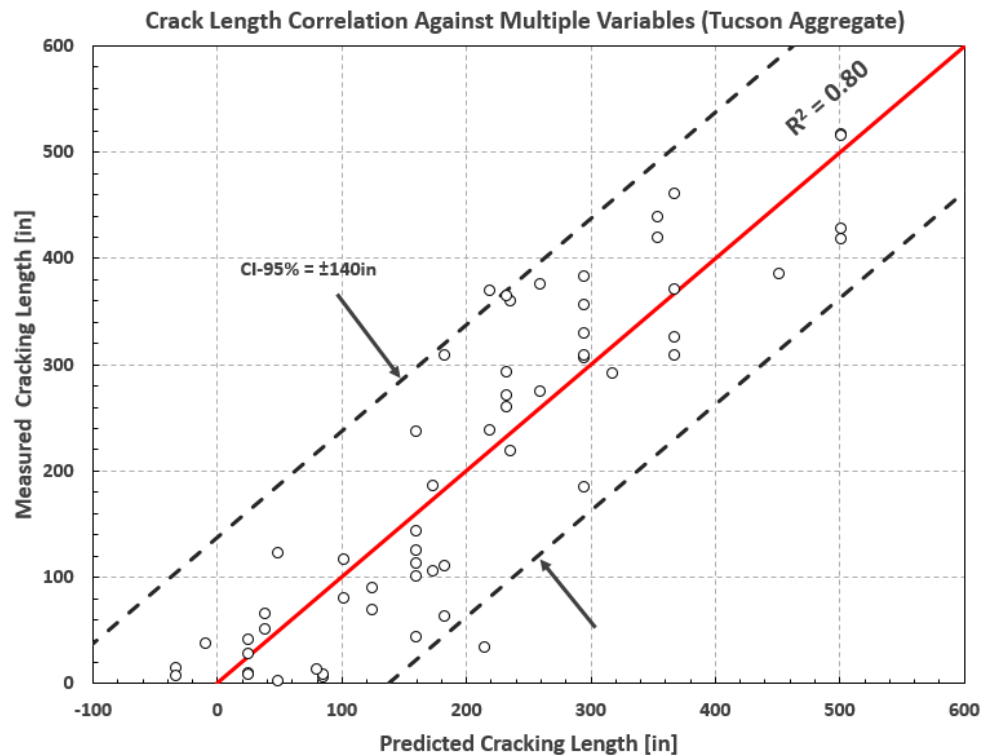


Figure 8.14: Crack Length Correlation (Tucson Aggregate)

The second correlation involves the data obtained from prisms made with granite aggregates. This aggregate was crushed, having significantly higher angularity than the other mixes, and thus, tended to resist cracking at reduced covers in comparison to the Tucson and pea gravel aggregates. The same parameters and linear regression model as the correlation for the Tucson mix was used. The derived correlation for the granite specimens can be seen in the following formula and is plotted in Figure 8.15. The same general trends in the coefficients for each parameter can be observed. However, the same 95% confidence interval has been applied to the correlated data, but the data points are not in perfect alignment with the band, or line of best regression for that matter. This implies that this aggregate is likely missing a parameter that was not included in the correlation, or one of the parameters has poor statistical significance, resulting in a lower R^2 -value of 0.71. In either case, the provided correlation is a rough predictor of cracking for prisms made with similar aggregates.

$$CL = 84.53\left(\frac{Volume}{Depth_{avg}}\right) + 85.78 \times SW_{area} - 85.78 \times SW_{angle} - 1156 \times Cover - 312.5$$

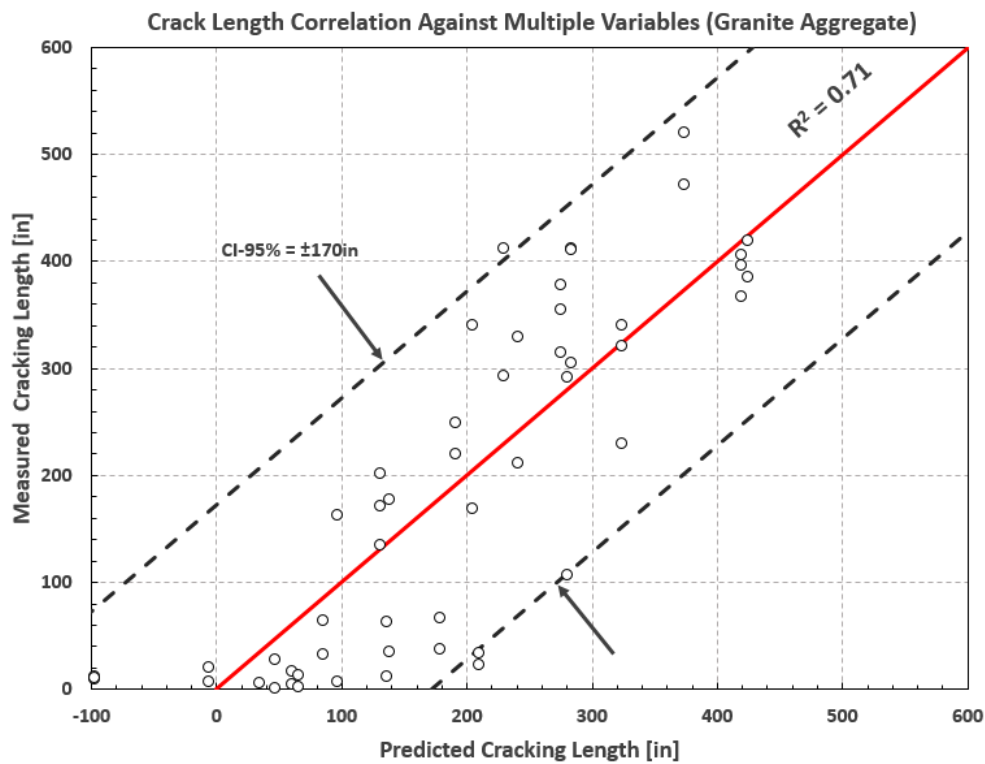


Figure 8.15: Crack Length Correlation (Granite Aggregate)

The third splitting propensity correlation pertains to data obtained for pea gravel mixes. This aggregate was comprised of rounded river rocks of small size, and thus, had poor resistance to splitting at reduced cover. As before, the same sets of parameters were selected with the same multivariate linear regression process. The correlation for pea gravel aggregates is provided in the following formula and plotted in Figure 8.16. The same general trends for the coefficients in front of the independent parameters are observed with the exception of the coefficient related to sidewall angle, which is exceptionally small. This implies that sidewall angle has little statistical significance related to pea gravel aggregates; the other parameters such as cover, average planform area, and sidewall area have a much more dominant influence on cracking. The resulting R^2 -value is 0.79, and thus, is a reasonable predictor of cracking for prisms made with similar aggregates.

$$CL = 55.95\left(\frac{Volume}{Depth_{avg}}\right) + 144.2 \times SW_{area} + 1.191 \times SW_{angle} - 1107 \times Cover - 196.4$$

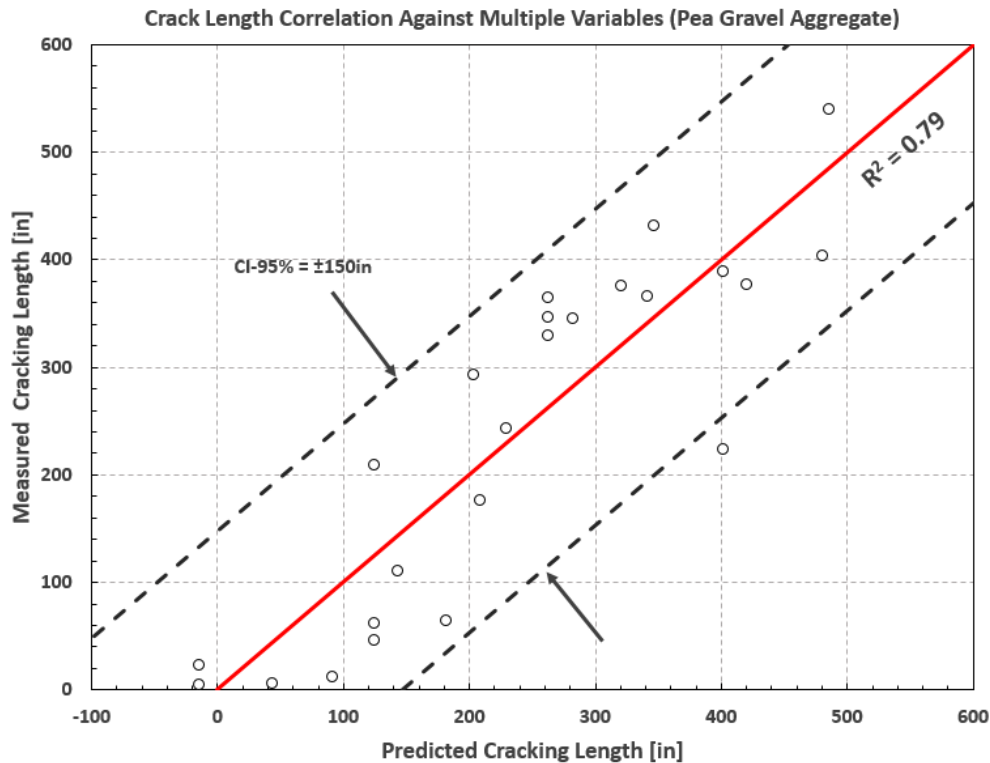


Figure 8.16: Crack Length Correlation (Pea Gravel Aggregate)

A fourth correlation can be seen below which includes all of the aforementioned prisms and aggregates that experienced cracking. Since it is a composite of all mix designs, with no parameter to differentiate between the mixes, the scatter is inherently higher; this is highlighted in Figure 8.17. While the correlation is not as refined, exhibiting a R^2 -value of 0.71, it encompasses all of the observed samples, and thus, can be used as a back-of-the-envelope way of predicting splitting propensity performance of an arbitrary mix if wire geometry and concrete cover is known.

$$CL = 106.0 \left(\frac{\text{Volume}}{\text{Depth}_{avg}} \right) + 93.6 \times SW_{area} - 13.32 \times SW_{angle} - 1112 \times \text{Cover} - 967$$

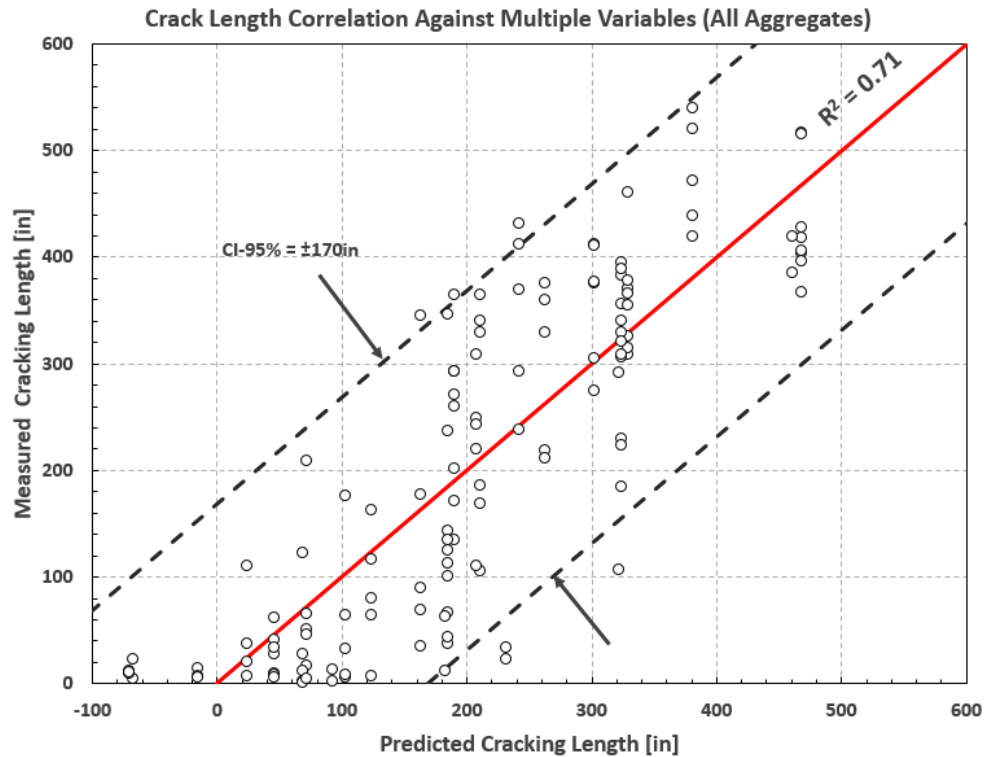


Figure 8.17: Crack Length Correlations (All Aggregates)

It has been demonstrated by this section that splitting propensity can be approximately described with a four parameter regression model. One parameter, the concrete cover, is a property of the prestressed member, whereas the other three parameters quantify the effects of wire geometry on splitting propensity. The following warning, similar to the transfer length correlations, must be given. The units of the splitting propensity correlations are mixed: wire geometry is measured in millimeters, or degrees in the case of sidewall angle, cover is measured in inches, and the resulting crack length is measured in inches. These correlations provide an approximate way to predict splitting behavior of members at reduced concrete cover with a wire of given geometry.

Chapter 9 - Repetition Demonstration

One of the primary objectives of the Indent Profiling System is the collection of sufficiently large amounts of data to form statistically relevant sample sizes of extracted indent features. As such, the goal is to acquire all indent geometry associated with a complete repetition of the indent rollers used to form the indentations into the steel wires. Collection of data exceeding one complete revolution of the indent rollers is unnecessary as the resulting data would not be statistically unique since the indent rollers continue to form repetitions of previously created indents. The indent rollers, visualized in Figure 1.3, are typically 8 inches in diameter, thus, it is necessary to scan roughly 25 inches of wire to collect all unique indents formed by the indent rollers during the manufacturing process.

The Indent Profiling System can measure wires 26 inches long while utilizing the tailstock of the lathe assembly, and 30-inch lengths without the tailstock, allowing the system to capture the effects of one complete indent roller repetition. Some of the wire specimens observed in Chapter 7 show signs of indent roller tooth damage, the component responsible for forming the indented geometry of the wire, leaving malformed indents. These malformed indents provide a unique visual basis for confirming the capture of a complete repetition and will be the basis of discussion of the sections that immediately follow.

9.1 Observations of Indent Repetition

During the data collection process, multiple wires were observed that featured indent deformities caused by imperfections in the indent roller teeth. These malformed indents serve as a visual way to confirm that the Indent Profiling System is capturing the statistically unique indents formed by one full repetition of the indent rollers. Malformed indents can be thought of as the fingerprint of the associated indent roller since these imperfect indents are easy to visually identify in subsequent repetitions of the roller. An illustration of this fingerprint is shown in Figure 9.1, in which, a corner of an indent in the center row of the scan suffers from damage caused by a chipped indent roller tooth. Deformities such as the one illustrated in the Figure 9.1 represent a convenient tracking feature.

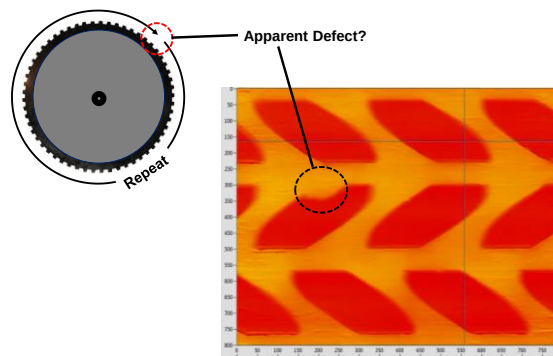


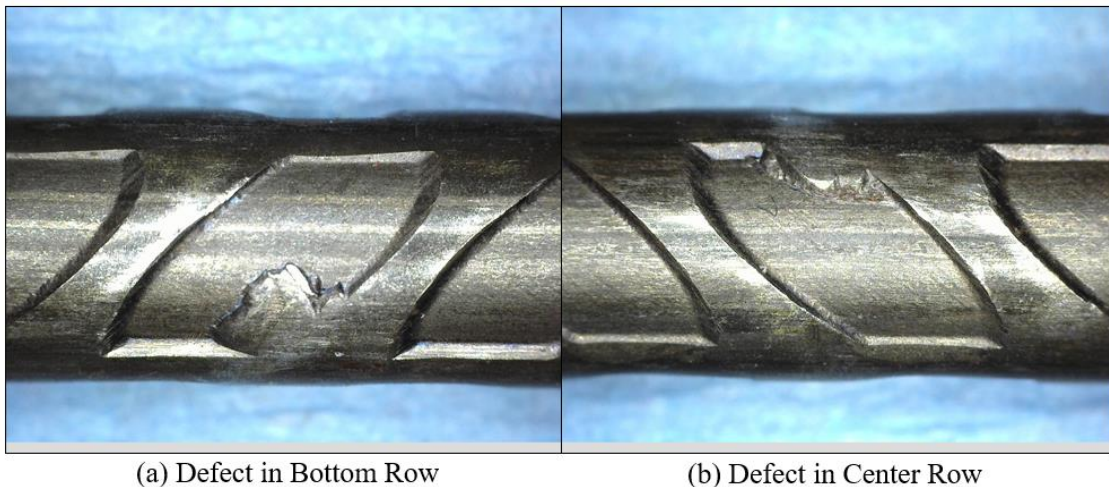
Figure 9.1: Isolation of Indent Roller Defects

This is better illustrated by referring to a more complete height-map image of an entire 26-inch scan of a specimen, wire “WF”, that was included Section 7.1. Figure 9.2 shows two detected indents that were the result of damage to roller teeth; the height-map depiction of defects in two adjacent rows are shown at the beginning of the full wire scan.



Figure 9.2: Defects Near Beginning of Scan

The wire specimen in question that displays the obvious defects is wire type WF, the same wire is listed at the beginning of the report that shows malformed indents in the three-dimensional model portrayed in Figure 2.3. These defects are not a scanning error; they are physically observable malformed indents that are clearly visible to the naked eye. This observation is visible in Figure 9.3 which offers an enhanced view provided by a digital microscope. Figure 9.3(a) corresponds to the defect detected in the bottom row of Figure 9.2, whereas Figure 9.3(b) corresponds to the deformity in the center indent row.



(a) Defect in Bottom Row

(b) Defect in Center Row

Figure 9.3: Digital Microscope Image of Deformed Indents (Wire WF)

Later in the completed scan, another instance of the same malformed indents is clearly visible. This is seen in Figure 9.4. The distances between these deformed indent patterns are, on average, 22.6 inches (575mm) apart from one another, corresponding to an average roller diameter of 7.2 inches. Malformed indents were found on other wire specimens as well; however, they are clearly

visible on wires with deeper indentations. Since indent rollers are subjected to higher stresses when deeper indentations are being made, increased wear and tooth chipping is more common.

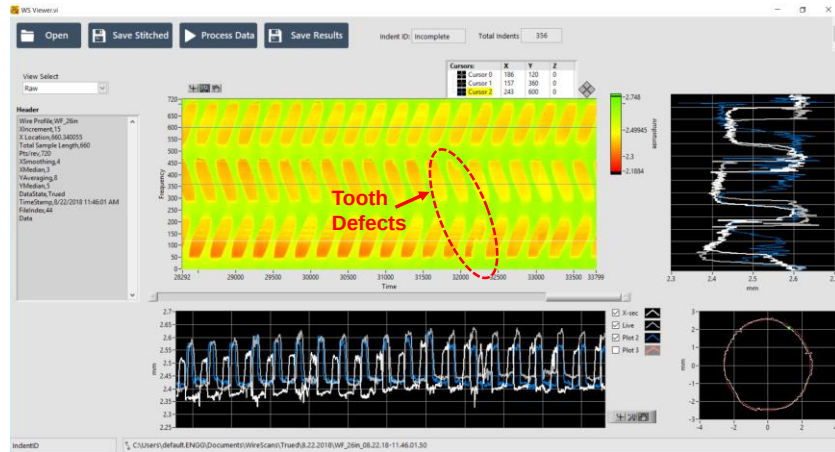


Figure 9.4: Defects Near End of Scan

9.2 Differing Number of Indents for Individual Rows

Another interesting phenomenon that was observed by the Indent Profiling System is that indent rollers of varying diameters were used to create the indent patterns on the same indented wire. By looking at the unique indents, identified by malformed features, this observation is clear. By closer observation of Figure 9.2 and Figure 9.4 it can be noted that the deformities change positions with respect to each other as the scan progresses. This is visualized in Figure 9.5 which is a composite image of the two aforementioned figures. It can be clearly seen that the malformed indents shift in relative position from the beginning of the scan to the end of the scan after one revolution of their respective indent rollers are complete. The shift in the relative positions of the visually identical defects suggests that something is different about the indent rollers for each row.

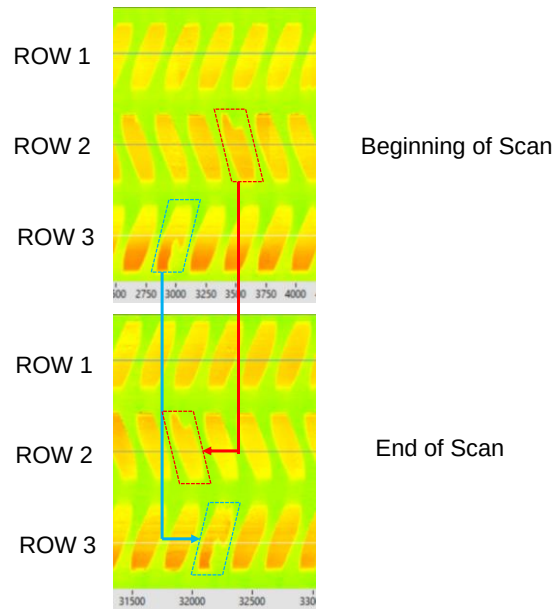


Figure 9.5: Comparison of Adjacent Indent Defects

Further inspection of the resulting processed data indicated that the pitch of each indent row was identical across the entire length of the scan. This implies that the indent rollers are made with a varying number of teeth, and thus, have differing diameters, but preserve the indentation pitch of each row. This is confirmed by the fact that the central row has three fewer indents registered for one repetition of the indent roller. Does the differing number of teeth per indent roller, or varying roller diameter matter? Does it directly contribute significantly to accelerated wear of the smaller indent rollers since each tooth is subjected to creating more indentations than adjacent rollers? Perhaps not, but it serves as a testament the ability of the Indent Profiling System to identify the intricacies of the manufacturing process.

Chapter 10 - Go/No-Go Criteria

The Indent Profiling System provides the capability of assessing all of the unique indents that characterize a particular wire. Due to the large number of samples that the system can process, it is possible to identify the manufacturing variations seen across the entire length of the wire and on a row-by-row basis. These extensive measurements can then be used to determine if the sampled wire is suitable for use, passing the requirements of the aforementioned measurement standards as well as additional specifications decided upon between the consumer and the producer. The purpose of this short section is to interpret how the measured indentation geometry can be used in conjunction with current measurement standards and the newly developed correlations to determine the grounds for wire acceptance or rejection.

10.1 Evaluation by ASTM A881/ ISO 10138-2

The most predominant measurement standards pertaining to indented steel wires were the source of extensive discussion in Chapter 2. These standards, ASTM A881 and ISO 10138-2, prescribed the acceptable ranges that certain indentation parameters must occupy, based on the nominal diameter and indentation shape of the wire being measured. Indentation centerline depth, nominal indent length, and indent pitch are amongst the required parameters to be measured. Further requirements, such as the range of acceptable values for sidewall angles, can be decided upon by mutual agreement between the consumer and the producer. The allowable ranges that these parameters must occupy are provided in Table 1.1 and Table 2.1 for both ASTM A881 and ISO 10138-2 respectively.

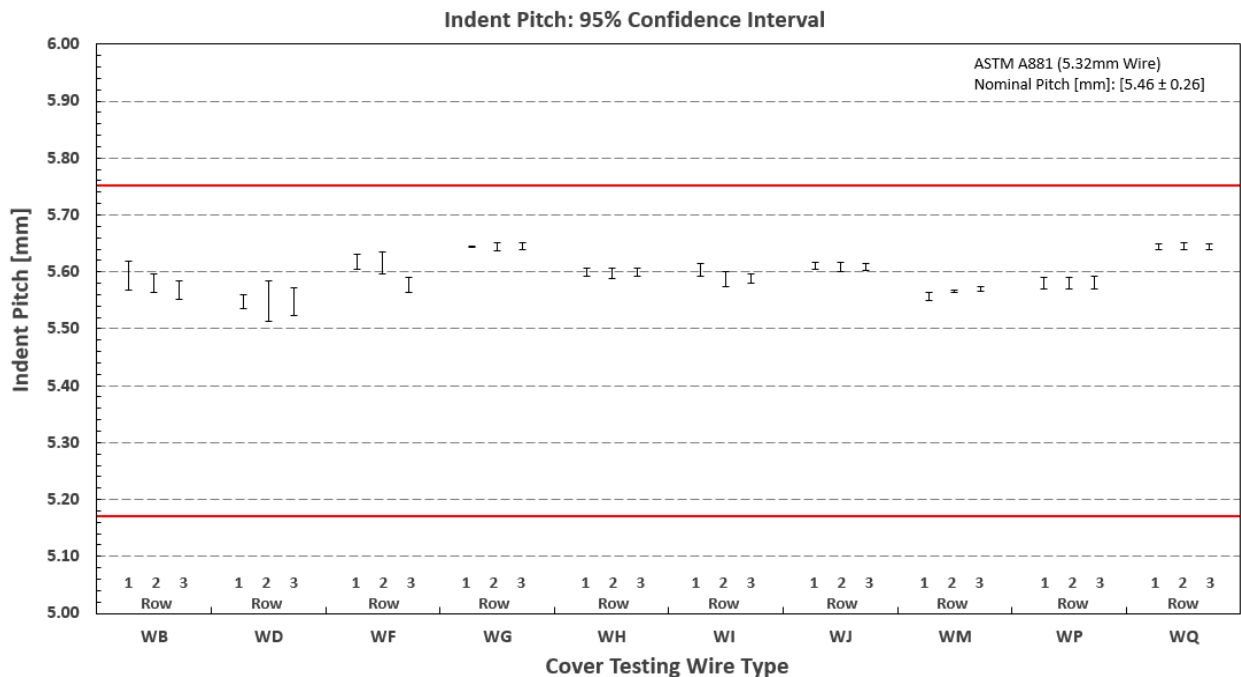


Figure 10.1: Measured Variations of Indent Pitch

Figure 10.1 provides a confidence interval plot of the measured indentation pitch of each cover testing wire that was highlighted in section 7.1. The Indent Profiling System extracted significant quantities of data for these wires; each indent row has over 100 unique measurements of pitch. As

such, the errors bands on the plot describe where 95% of the measured values are contained. No manufacturing process is perfect; thus, the confidence interval represents the statistical distribution of the measured values, rather than a simple mean which would not be sufficient in describing the manufacturing variations.

The red lines on the plot in Figure 10.1 indicate the allowable range dictated by ASTM A881 for indent pitch for wires with nominal diameters of 5.32mm. From the confidence intervals it is apparent that all of the wires would pass the requirements for pitch, as no confidence interval exceeds the band described by the red lines.

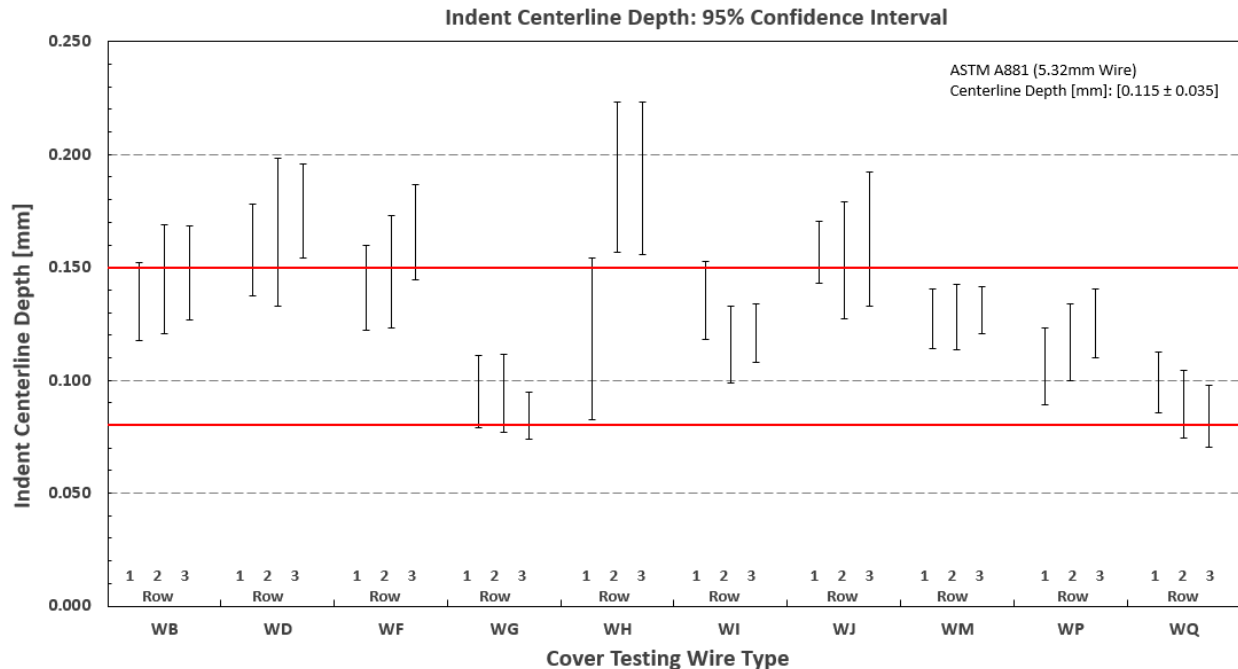


Figure 10.2: Measured Variations of Indent Centerline Depth

Another parameter required by the measurement standards is indentation depth, measured along the centerline of the indent profile. This critical parameter sees more significant manufacturing variations as the rollers are subjected to wear, damage, and differences in hydraulic loading; additionally, this parameter can vary from row to row. A confidence interval plot describes the measured indentation depth data in Figure 10.2. Once again, the red lines indicate the bounds that ASTM A881 prescribes for indent depth, falling between 80-150 μ m for 5.32mm wires. The grounds for acceptance or rejection (Go/No-Go) in this case is less obvious, as many of the confidence intervals clearly extend past the allowance band; in some situations, the intervals are completely excluded by the band.

Some of the wires, namely WM and WP, would be guaranteed to be accepted since the confidence intervals are contained completely by the band. However, the other wires have variations from the manufacturing process that prevent all of the observed indents from falling within the acceptable range for indentation depth. This implies that, depending on where the measurements are taken, some wires are not necessarily statistically impossible to meet the ASTM A881 requirement, but are statistically improbable to be accepted. Such wires include WD, WH, and WJ and can be seen in Figure 10.2. Other wires such as WB, WG, and WQ are statistically probable to be accepted, but are not guaranteed to be accepted. In either situation, the requirements outlined by ASTM A881

are insufficient to be used to accept or deny a wire once statistically relevant sample sizes are involved. Are only the mean values to be used to determine if the wire abides by ASTM A881? Do only 80% of the indents need to fall within the allowance band? These questions are not addressed by current measurement standards, as the standards do not adequately take into account the manufacturing variations that are seen in practice.

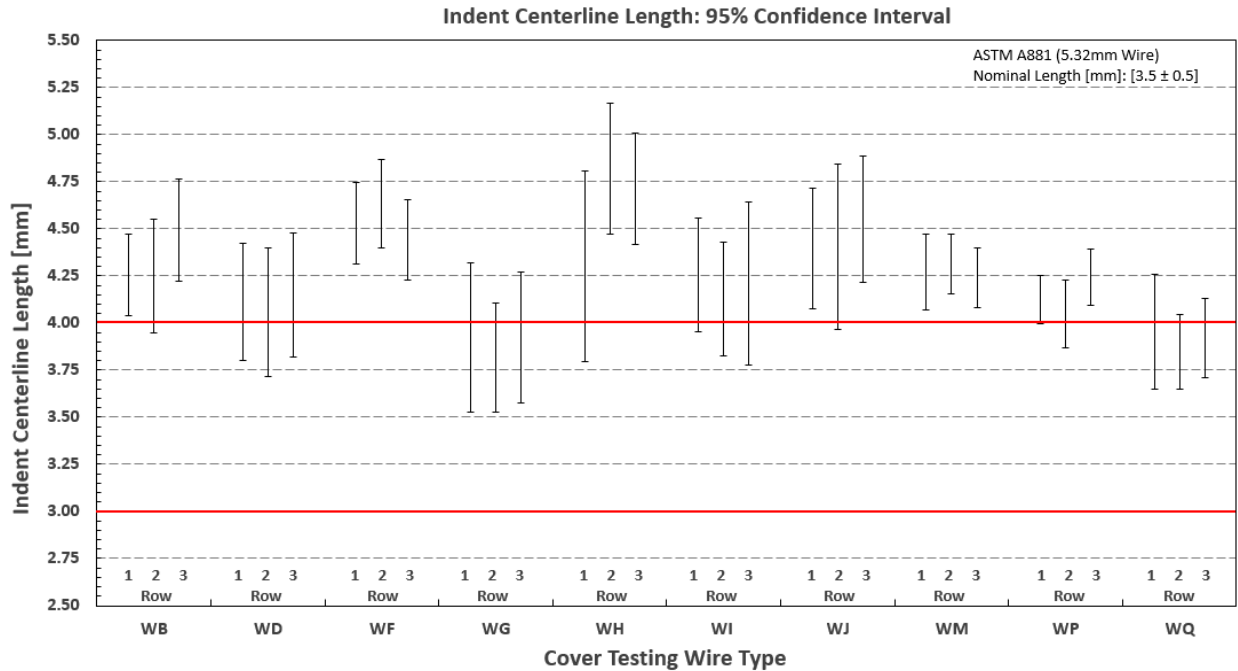


Figure 10.3: Measured Variations of Indent Length (Centerline)

Figure 10.3 reinforces the observations stated previously with a confidence interval plot of nominal indentation length. It is clear that a majority of the sampled wires have confidence intervals that fall outside of the band of allowed values. Once again, wires WG and WQ are statistically probable to pass the ASTM A881 requirement, whereas other wires would fail to meet the same criteria.

The observations of mean values alone are not sufficient to characterize the manufacturing variations seen in practice, and thus, would be a poor choice to be used as acceptance or rejection criteria. Once statistically relevant sample sizes of indent geometry measurements are involved, it is necessary to take into consideration the statistical distribution of the data that describes the variance of the manufacturing process. Thus, it is proposed that 80% of the values contained by each individual row must fall within the band of allowable values. This ensures that a majority of the indents must meet the prescribed values and that the rows must be similar in quality while allowing for variations in the manufacturing process.

10.2 Comparison to Correlations

This subsection highlights the potential use of the correlations developed in Chapter 8 to determine the suitability of a given wire. This method represents a significant departure from the current measurement standards as it would require the wire to adhere to desired performance criteria rather than being accepted or rejected on the grounds of indentation geometry alone. It has been shown that transfer length and splitting propensity are strongly correlated with wire geometry, and thus, certain combinations of indentation geometry directly influence performance criteria.

$$TL = -0.260\sqrt{RS} - 1.576 \times Volume - 1.383 \times SW_{area} + 34.19$$

Therefore, instead of requiring the indentation geometry to fall within a particular range, an alternative would be to specify desired values for certain performance criteria. For example, a specific transfer length may be desired at a given release strength (TL=10in, RS=4500psi). By using the transfer length correlation listed above, it is clear that certain combinations of indent volume and sidewall area can be used to achieve the desired transfer length at the particular release strength. If the transfer length and release strength are fixed values, then the geometry of a given wire dictates if the wire can, or cannot, provide the desired performance criteria.

$$CL = 106.0\left(\frac{Volume}{Depth_{avg}}\right) + 93.6 \times SW_{area} - 13.32 \times SW_{angle} - 1112 \times Cover - 967$$

This same methodology can be applied to splitting propensity (crack length) which is also significantly influenced by indent geometry. The same parameters that inherently produce better bond, and thus transfer length, are also related to increases in splitting propensity at reduced cover. Therefore, trade-offs must be made to ensure reasonable compromise between the two performance criteria. From a design standpoint, it is not realistic to have a short transfer length at a low release strength while also having adequate resistance against splitting at significantly reduced concrete cover.

If a given resistance against splitting propensity is desired, the confidence interval can be added to the crack length correlation given above. Then, for a given wire, of which the geometry is known, it is possible to calculate the amount of concrete cover required to satisfy the equation. Alternatively, if the desired splitting propensity and concrete cover is known, then it is possible to evaluate the possible combinations of wire geometry that satisfy the relation. Once again, if the desired splitting propensity and concrete cover represent fixed values, then the geometry of a given wire dictates if the wire can, or cannot, provide the desired performance criteria.

This method would allow wires to be accepted or rejected based on whether or not the indentations can provide the desired performance criteria. Current measurement standards do not state which geometric features contribute most significantly to performance criteria, and instead require the parameters to fall within prescribed bands. This does not necessarily guarantee that wires that pass ASTM A881 and ISO 10138-2 provide desirable performance characteristics. By evaluating the effects of wire geometry on wire-concrete performance criteria it is possible to select wires based on the desired performance characteristics, using correlations such as those listed above. This way, design is governed by performance criteria rather than arbitrary restrictions on indentation geometry.

Chapter 11 - Conclusions

This dissertation highlighted the current limitations of measurement standards, methodologies, and automated equipment pertaining to the evaluation of the indentation geometry of indented steel wires used in prestressed concrete crossties. Currently, measurement standards such as ASTM A881 and ISO 10380-2 cover only a handful of indentation parameters. These standards often do not prescribe how the limited amounts of indentation geometry are measured, the tools used, or the accuracy of the equipment used. This prevents consistency of measurements between operator-to-operator and lab-to-lab, severely mitigating the usefulness of these standards. Many of the indentation geometry measurements required by these standards are not dictated; instead, they are agreed upon between the producer and consumer. Furthermore, these standards do not identify how specific indentation geometry leads to favorable, or unfavorable, wire-concrete performance; wires can have geometry that passes the requirements of the standards but fail to have sufficient performance during integration into the prestressed concrete system. Manual measurements of these parameters are time-consuming, preventing their applicability in a real-time manufacturing environment; furthermore, they are error prone and fail to capture statistically relevant sample sizes that are useful in characterizing the produced wire and assessing its quality.

A laser-based measurement system was created for a prior FRA project to address the deficiencies with the manual measurement processes [37][48]. This system was the state of the art leading up to this research. The system utilized a point displacement laser that traversed along the length of wire to generate a scan of the wire surface and programmatically extract indentation geometry. This system represented a significant improvement in terms of repeatability, as the extracted geometry was now independent from operator-to-operator and from lab-to-lab. However, it could only extract features on a small segment of wire and could not generate statistically relevant sample sizes due to how long it took for the system to generate wire scans. This limited its ability to be used in a real-time manufacturing environment or assess the quality of a full segment of wire that captures one full revolution of the indent rollers. A more advanced measurement system was needed to address these shortcomings.

This dissertation overviewed the creation of a laser-based Indent Profiling System as part of the larger FRA project titled *Developing a Prism Qualification Test to Ensure Adequate Splitting Resistance in Pretensioned Concrete Railroad Ties* [51]. This system was mechanically designed, assembled, and automated by John Bloomfield from the Technology Development Institute. The author developed algorithms to filter erroneous data from the scans, correct for sensor misalignment, account for off-bore rotations caused by nonconcentric specimen chucking or inherent wire bow, and scan segment splicing based on preliminary data from the Indent Profiling System. The author then highlighted algorithms to identify individual indents and extract numerous indentation geometry parameters. This system is accurate, can reliably extract indentation geometry from operator-to-operator, captures statistically relevant sample sizes, and operates fast enough to be amenable to be implement in a plant environment to regularly evaluate indented steel wire as it is being manufactured.

The author used the Indent Profiling System to measure three primary sets of indented steel wires. A subset of wires was from those used in recent industry. These wires were used to create concrete prisms from prior FRA projects and the current one [51] in order to assess the effect of wire geometry on wire-concrete performance metrics such as transfer length and splitting propensity. Another subset of wires was extracted from crossties that were removed after years in service in

track [43]; these represented wires that exhibited excellent wire-concrete system performance and served as a useful historical sample of specimens that work well in practice. A third subset of wires were fabricated with machined indents of known geometry as part of a prior FRA project [37] and were used to validate calibration of the Indent Profiling System and evaluate the accuracy of the indent geometry extraction algorithms.

The multitude of wire data was used to correlate indent geometry data against wire-concrete performance metrics such as transfer length and splitting propensity obtained by prisms using the same indented wires at reduced concrete covers, release strengths, and aggregate mix types. This allowed the author to assess which geometric properties had favorable, or unfavorable, influence on performance criteria; this resulted in critical observations in improvements that current measurement standards need to include in order to cover parameters that typically correlate to good system performance. The statistically relevant sample sizes that the Indent Profiling System is capable of measuring raised serious concerns about the acceptance criteria of current measurement standards and the author proposes Go-NoGo criteria to address these newfound issues.

Finally, a draft ASTM proposal is provided titled *Standard Practice for Measuring Indented Steel Wire Geometrical Parameters* that issues guidance on where critical indentation geometry should be manually or programmatically measured; this standard is currently on track for acceptance. Formulas are provided that calculate indentation geometry based on lessons learned during the development of the Indent Profiling System. Furthermore, sensitivity analysis is performed on the formulas outlined in the proposed ASTM standard in order to evaluate the sensitivity of the measured parameters based on critical dimensions and measurement tool uncertainty. The analytical results of the sensitivity analysis were then confirmed by stochastic methods.

The contributions of the author have yielded a capable Indent Profiling System that can characterize all unique indents contained by a segment of wire, that reliably and independently extracts the geometry regardless of the operator, and operates quickly enough to be useful in a plant environment. Furthermore, it was shown how specific indentation parameters correlate to favorable wire-concrete performance. Changes to current standards were proposed and new standards will help standardize the measurement process of indented wire geometry. These represent significant advancements in the measurement technology, measurement standards, and understanding of the physical processes of wire-concrete performance in the field of prestressed concrete railroad ties that utilize indented steel wires.

11.1 Insufficiencies with Current Indent Geometry Measurement Methods

In summary, the insufficiencies with current measurement standards pertaining to indented steel wires are as follows. First, common measurement standards such as ASTM A881 and ISO 10138-2 do not identify which geometrical parameters contribute most significantly to the performance of the wire. Second, the measurement procedures for obtaining the required indent features for the standard do not provide repeatable, reliable results between different operators. Often the measurement process is determined by mutual agreement between the producer and the consumer and is not a standard measurement that can be compared with other manufacturing processes or products. Third, determining indent geometry for the current measurement standards is a laborious endeavor; it is time consuming and does not integrate easily into a production environment. Often, wire samples are sent out to measurement labs only when process changes have been made to check for compliance with the measurement standards. This is hardly ideal since the manufacturing process of indented steel wires varies on an hourly basis as the indent roller teeth

wear down or are damaged, rather than on a sparse interval as the testing schedule implies. Finally, sample sizes are not statistically relevant due to the time it takes to collect the data and the inherent uncertainties with the current measurement processes. The low sample sizes fail to capture the intricacies of the manufacturing process since no two indents are identical and significant variance can be seen across neighboring indent rows.

Early wire scanning technology took great strides to address the insufficiencies with the current measurement standards and attempted to more accurately understand the relationship between geometrical indent features and favorable performance criteria. The system could collect high resolution data and extract a variety of indent features above and beyond those dictated by current measurement standards. Some key indent features were found that corresponded with desirable wire performance. Additionally, it could extract features in a reliable, predictable manner across a wide variety of tested wires. However, the system was too slow to be a device that would be applicable to a production environment and mostly found use as a research tool. The system could not collect statistically relevant sample sizes that could accurately characterize the manufacturing process of the wires due to the considerable time it took to operate.

This research highlighted the need for a device that has the desirable capabilities of the early wire scanning system and addresses the majority of its disadvantages. The development and implementation of such a device was described in great detail during the majority of this report. The Indent Profiling System that was the direct result of this research effort is significantly faster and collects statistically relevant sample sizes. The system was used to address the insufficiencies with current measurement methodologies. It was used to identify which geometrical parameters contribute most significantly to the performance of the wire by comparing captured wire geometry with empirical prestressed concrete prisms results. It could provide repeatable, reliable results for extracted indent features between different operators since the system is completely automatic and the features are extracted via computer algorithms. Furthermore, it could collect statistically relevant sample sizes, assessing all unique indents formed by the manufacturing process, in short duration. This system represents a departure from current manual methods and has proven to be a valuable research and production quality monitoring tool.

11.2 The Indent Profiling System

The Indent Profiling System is a non-contact laser-based device capable of measuring the indentation geometry of steel wires used in the manufacture of concrete railroad ties. It was designed to address the shortcomings of the current manual methods used to assess the quality of indented wires. The manual methods provide insufficient sample sizes due to the time-consuming nature of the measurements, furthermore, the collected information is challenging to extract in a repeatable manner using manual procedures. The Indent Profiling System remedies these issues by analyzing all of the unique indents formed by the indent rollers during the manufacturing process and extracting the geometric features in a repeatable, accurate manner.

The first stage of this research was to design and implement an automated Indent Profiling System to produce unbiased, statistically-relevant sample sizes. After motion control and data acquisition of the system was implemented, calibration techniques and data manipulation steps were developed to enhance the quality of the data being received. Then, the system was applied to measure specimens of known geometry, namely calibration cylinders and machined indents, to

verify the correct and reliable operation of the system and quantify expected measurement uncertainties.

The second stage involved the application of the Indent Profiling System to measure the indent characteristics of a multitude of indented wires. A sampling of these wires were from modern industry, a subset were wires that were extracted from historical crossties that had been in track for upwards of multiple decades, and another set of wires were created with known “machined indents” for use with system checkout. In conjunction with the transfer length and splitting propensity testing of concrete prisms the Indent Profiling System results were then used to extensively investigate which geometrical parameters of indented wires contributed most significantly, or detrimentally, to prestressed member performance criteria.

The Indent Profiling System utilizes a blue sheet-laser to capture the indent geometry with an axial spatial resolution of 20 μ m. The laser is mounted on a lathe chassis that allows the system to scan wires up to 30 inches in length, unwrapping the three-dimensional surface into a two-dimensional height-map. Scan filtering is applied to reduce scan noise and enhance data visualization. Calibration procedures were developed to eliminate system misalignment and algorithms were created capable of removing the inherent bow of the indented wires. The resulting scans were within $\pm 2\mu$ m of accuracy for the trued wire surface. An assessment of the system measurement uncertainty was 8.3 μ m and could be significantly reduced with data filtering and averaging. Data processing steps were developed that could reliably identify the locations of the indent rows and could recognize individual indents. A trapezoid fit was then applied to the indent data, allowing for all relevant two and three-dimensional indent features to be extracted.

One of the primary objectives of the Indent Profiling System was the collection of sufficiently large amounts of data to form statistically relevant sample sizes of extracted indent features. As such, the system was designed to acquire all indent geometry associated with a complete repetition of the indent rollers used to form the indentation geometry into the steel wires. Collection of data exceeding one complete revolution of the indent rollers is unnecessary, as the resulting data would not be statistically unique since the indent rollers continue to form repetitions of previous created indents. It was demonstrated that the system could be used to capture all unique indent geometry representing the complete pattern formed by the indent rollers.

The Indent Profiling System was used to measure the indent characteristics of a multitude of indented wires. The first set of wires, those commonly used in modern industry, represented a wide variety of indent depths and indentation shapes, additionally, the wires feature considerable differences in sidewall angles used in practice. These selected wires shared a common “chevron” pattern and are nominally 5.32mm in diameter. The geometrical results obtained from these modern wires were used to analyze the variations of the individual parameters on a row-by-row basis and across the entire specimen. Furthermore, concrete prestressed prisms were created using the same wires; the geometrical features could then be correlated against measured performance criteria of the test prisms such as transfer length and splitting propensity, thus determining which geometrical characteristics have the most significant influence on wire-concrete performance. Wires extracted from pre-existing concrete railroad ties in service represented the second set of wires. These wires formed the basis for wire geometry that tends to work well in practice, as many of the crossties that the wires were extracted from performed favorably over the course of decades. Some of the concrete ties were subjected to an estimated 4 billion gross axle tons of loading during the service life of the tie, indicating favorable wire-concrete performance. The third group of wires, those with fabricated “machined” indents, were used for system calibration and verification

of feature extraction algorithms. The results from scanning the machined wires indicated that the feature extraction algorithms were functioning as intended.

During the course of this research it was found that large variations exist from row to row on the indented wires that were subjected to processing. Often, the geometric parameters were so different from row to row that the measured statistical distributions did not overlap; this was particularly observable in metrics such as sidewall angle and sidewall area. Additionally, it was found that many of the measured parameters exceeded the bounds set by ASTM A881 and ISO 10138-2. The Indent Profiling System represents a departure from current manual measurement methodologies, collecting quantities of data that can adequately characterize the manufacturing process. Furthermore, the system has been used to further the understanding of how indentation geometry directly contributes to desirable performance characteristics.

11.3 Correlation of Indent Geometry with Performance Criteria

During this research, the Indent Profiling System proved its ability to accurately extract indentation geometry of the wires subjected to test. The calibration procedures and wire cast correction algorithms ensured that wire scans were generated with micron levels of precision. From these calibrated scans, the system could extract dozens of geometric parameters, analyzing hundreds of unique indents at a time. This allowed for manufacturing variations to be analyzed from indent to indent and on a row-by-row basis. Furthermore, the results from the Indent Profiling System were correlated with empirical performance characteristics of prisms constructed using the same wires. Strong correlations were developed that related indentation features with wire-concrete performance criteria such as transfer length and splitting propensity.

The Indent Profiling System represents a departure from current manual measurement methodologies, collecting quantities of data that can adequately characterize the manufacturing process and has been used to further the understanding of how indentation geometry directly contributes to desirable performance characteristics.

Chapter 12 - References

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Appendix A - ASTM Proposal

This appendix contains an ASTM proposal titled *Standard Practice for Measuring Indented Steel Wire Geometrical Parameters*. Its purpose is to dictate measurement methodology of indented steel wires to ensure consistent extraction of indentation geometry from operator-to-operator and from lab-to-lab. The author made significant contributions to this ASTM proposal; formatting changes and the inclusion of the important parameter of Bite Per Length, which correlates strongly to wire-concrete performance criteria, were added after the contributions of the author. This ASTM proposal is currently out of sub-committee and is on track for acceptance. By the time the reader has viewed this dissertation, it is likely already a standard measurement practice.



1 Date: July 2, 2024
2 To: Subcommittee A01.05
3 Tech Contact: Chris Reeve, creeve@insteel.com
4 Work Item #: WK91484
5 Ballot Action: Proposed new Standard Practice

6 **Rationale:** The definitions and procedures for measuring geometrical characteristics of indented wire are
7 provided so that purchasers and suppliers have common definitions and measuring procedures for indent
8 characteristics. The intention of these definitions and measuring methods is not to provide a dimensional
9 specification for indent characteristics, but rather common measurement procedure(s) for quantifying indent
10 geometry.

11 This practice was developed to specifically characterize indents from ASTM A881/A881M wire for use in
12 prestressed concrete; however, this practice could be applied to other indented wire products.

13

14

15 Standard Practice for 16 Measuring Indented Steel Wire Geometrical Parameters¹

17

18 **Designation:** The ASTM designation, to be located after the Title, will be assigned by
19 Headquarters on submittal for approval.

20

21 1. Scope*

22 1.1 This standard defines the procedures to measure geometrical features of indented wires.

23 1.2 This standard applies to steel wires with discrete indents at a reoccurring pitch, including,
24 but not limited to, patterns of the “chevron” and “elliptical” shape. An example of these types of
25 indented wire is shown in Figure 1.

¹ This practice is under the jurisdiction of ASTM Committee and is the direct responsibility of Subcommittee.
Current edition approved XXX XX, XXXX. Published XXX XXXX. DOI: 10.1520/XXXXXX-XX.

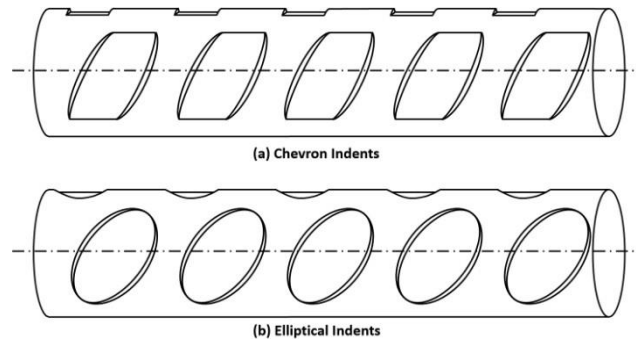


Figure 1: Chevron Type Indent and Elliptical Type Indent

1.3 Quantitative limits are not addressed and are established in the general requirements, or individual product specifications, or both; or when applicable, as agreed to between supplier and user.

1.4 The values stated in either inch-pound units or SI units are to be regarded separately as standard. Within the text, the inch-pound units are shown in brackets. The values stated in each system may not be exact equivalents; therefore, each system shall be used independently of the other. Combining values from the two systems may result in non-conformance with the specification.

1.5 This standard does not purport to address all of the safety concerns, if any, associated with the use of this standard. It is the responsibility of the user of this standard to establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use.

2. Terminology

2.1 Definitions of Terms Specific to This Standard:

2.1.1 Indent. An intentional depression of the wire surface having a measurable depth, width and pitch.

2.1.2 *Two-Dimensional (2D) Wire Indent Parameters.* Two-Dimensional indent features are shown in Figure 2.

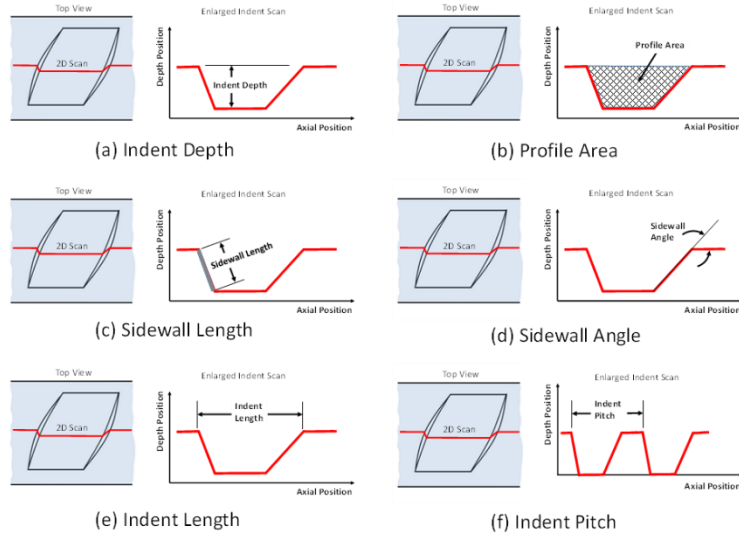


Figure 2: 2D Wire Indent Parameters

2.1.3 *Three-Dimensional (3D) Wire Indent Parameters*. Three-Dimensional indent features are shown in Figure 3.

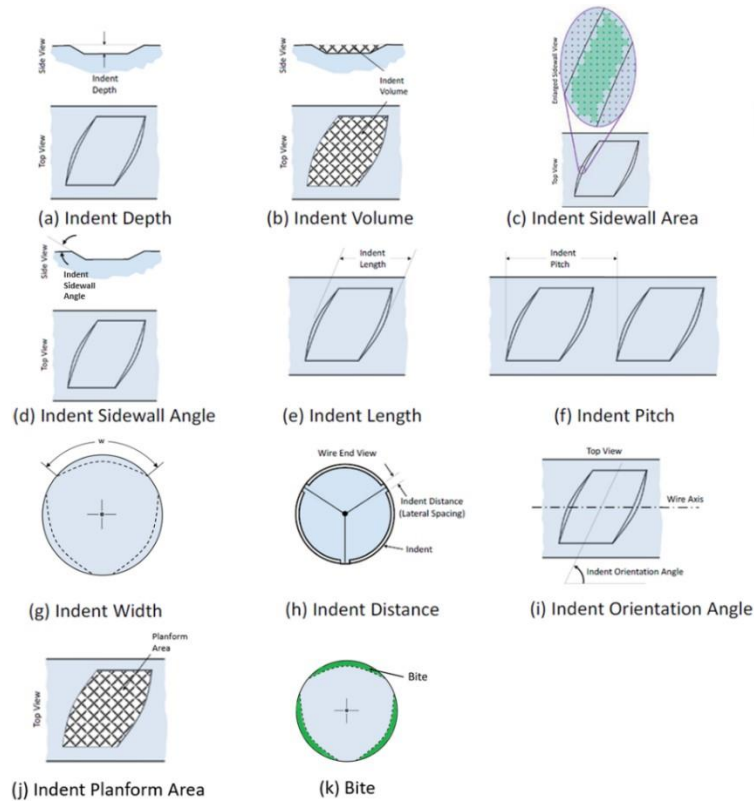


Figure 3: 3D Wire Indent Parameters

3. Significance and Use

3.1 The definitions and procedures for measuring geometrical characteristics of indented wire are provided so that purchasers and suppliers have common definitions and measuring procedures for indent characteristics. The intention of these definitions and measuring methods is not to provide a dimensional specification for indent characteristics, but rather common measurement procedure(s) for quantifying indent geometry.

3.2 This practice was developed to characterize indents from ASTM A881/A881M wire; however, this test method could be applied to other indented wire products, such as the wire used in A886 strand.

4. Indent Characteristics

4.1 *Indents* – This standard applies to indents that are formed in discrete rows, typically three rows with each row aligned parallel to the wire axis, with indents in fixed orientation in each row, and with the rows spaced uniformly around the wire. For the case of a three-row wire, the orientation for one row of indents is typically inclined in the opposite direction to the other two rows (Note 1).

Note 1: Indents are typically formed by drawing smooth wire through three indenting rollers oriented 120 degrees apart. There is a periodic cycle (or repeat) in the indent patterns associated with each row of indents, corresponding to the number of teeth on the associated roller.

4.2 *Type* – Two examples of indented wire are shown in Figure 3(a) and 3(b). Figure 3(a) is a chevron pattern while Figure 3(b) is an elliptical pattern.

5. Indent Measurement Requirements

5.1 Indent parameters shall be measured along the centerline axis for each indent, and along a minimum of two additional axial lines parallel to the x-axis of the wire, as shown in Figure 4.

5.2 A minimum of two indents along each of the indent rows shall be measured.

5.3 Indents selected for measurements shall be free of damage via visual inspection and shall represent complete indents. Indents formed with chipped or otherwise damaged roller teeth shall be avoided.

5.4 A minimum magnification of 5x shall be used to visually determine measurement point locations.

5.5 To maintain consistent axial direction orientation of the indented wire for repeated measurements, an identifying mark shall be affixed to one end of the wire specimen.

5.6 To uniquely identify circumferential row orientation, an identifying mark shall also be affixed to one of the indented rows (Note 2).

Note 2: Certain indent features, such as indent sidewall angle, have unique Left-hand and Right-hand characteristics. Marking one end of the wire provides unique identification of the Left-hand and Right-hand orientations of these indent characteristics for a given

indent row. Due to the indent drawing process, the roller teeth uniquely define the indents formed on a given row.

5.7 Measurements in the radial dimension (y-direction) shall have a minimum resolution of 5 microns [0.0002 in.].

5.8 Measurements in the axial dimension (x-direction) shall have a minimum resolution of 25 microns [0.001 in.].

5.9 Measurements in the circumferential dimension (z-direction) shall have a minimum resolution of 25 microns [0.001 in.].

5.10 Measurements shall be made with either contact (stylus) or non-contact (optical) instruments with the specified minimum resolutions. For a mechanical stylus, the maximum ball contact diameter shall be 1.0 mm [0.04 in.]. The maximum spot size in the case of a non-contact optical measurement shall be 50 microns [0.002 in.].

6. Procedures for Indent Feature Measurement

6.1 General Measurement Requirements

6.1.1 Profile measurements shall be taken along a minimum of three parallel axial lines traversing a minimum of two indents per indent row. This is illustrated for an individual row of indents in Figure 4. All profiles for a single indent row shall share a common axial (x-component) datum. Measurements of the indent profiles shall be made in the radial direction (y-direction) about a common rotational axis, as illustrated in Figure 5.

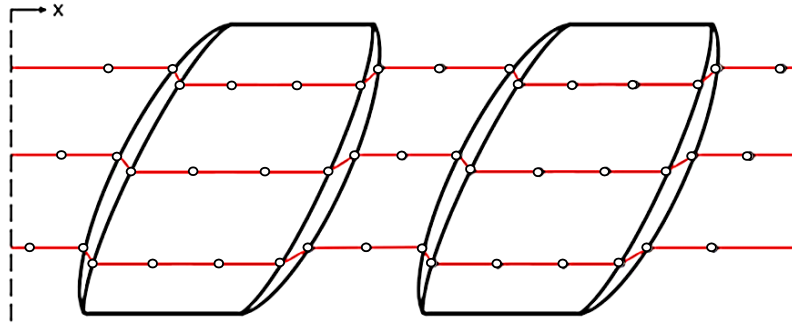


Figure 4: Minimum Profiles for Indent Measurement

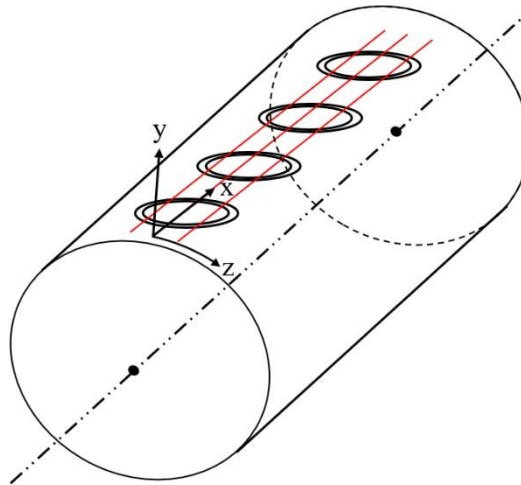


Figure 5: Radial Measurements about a Common Axis

6.1.2 Locations of the axial profiles shall be equidistant from adjacent profiles, as is illustrated in Figure 6. The centerline profile shall lie in the middle of the assessed indent width when an odd number of measurement profiles are used. A minimum of three profiles are required across each indent (Note 3).

Note 3: Achieving a greater number of profiles will likely increase how well the discrete profiles characterize the indent geometrical features. This is well suited for profiles generated using an automated measurement system. An automated scanning system is not limited by the small number of scans shown in Figure 6. It can accommodate scanning the entire circumferential surface of the indented wire with an interval set by the

desired number of profiling lines per revolution; which can easily be 720 lines per revolution, or 0.5° increments.

Even numbers of scan profiles are permissible, provided that a measurement profile falls within 10% of the centerline indicated by the width of the indent. In the case of even numbers of scan lines, the closest profile to the centerline shall be used for calculations requiring centerline measurements.

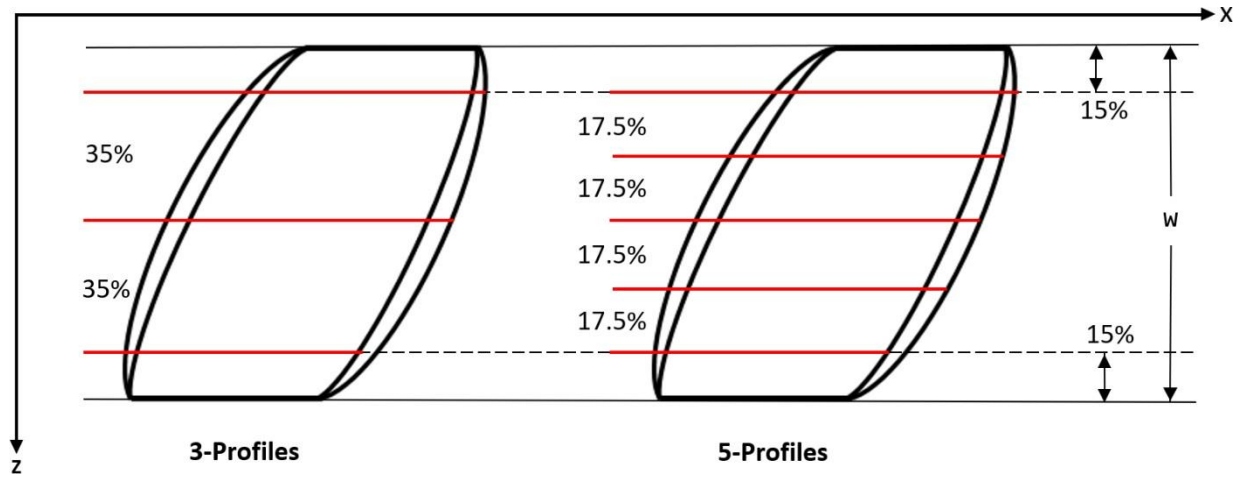


Figure 6: Measurement Profile Locations

The spacing between the measurement lines is determined as a percentage of the indent width and the margin.

$$spacing\% = \frac{100\% - margin * 2}{n - 1}$$

(1)

Where n represents the number of profiles and margin is the amount of spacing from the edge of the indent (nominally 15% as shown in Figure 6).

6.1.3 Features of the indents are to be extracted with respect to the trapezoidal template shown in Figure 7. A minimum of nine discrete sample points shall be extracted along each axial profile, for each indent.

6.1.4 The radial/vertical (y-component) and the axial (x-component) of these discrete points shall be measured as required by the algorithm associated with the individual features (Note 4).

Note 4: The accuracy requirements for the radial/vertical (y-component) measurements typically exceed those required for axial (x-component) measurements.

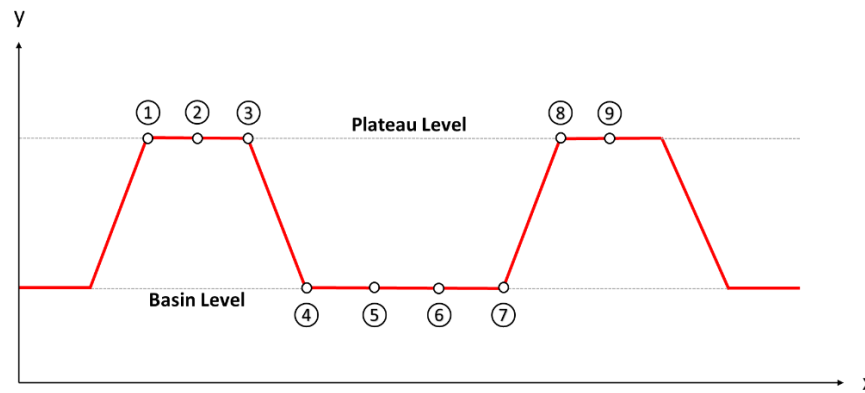


Figure 7: Measurement Locations for Indent Feature Extraction

6.2 Indent Feature Extraction

6.2.1 *Actual Average Wire Cross-sectional Area, A*. The actual average cross-sectional area in mm^2 [in^2] shall be calculated by dividing the mass [weight] per linear mm [in.] of the specimen in kg [lb] by $7.850 \times 10^{-6} \text{ kg/mm}^3$ (mass of 1mm^3 of steel) [0.2836 (weight of 1 in^3 of steel)].

6.2.2 *Effective Wire Diameter, D*. An effective diameter shall be calculated as the diameter of a circle having area equal to the actual average wire cross-sectional area.

6.2.3 *Indent Width, w*. Each indent has a single unique value for width; a visualization of indent width is given in Figure 8. Width is defined as the arc length between the edges where the indent intersects with the undeformed space between indent rows. Two different methods provide acceptable assessment of indent width (Note 5).

Note 5: In the case of indents that gradually transition into the non-indented space between indent rows, as opposed to those with a clearly defined edge, a visual approximation is acceptable.

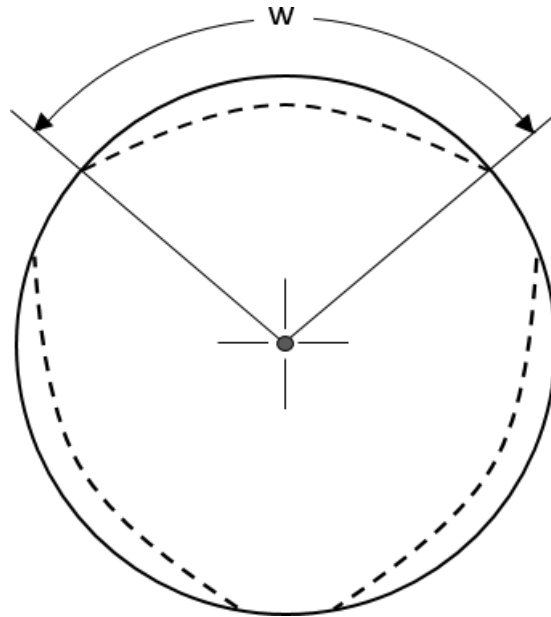


Figure 8: Indent Width, w

6.2.3.1 Unwrapping Method: The indent width is obtained in terms of measurements of the z -coordinates of lines bounding the indent pattern, designated by points 1 and 2 in Figure 9, where the z -coordinate describes the circumferential (or unwrapped surface) distance between measurement points. Points 1 and 2 may be discerned visually or by using statistical methods if the measurement procedure is automated.

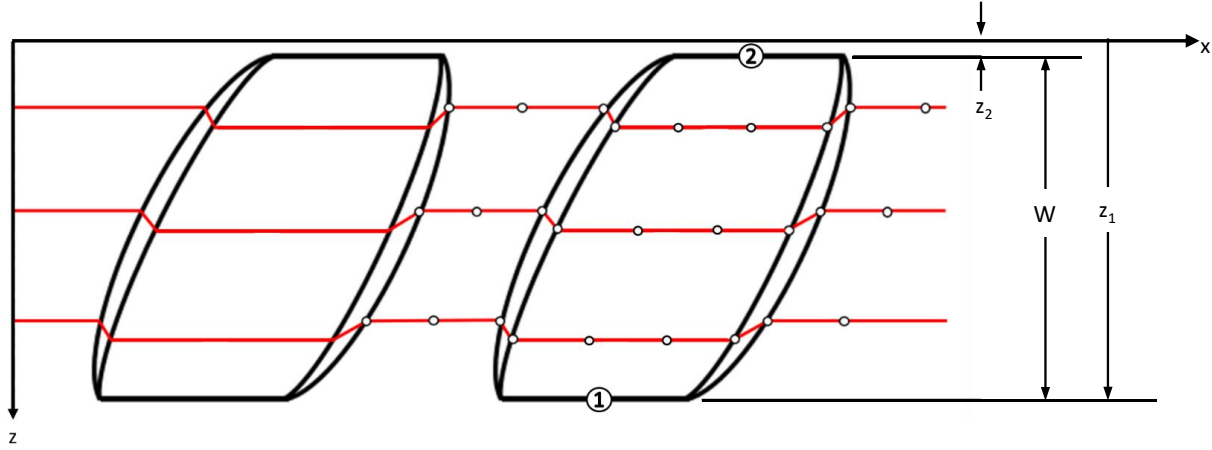


Figure 9: Measuring Indent Width Using Unwrap Method

The indent width shall be calculated as follows,

$$W = z_2 - z_1$$

(2)

6.2.3.2 Linear Method: Since the nominal wire diameter, D , is known, a simple linear measurement, $L_{w,i}$, can be made to determine indent width. A linear measurement device is used to determine the distance between the edges of the indent that define the indent width, as shown in Figure 10.

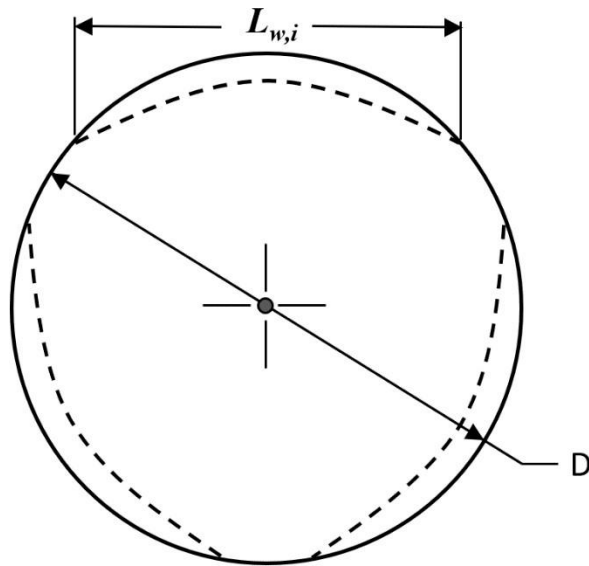


Figure 10: Linear Measurement Used to Obtain Indent Width

The indent width (Figure 8), w_i , for each indent, shall be evaluated as follows:

$$w_i = D \sin^{-1} \left(\frac{L_{w,i}}{D} \right)$$

(3)

6.2.4 *Indent Distance, e* . The indent distance is defined as the arc length of the undeformed space located between each set of indented rows (Note 6). This is visualized in Figure 11.

Note 6: Due to the difference in indent locations between adjacent rows, an approximation is used to obtain the average indent distance.

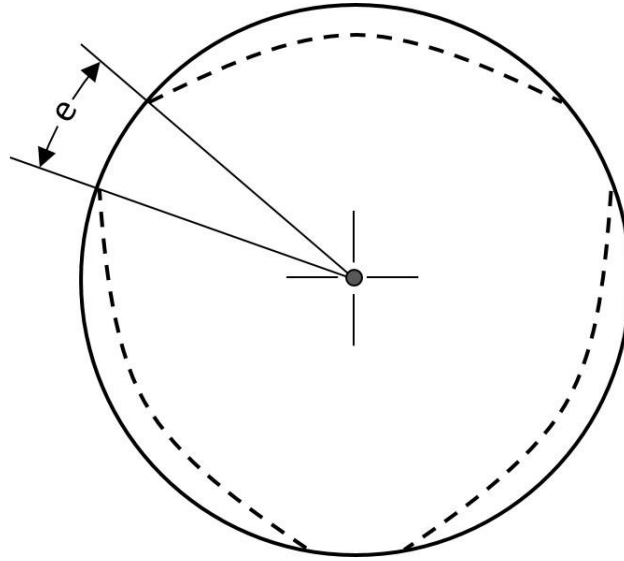


Figure 11: Indent Distance

The average indent distance is

$$w_{avg} = \frac{1}{N} \sum_{i=1}^N w_i$$

$$e = \frac{\pi D - n_r \cdot w_{avg}}{n_r}$$

(4)

Where D is the nominal diameter of the wire, N is the number of indents over which width was assessed, w_{avg} is the average indent width, and n_r is the number of indent rows.

6.2.5 *Orientation Angle, ϕ* . Each indent has a single orientation angle. This is evaluated by determining the coordinates of the center position of the basin for each profile (the midpoint between x_4 and x_7 shown in Figure 7) and performing a fit of least squares on those center points to obtain the orientation angle of the indent. This can be visualized in Figure 12; the square points represent the center of the basin for each measured profile, and the dashed line indicates the line of best fit through those points, from which, orientation is measured.

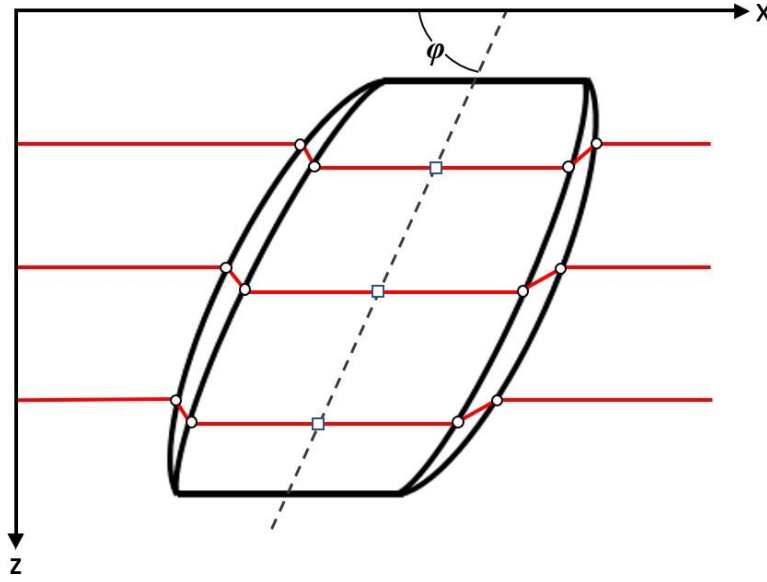


Figure 12: Orientation Angle, ϕ

Orientation angle shall be evaluated as follows:

$$\bar{X} = \frac{\sum_{i=1}^n x_i}{n}, \bar{Z} = \frac{\sum_{i=1}^n z_i}{n}$$

$$m = \frac{\sum_{i=1}^n (x_i - \bar{X})(z_i - \bar{Z})}{\sum_{i=1}^n (x_i - \bar{X})^2}$$

$$\phi = \tan^{-1}(m)$$

(5)

Where x_i and z_i are the coordinates of the center of the basin for each profile, X and Z are the average coordinates of those center points for all profiles, and n is the number of profiles. The slope of the line of best fit, m , is in turn used to compute the orientation angle for the indent, ϕ (Note 7).

Note 7: The coordinates of the center of the basin for each profile indicated in Figure 12 can be determined from a trapezoidal fit to the measured points shown within the indent.

6.2.6 *Average Indent Depth, d_{avg}* . For each set of sampled measurements along a line, the y-coordinate of the points 2, 5, 6, and 9 shall be measured, as shown in Figure 13. These points shall be located away from the sloped sidewalls of the indents and preferably located in the center of the indent plateaus and basins respectively, as shown. Points 2 and 9 define the plateau level, whereas points 5 and 6 define the basin level.

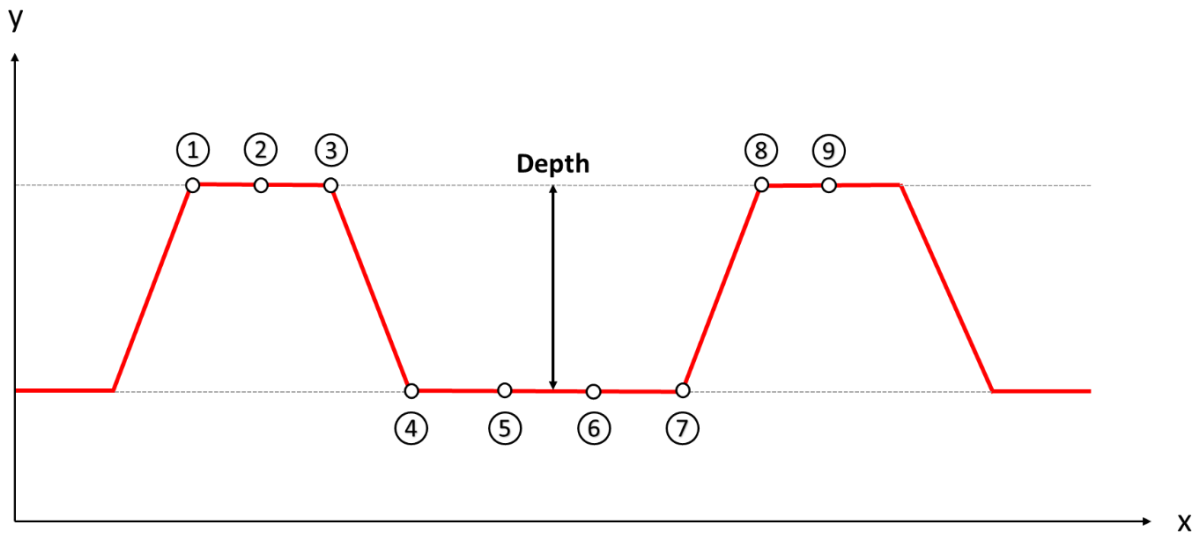


Figure 13: Indent Depth

The depth of the i^{th} indent profile is given by,

$$d_i = \frac{1}{2}(y_2 + y_9) - \frac{1}{2}(y_5 + y_6)$$

(6)

where y_5 and y_6 are taken at positions 1/3 and 2/3 along the basin length to obtain an average of the basin depth. If a trapezoidal fit is used to define the indent profiles, then the well-defined corners of this trapezoidal fit can be used to define its depth. However, when making manual measurements the y-coordinate for these corner points can be distorted due to the bulging of the indent created by the roller teeth. Hence, for manual measurements of depth, the points used are away from these corners (namely, points 2,9,5,6).

The average depth of the measured indent shall then be evaluated from a minimum of three depth assessments yielding,

$$d_{avg} = \frac{1}{n} \sum_{i=1}^n d_i$$

(7)

Where n is the number of measured profiles for the given indent.

6.2.7 Indent Pitch, l_{pitch} . The indent pitch shall be determined using the centerline profile measurements. The x-components of points 1 and 8, which represent the transitions between the sidewall and the plateau, are measured to obtain pitch. This is depicted in Figure 14.

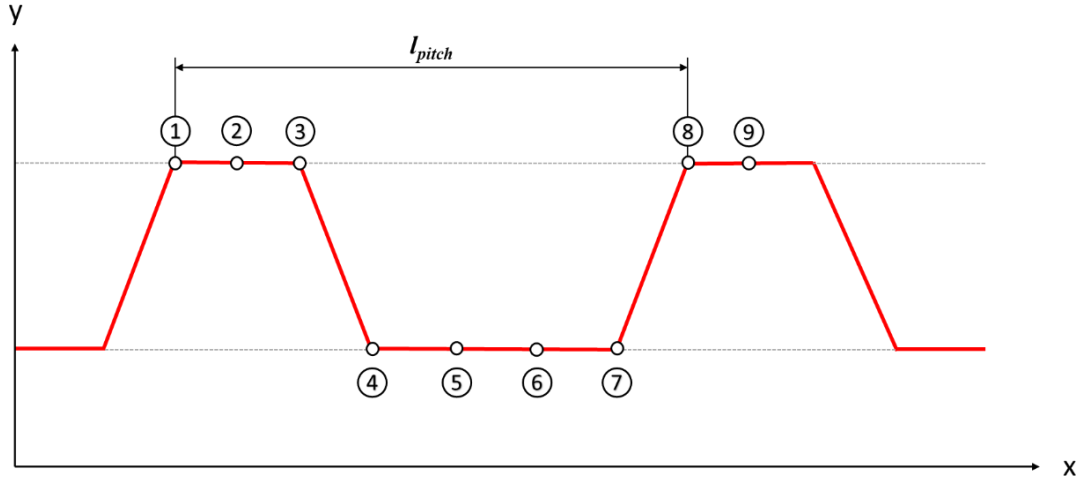


Figure 14: Indent Pitch

The pitch for the indent is given by (Note 8),

$$l_{pitch} = x_8 - x_1$$

(8)

6.2.8 Indent Length, l_{indent} . The indent length shall be measured with the centerline profile.

The x-component of points 3 and 8, the transition between the sidewall and the plateau, are measured to obtain the length of the indent. This is visualized in Figure 15.

Note 8: The pitch associated with a given indented wire has been observed to vary from one row to another. Therefore, a row-averaged pitch may also be defined. A row-averaged pitch is readily evaluated using an automated scanning system which is capable of scanning over numerous indents along the axis of the indented wire.

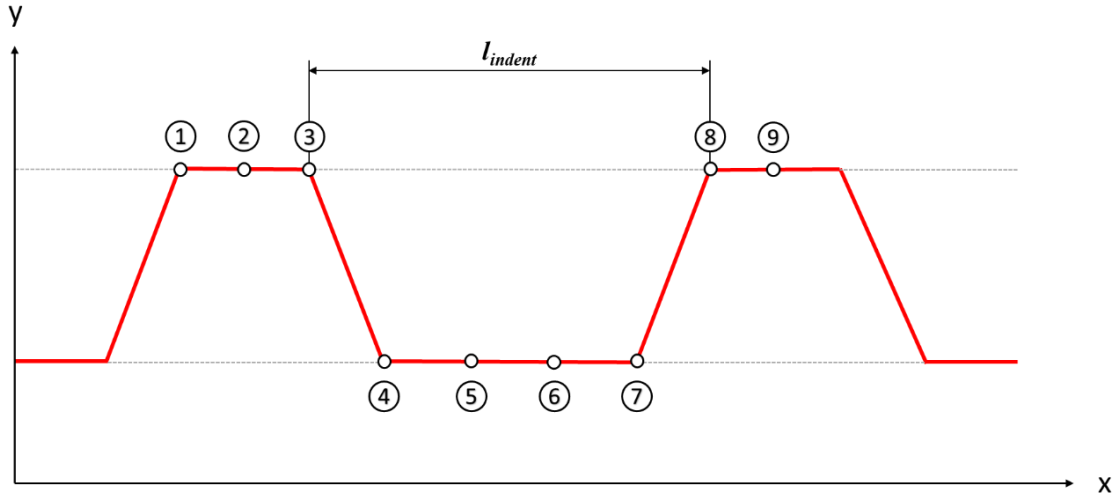


Figure 15: Indent Length

The indent length measured along the centerline shall be evaluated as follows:

$$l_{indent} = x_8 - x_3$$

(9)

6.2.9 Indent Basin Length, l_{basin} . The indent basin length shall be measured with the centerline profile. The x-components of points 4 and 7, which represent the transitions between the sidewall slopes and the basin, are measured to obtain basin length. This is depicted in Figure 16.

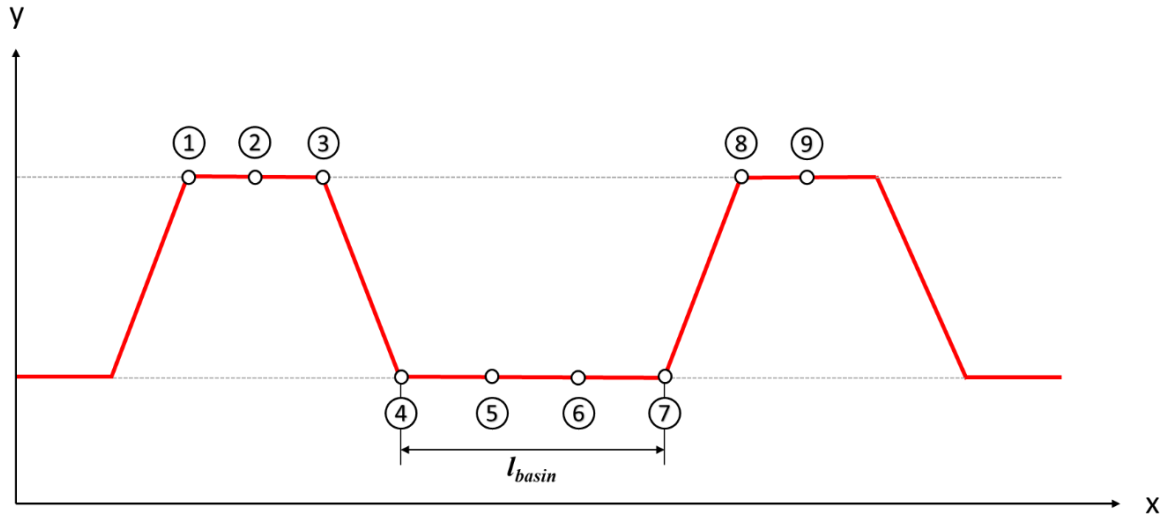


Figure 16: Indent Basin Length

The indent basin length measured along the centerline shall be evaluated as follows,

$$l_{basin} = x_7 - x_4$$

(10)

6.2.10 Indent Plateau Length, $l_{plateau}$. The indent plateau length shall be determined from

measurements along the centerline profile. The x-components of points 1 and 3, which represent the transitions between the sidewall slopes and the plateau level, are measured to obtain the plateau length. This is depicted in Figure 17.

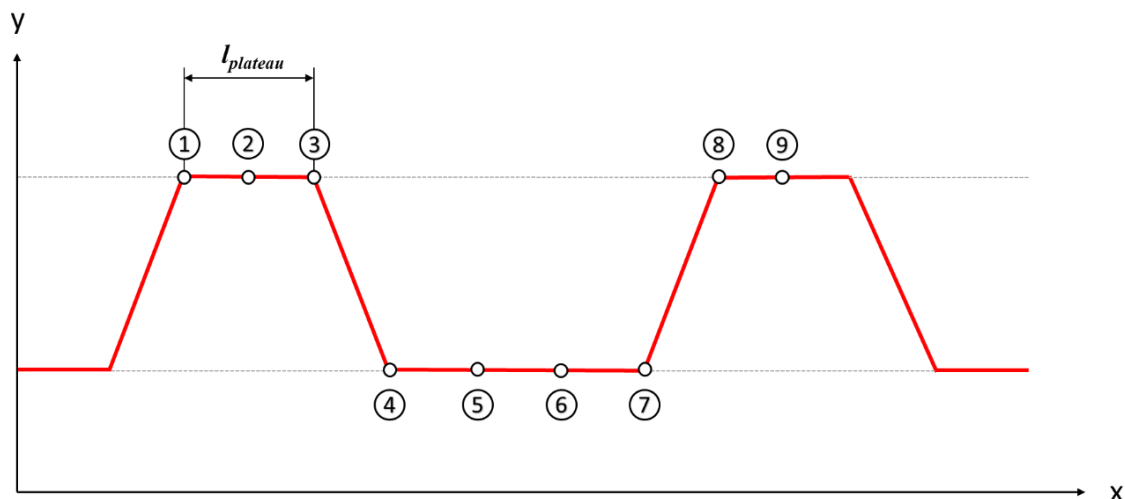


Figure 17: Indent Plateau Length

The indent plateau length measured along the centerline is determined as follows:

$$l_{plateau} = x_3 - x_1$$

(11)

6.2.11 *Indent Sidewall Angle, θ_R , θ_L , and θ_{eff} .* The sidewall angle shall be assessed at least along the centerline profile of the indent (Note 9), and shall be determined in terms of the trapezoidal element shown in Figure 18.

Note 9: The sidewall angle associated with a given indent has been observed to vary significantly across the width of the indent. Therefore, it is recommended to use the average sidewall angles of all of the axial profiles taken for the given indent, rather than relying on the centerline profile alone to characterize the side-wall angle property.

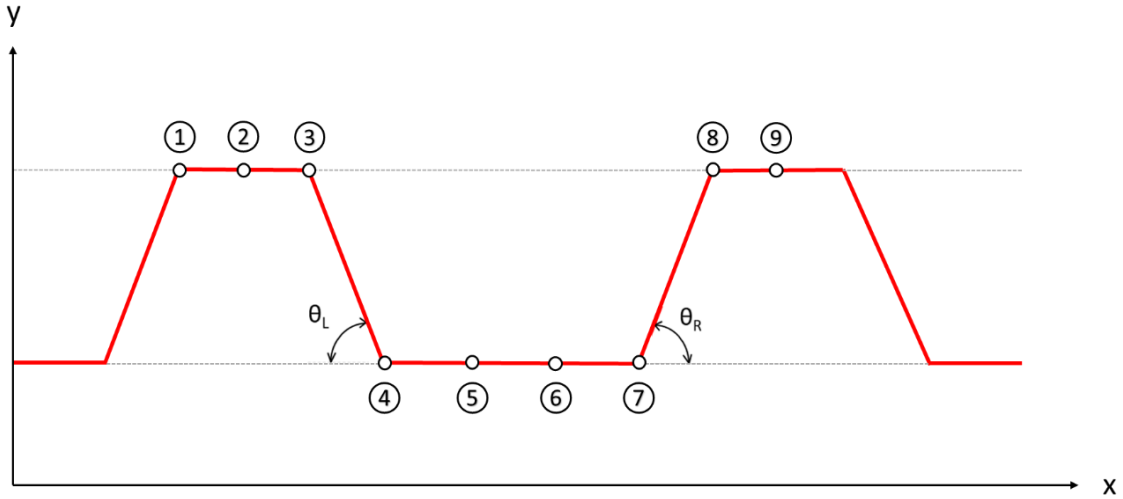


Figure 18: Indent Sidewall Angle

Each side of a given indent has a unique sidewall angle. The left sidewall angle shall be evaluated as follows for the given profile,

$$\theta_L = \tan^{-1} \left(\frac{d_i}{x_4 - x_3} \right) \quad (12)$$

Similarly, the right sidewall angle shall be evaluated as,

$$\theta_R = \tan^{-1} \left(\frac{d_i}{x_8 - x_7} \right) \quad (13)$$

Where d_i is defined as the depth for the given profile.

Since the axial distances of the left and right sidewalls are very small (for example, distance from x_4 to x_5), a more pragmatic definition of an “effective average” sidewall angle, θ_{eff} , can be used. This effective average sidewall angle shall be evaluated in terms of the plateau and basin lengths as follows:

$$\theta_{eff} = \tan^{-1} \left[\frac{d_i}{\frac{1}{2} (l_{indent} - l_{basin})} \right] = \tan^{-1} \left[\frac{d_i}{\frac{1}{2} [(x_8 - x_3) - (x_7 - x_4)]} \right]$$

(14)

6.2.12 *Indent Sidewall Length, l_L , l_R , l_{eff} .* The sidewall lengths are defined by the trapezoidal element shown in Figure 19.

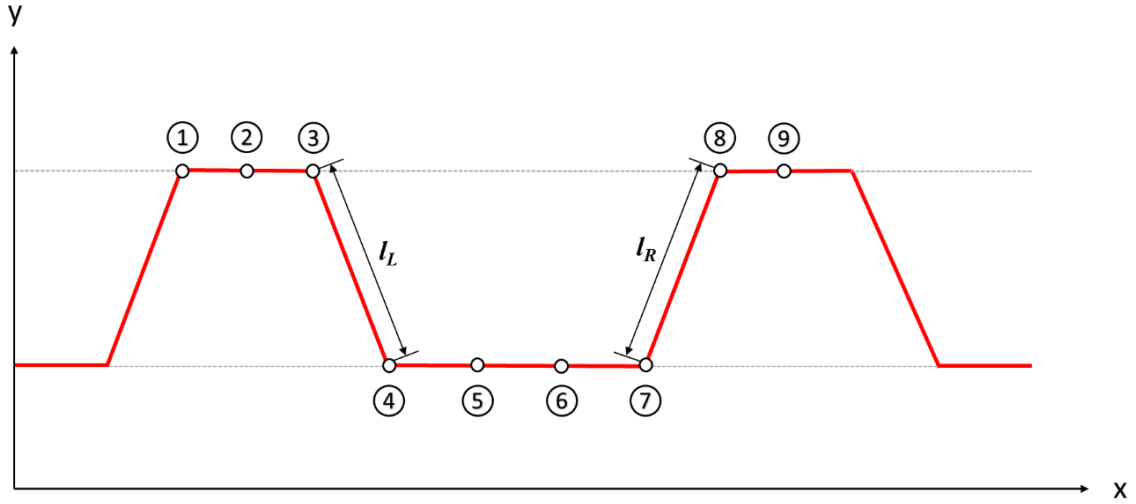


Figure 19: Indent Sidewall Length

Each side of the indent for a given profile has a unique sidewall length. The left sidewall length shall be evaluated as follows for the given profile:

$$l_L = \sqrt{d_i^2 + (x_4 - x_3)^2}$$

(15)

Similarly, the right sidewall angle shall be evaluated as,

$$l_R = \sqrt{d_i^2 + (x_8 - x_7)^2}$$

(16)

Where d_i is defined as the depth for the given profile.

Since the lateral distances of the left and right sidewall lengths are very small, a more pragmatic definition of “effective average” sidewall length, l_{eff} , can be used. This effective average sidewall length shall be evaluated in terms of the plateau and basin lengths as follows:

$$l_{eff} = \sqrt{d_i^2 + \left[\frac{1}{2} (l_{indent} - l_{basin}) \right]^2} = \sqrt{d_i^2 + \left[\frac{1}{2} ((x_8 - x_3) - (x_7 - x_4)) \right]^2}$$

(17)

6.2.13 Indent Sidewall Area, A_{sw} . The sidewall area, the surface area of the sidewall, has a unique value for each side of the indent. It is calculated using the average sidewall length of the given side as well as the width of the indent.

The sidewall area for a given side of an indent shall be calculated as follows:

$$A_{sw} = \left[\frac{1}{n} \sum_{i=1}^n l_i \right] w$$

(18)

Where n is the number of equally spaced profiles for the given indent, l_i is the sidewall length of a given profile (l_R , l_L), and w is the width of the given indent.

6.2.14 Indent Planform Area, S . The two-dimensional surface area of the indent, S , shall be calculated as follows,

$$S = \left[\frac{1}{n} \sum_{i=1}^n l_{indent,i} \right] w$$

(19)

Where n is the number of equally spaced profiles for the given indent, $l_{indent,i}$ is the indent length of a given profile, and w is the width of the given indent.

6.2.15 *Indent Profile Area, A*. The profile area associated with a single axial profile of an indent shall be defined as the trapezoidal area depicted in Figure 20.

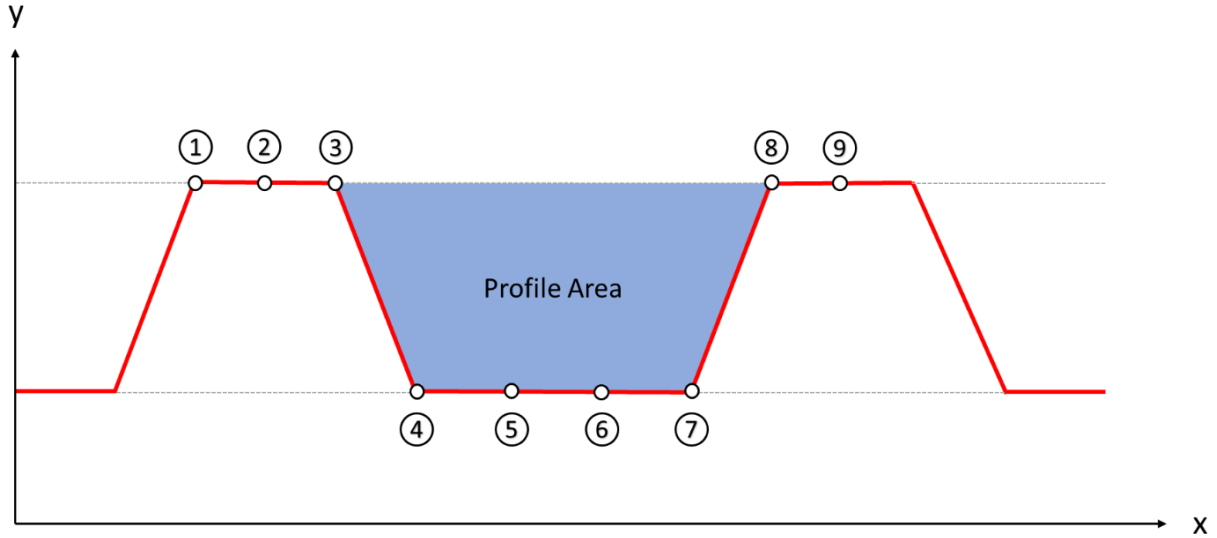


Figure 20: Indent Profile Area

The profile area for a given element shall be calculated as follows:

$$A_i = \frac{1}{2} (l_{indent} + l_{basin}) d_i$$

(20)

Alternatively,

$$A_i = \frac{1}{2} ([x_8 - x_3] + [x_7 - x_4]) d_i$$

(21)

Where d_i is defined as the depth for the given profile. l_{indent} and l_{basin} are defined as the indent length and basin length of the profile, respectively.

6.2.16 *Indent Volume, V*. The volume of an indent shall be calculated using the average trapezoidal profile area, as well as the width of the given indent.

Indent volume shall be calculated as follows:

$$V = \left[\frac{1}{n} \sum_{i=1}^n A_i \right] w$$

(22)

Where n is the number of equally spaced profiles measured for the given indent, A_i is the profile area of each equally spaced profile, and w is the width of the given indent.

6.2.17 *Bite Per Length, BPL*. The Bite Per Length of an indent is calculated using the width,

depth, and pitch of an indent. The “bite” of the indent is the product of the width and the average depth of the indent, and represents the projection of the sidewall area onto a plane perpendicular to the axis (x-axis) of the wire, as depicted in Figure 3(k) (Note 10).

Note 10: Bite Per Length, BPL, has been shown to have a significant correlation with transfer length. It represents a way to quantify the amount of concrete displaced as the wire pulls through the concrete during the detensioning process.

Indent Bite Per Length Per Row, BPRL, shall be calculated as follows:

$$BPLR_i = \left[\frac{(w_{avg})(d_{avg})}{l_{pitch}} \right]_i$$

(23)

Where w_{avg} is the average width of the indents, d_{avg} is the average depth of the indents, and l_{pitch} is the average pitch of the indents in the i^{th} row.

365 The total or overall Bite Per Length of the entire section of wire, accounting for all
indent rows,

366 is calculated as follows:

$$BPL = \sum_{i=1}^{n_r} BPLR_i \quad (24)$$

369 Where $BPLR_i$ represents the indent Bite Per Length for a given row and n_r indicates the
number

370 of indent rows of the measured wire (Note 11).

371 Note 11: It is the total BPL that has a direct influence on the transfer length.

372 7. Report

373 7.1 When requested by purchaser, a report shall be made available. The format shall
be as

374 agreed upon. Measurements to be included shall be selected from the following:

375

376 7.1.1 Actual Average Wire Cross-sectional Area (6.2.1)

377 7.1.2 Effective Wire Diameter (6.2.2)

377 7.1.3 Indent Width (6.2.3)

378 7.1.4 Indent Distance (6.2.4)

379 7.1.5 Orientation Angle (6.2.5)

380 7.1.6 Average Indent Depth (6.2.6)

381 7.1.7 Indent Pitch (6.2.7)

382 7.1.8 Indent Length (6.2.8)

383 7.1.9 Indent Basin Length (6.2.9)

384 7.1.10 Indent Plateau Length (6.2.10)

385 7.1.11 Indent Sidewall Angle (6.2.11)

386 7.1.12 Indent Sidewall Length (6.2.12)

387 7.1.13 Indent Sidewall Area (6.2.13)

388 7.1.14 Indent Planform Area (6.2.14)

389 7.1.15 Indent Profile Area (6.2.15)

390 7.1.16 Indent Volume (6.2.16)

391 7.1.17 Bite Per Length (6.2.17)

392 7.1.18 Other items, as agreed upon

393

394 7.2 A representative photo of an indent from each row will be included in the report.

395 8. Keywords

396 8.1 Indented wire; steel wire, indent geometry, transfer length, bite per length

Appendix B - ASTM Proposal Uncertainty Analysis

The ASTM proposal outlined in the previous appendix provided recommendations for the measurement techniques of critical geometric features of indented wires. These features are obtained by taking measurements at prescribed points and entering them into the provided formulas. However, no measurement is perfect and has inherent measurement uncertainty. Measurement uncertainty is influenced by where measurements are taken, the uncertainty of the measurement system itself, and the sensitivity of the governing equations to all the factors involved.

This section focuses on the measurement uncertainties of certain of critical parameters outlined in the ASTM proposal. Specifically, it focuses on the twelve two-dimensional measurements obtained from the axial profiles, illustrated in Figure B.1. Due to the simplicity of the two-dimensional indent features, easily obtainable analytical solutions exist for measurement uncertainty.

The important indent geometry parameters of interest are specified in ASTM A881, ISO 10138-2, and, in addition, those used in correlations to predict transfer length and splitting propensity. The driving measurement uncertainties of the measurement systems itself are axial (σ_z), circumferential (σ_θ), and radial (σ_r). The parameters of interest pertaining to uncertainty analysis are summarized below. Parameters obtained purely from 2D axial “scans” are of primary interest, marked with diamonds, and will be subjected to detailed uncertainty analysis.

ASTM A881

◇ Sidewall Angle

◇ Indent Depth

◇ Indent Length

◇ Indent Pitch

Orientation Angle

ISO 10138-2

Indent Distance (Rib Width)

Additional Correlation Parameters

◇ Basin Length

◇ Plateau Length

◇ Sidewall Length

◇ Profile Area

Sidewall Area

Planform Area

Indent Volume

B.1 Measurement System Uncertainties (Indent Profiling System)

The system measurement uncertainties are characteristic of the scanning or measurement system being used; these are defined as: radial (σ_r), axial (σ_z), and circumferential (σ_θ). These measurement uncertainties will be used to determine the uncertainties of the indent parameters of interest. Estimations of these measurement uncertainties are provided in the following subsections and are specific to the Indent Profiling System, but may be reasonable approximations of typical non-contact measurement techniques.

B.1.1 Radial Measurement Uncertainty

A precision ground cylinder with an RMS roughness of $0.25\mu\text{m}$ was scanned. After system misalignment and off-axis skew was eliminated via software the standard deviation of the height measurement, r , was determined to be $\sigma_r=8.31\mu\text{m}$. Furthermore, since the system takes 576,000 samples in a single 16mm scan it follows that,

$$U_r = \pm t_{95,\infty} \sigma_r = \pm 1.96(8.31\mu\text{m}) = \pm 16.29\mu\text{m}$$

B.1.2 Axial Measurement Uncertainty

The axial measurement uncertainty is an inherent property of the line laser being used, the LJ-V7060. The axial sensor data is binned in data intervals of $20\mu\text{m}$, thus, the discrete uncertainty can be considered $10\mu\text{m}$ in the worst case scenario. This is also very close to the axial uncertainty obtained using a digital microscope for manual measurements.

$$\begin{aligned} \sigma_z &= \pm 10\mu\text{m} \\ U_z &= \pm t_{95,\infty} \sigma_z = \pm 1.96(10\mu\text{m}) = \pm 19.60\mu\text{m} \end{aligned}$$

B.1.3 Circumferential Measurement Uncertainty

A 7200 pulse per revolution rotary encoder is used to trigger the line scanner. For a wire of given diameter, say 5.32mm , the circumferential uncertainty is obtained,

$$\begin{aligned} \sigma_\theta &= \pm \frac{\pi \cdot d_{\text{wire}}}{ppr} = \pm \frac{\pi \cdot 5320\mu\text{m}}{7200} = \pm 2.32\mu\text{m} \\ U_\theta &= \pm t_{95,\infty} \sigma_\theta = \pm 1.96(2.32\mu\text{m}) = \pm 4.55\mu\text{m} \end{aligned}$$

B.2 Analytical Solutions

Analytical solutions for the measurement uncertainties were obtained for all relevant two-dimension indent features. The features reside along a typical axial profile taken wherever an indent exists. Figure B.1, illustrated blow, indicates the measurement locations of the proposed standard.

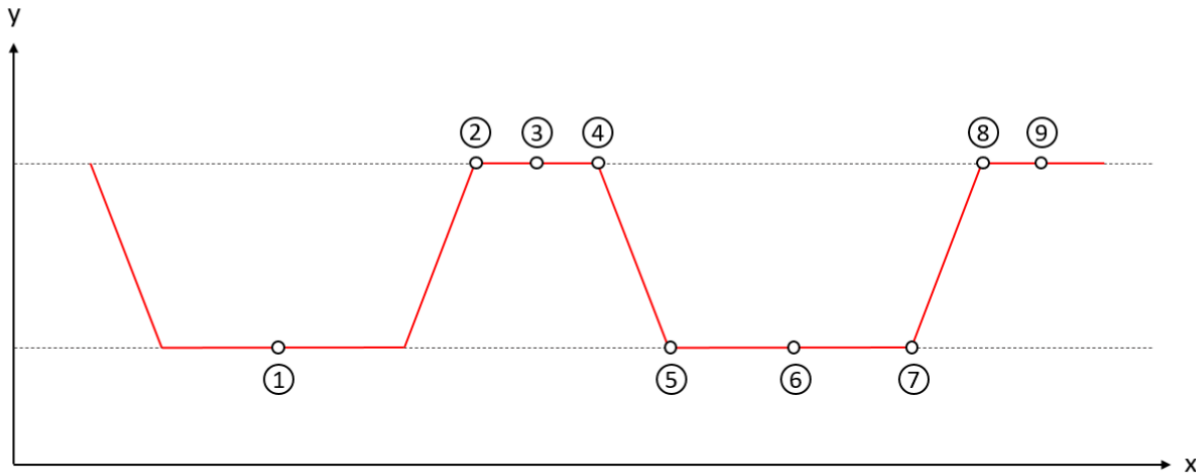


Figure B.1: 2D Measurement Locations

The analytical solutions for indent feature measurement uncertainty are summarized below,

$$\begin{aligned}
\sigma_d &= \sigma_r \\
\sigma_{l,pitch} &= \sigma_z \sqrt{2} \\
\sigma_{l,indent} &= \sigma_z \sqrt{2} \\
\sigma_{l,basin} &= \sigma_z \sqrt{2} \\
\sigma_{l,plateau} &= \sigma_z \sqrt{2} \\
\sigma_{\theta,L} &= \frac{180}{\pi} \frac{1}{d^2 + (x_5 - x_4)^2} \sqrt{\sigma_r^2 (x_5 - x_4)^2 + 2\sigma_z^2 d^2} \text{ deg} \\
\sigma_{\theta,R} &= \frac{180}{\pi} \frac{1}{d^2 + (x_8 - x_7)^2} \sqrt{\sigma_r^2 (x_8 - x_7)^2 + 2\sigma_z^2 d^2} \text{ deg} \\
\sigma_{\theta,avg} &= \frac{180}{\pi} \left[\frac{l_i - l_b}{4d^2 + (l_i - l_b)^2} \right] \sqrt{4\sigma_r^2 + 16\sigma_z^2 \left[\frac{d}{(l_i - l_b)} \right]^2} \text{ deg} \\
\sigma_{length,L} &= [d^2 + (x_5 - x_4)^2]^{-0.5} \sqrt{\sigma_r^2 d^2 + 2\sigma_z^2 (x_5 - x_4)^2} \\
\sigma_{length,R} &= [d^2 + (x_8 - x_7)^2]^{-0.5} \sqrt{\sigma_r^2 d^2 + 2\sigma_z^2 (x_8 - x_7)^2} \\
\sigma_{L,avg} &= 2\sigma_r d \left[4d^2 + ((x_8 - x_4) - (x_7 - x_5))^2 \right]^{-0.5} \\
\sigma_{area} &= \frac{1}{2} \sqrt{\sigma_r^2 (l_i + l_b)^2 + 4\sigma_z^2 d_i^2}
\end{aligned}$$

Where,

$$\begin{aligned}
d &= \frac{1}{2}(y_1 + y_9) - \frac{1}{2}(y_1 + y_6) \\
l_i &= l_{indent} = x_8 - x_2 \\
l_b &= l_{basin} = x_7 - x_5
\end{aligned}$$

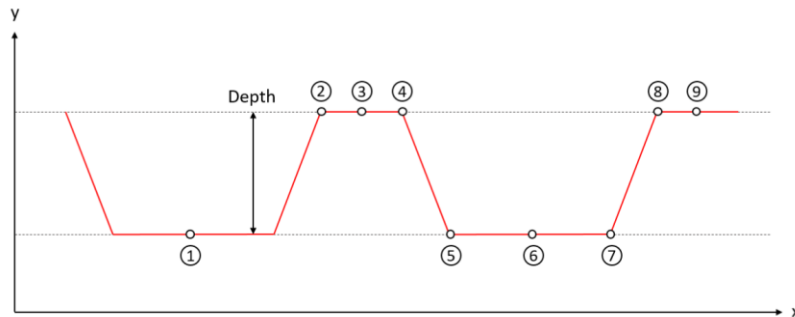
Detailed derivations of the analytical solutions are highlighted in the following subsections. These solutions can be assessed for a typical 5.32mm indented wire to predict the uncertainties that may be seen in practice. Imagine an idealized indent with a depth ($d=100\mu\text{m}$), a pitch ($p=5.60\text{mm}$), an indent length of ($l_i=4.50\text{mm}$), and a left and right sidewall angle of ($\theta=20^\circ$). For the standard deviations of the independent measurements use those which are nominal for the Indent Profiling System; $\sigma_r=8.31\mu\text{m}$ (standard deviation of the height measurement), $\sigma_z=10\mu\text{m}$ (standard deviation of the axial measurement). Using the aforementioned analytical solutions with the idealized 5.32mm indentation profile yields the expected measurement uncertainty of the two-dimensional indent parameters. The results are summarized in the following table.

Table B.1: Analytical Solutions for 2D Indent Parameter Measurement Uncertainties

Parameter		STDEV
Depth	[μm]	8.31
Pitch	[μm]	14.14
Length	[μm]	14.14
Basin	[μm]	14.14
Plateau	[μm]	14.14
θ_L	[deg]	1.80
θ_R	[deg]	1.80
θ_{Avg}	[deg]	1.67
Length L	[μm]	13.59
Length R	[μm]	13.59
Length Avg	[μm]	2.84
Area	[mm^2]	35126

It is clearly seen that the assessment of indent depth can only be improved by increasing the accuracy of the vertical measurements. Likewise, measurement uncertainties of indent pitch, indent length, indent basin length, and indent plateau length can only be improved by increasing the accuracy of the axial measurements. If indent sidewalls are similar on both the left and right side then using the averaging method yields marginally better results, however, the improvements in measurement uncertainty are lost if sidewall angles are significantly different from one another. The assessment of sidewall length sees significant improvements if the averaging method is used due to the sensitivity of the measurement to axial uncertainty. Finally, the uncertainty in the profile area of the indent is predominantly driven by the uncertainty of the vertical measurements, thus, improvements can only be made by increasing the accuracy of those particular measurements.

B.2.1 Indent Depth



Sensitivity Analysis:

The depth of a given trapezoidal element is given by,

$$d_i = \frac{1}{2}(y_3 + y_9) - \frac{1}{2}(y_1 + y_6)$$

Taking the derivative, noting that E is the absolute error,

$$d(d_i) = \frac{1}{2}dy_3 + \frac{1}{2}dy_9 - \frac{1}{2}dy_1 - \frac{1}{2}dy_6$$

$$E_{d_i} = \frac{1}{2}E_{y_3} + \frac{1}{2}E_{y_9} - \frac{1}{2}E_{y_1} - \frac{1}{2}E_{y_6}$$

This corresponds to,

$$(d_i - \bar{d}_i) = \frac{1}{2}(y_3 - \bar{y}_3) + \frac{1}{2}(y_9 - \bar{y}_9) - \frac{1}{2}(y_1 - \bar{y}_1) - \frac{1}{2}(y_6 - \bar{y}_6)$$

Squaring, noting that the cross-correlation terms go to zero since the assumption of independence between measurements is made,

$$(d_i - \bar{d}_i)^2 = \left[\frac{1}{2}(y_3 - \bar{y}_3)\right]^2 + \left[\frac{1}{2}(y_9 - \bar{y}_9)\right]^2 + \left[\frac{1}{2}(y_1 - \bar{y}_1)\right]^2 + \left[\frac{1}{2}(y_6 - \bar{y}_6)\right]^2 + \text{cross correlation terms}$$

The expected values are therefore,

$$\left[\frac{E(d_i - \bar{d}_i)^2}{N}\right]^{\frac{1}{2}} = \left[\frac{E\left[\frac{1}{2}(y_3 - \bar{y}_3)\right]^2}{N} + \frac{E\left[\frac{1}{2}(y_9 - \bar{y}_9)\right]^2}{N} + \frac{E\left[\frac{1}{2}(y_1 - \bar{y}_1)\right]^2}{N} + \frac{E\left[\frac{1}{2}(y_6 - \bar{y}_6)\right]^2}{N}\right]^{\frac{1}{2}}$$

This goes to,

$$\sigma_{d_i}^2 = \frac{1}{N-1} \sum (d_i - \bar{d}_i)^2$$

Equivalently,

$$\sigma_{d_i}^2 = \left(\frac{1}{2}\right)^2 \sigma_{y_3}^2 + \left(\frac{1}{2}\right)^2 \sigma_{y_9}^2 + \left(\frac{1}{2}\right)^2 \sigma_{y_1}^2 + \left(\frac{1}{2}\right)^2 \sigma_{y_6}^2$$

The standard deviation of the measurement can be described as,

$$\sigma_d = \frac{1}{2} \sqrt{\sigma_{y_3}^2 + \sigma_{y_9}^2 + \sigma_{y_1}^2 + \sigma_{y_6}^2}$$

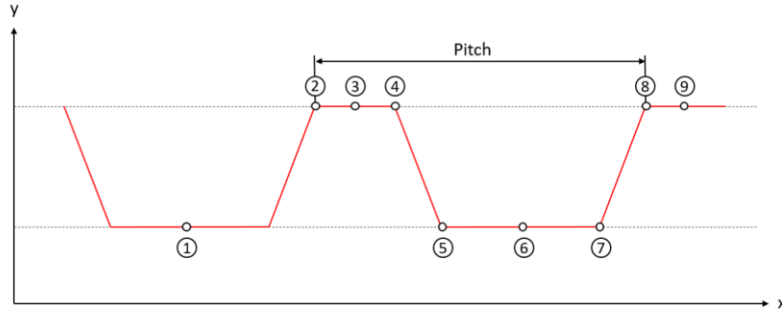
Observing that $\sigma_r = \sigma_{y_3} = \sigma_{y_9} = \sigma_{y_1} = \sigma_{y_6}$,

$$\sigma_d = \frac{1}{2} \sqrt{4\sigma_r^2} = \sigma_r$$

The uncertainty of the measurement, under which 95% of the values will fall, is approximately,

$$U_{d_i} = \frac{1}{2} \sqrt{U_{y_3}^2 + U_{y_9}^2 + U_{y_1}^2 + U_{y_6}^2} = \pm 2\sigma_{d_i}$$

B.2.2 Indent Pitch



Sensitivity Analysis:

The pitch of a given trapezoidal element is given by,

$$p_i = x_8 - x_2$$

Taking the derivative, noting that E is the absolute error,

$$d(p_i) = dx_3 + dx_2$$

$$E_{p_i} = E_{x_8} + E_{x_2}$$

This corresponds to,

$$(p_i - \bar{p}_i) = (x_8 - \bar{x}_8) + (x_2 - \bar{x}_2)$$

Squaring, noting that the cross-correlation terms go to zero since the assumption of independence between measurements is made,

$$(p_i - \bar{p}_i)^2 = (x_8 - \bar{x}_8)^2 + (x_2 - \bar{x}_2)^2 + \overset{\text{cross}}{\underset{\text{terms}}{\text{correlation terms}}}$$

The expected values are therefore,

$$\left[\frac{E(p_i - \bar{p}_i)^2}{N} \right]^{\frac{1}{2}} = \left[\frac{E[x_8 - \bar{x}_8]^2}{N} + \frac{E[x_2 - \bar{x}_2]^2}{N} \right]^{\frac{1}{2}}$$

This goes to,

$$\sigma_{p_i}^2 = \frac{1}{N-1} \sum (p_i - \bar{p}_i)^2$$

Equivalently,

$$\sigma_{p_i}^2 = \sigma_{x_8}^2 + \sigma_{x_2}^2$$

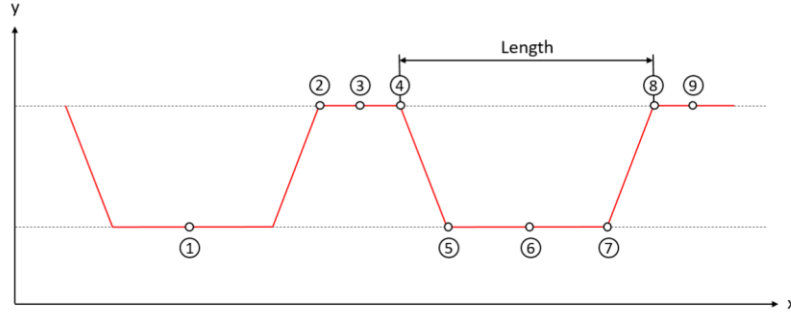
The standard deviation of the measurement can be described as,

$$\sigma_p = \sqrt{\sigma_{x_8}^2 + \sigma_{x_2}^2}$$

Observing that $\sigma_z = \sigma_{x_8} = \sigma_{x_2}$, this implies,

$$\sigma_{pitch} = \sigma_z \sqrt{2}$$

B.2.3 Indent Length



Sensitivity Analysis:

The sensitivity analysis for indent length is obtained in a manner identical to the indent pitch.

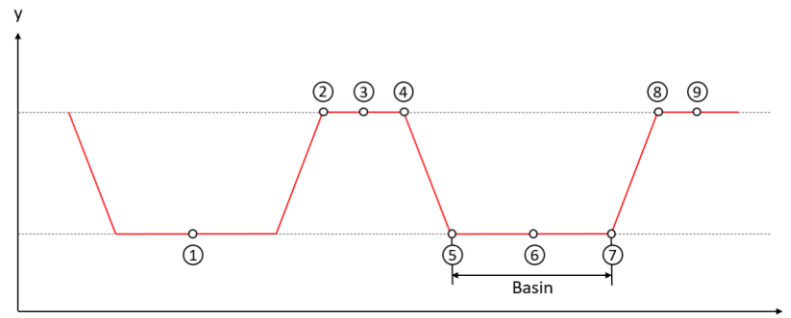
The pitch of a given trapezoidal element is given by,

$$l_{indent,i} = x_8 - x_2$$

This implies that for independent values of σ_{xi} ,

$$\sigma_{l,indent} = \sigma_z \sqrt{2}$$

B.2.4 Indent Basin (Length)



Sensitivity Analysis:

The sensitivity analysis for indent basin length is obtained in a manner identical to the indent pitch.

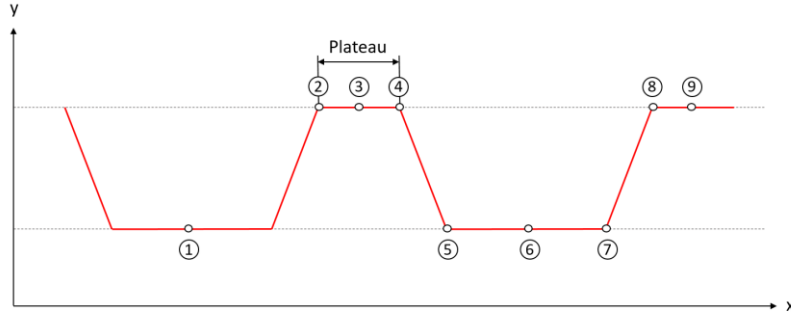
The basin length of a given trapezoidal element is given by,

$$l_{basin,i} = x_7 - x_5$$

This implies that for independent values of σ_{xi} ,

$$\sigma_{l,basin} = \sigma_z \sqrt{2}$$

B.2.5 Indent Plateau (Length)



Sensitivity Analysis:

The sensitivity analysis for indent plateau length is obtained in a manner identical to the indent pitch.

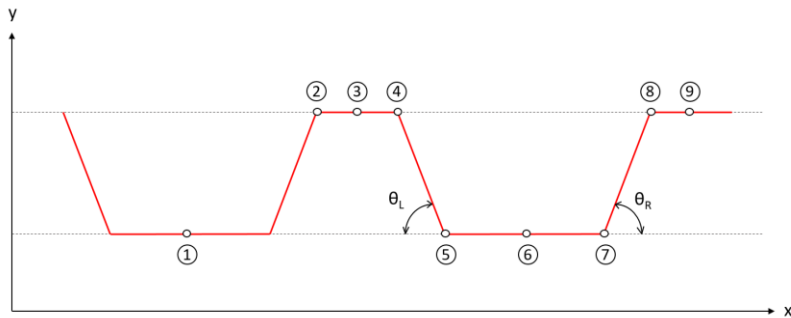
The plateau length of a given trapezoidal element is given by,

$$l_{plateau,i} = x_8 - x_4$$

This implies that for independent values of σ_{xi} ,

$$\sigma_{l,plateau} = \sigma_z \sqrt{2}$$

B.2.6 Indent Sidewall Angle (Left/Right)



Sensitivity Analysis:

The sidewall angle of a given trapezoidal element is given by the general relation,

$$\theta = \tan^{-1}\left(\frac{d_i}{span}\right) = \tan^{-1}\left(\frac{d_i}{x_8 - x_7}\right) = \tan^{-1}\left(\frac{d_i}{x_5 - x_4}\right)$$

Where “span” denotes the axial length of the sidewall. Referred to as “span” for the remainder of the analysis for conciseness.

From this general relation the left sidewall angle is defined as,

$$\theta_L = \tan^{-1}\left(\frac{d_i}{span}\right) = \tan^{-1}\left(\frac{d_i}{x_5 - x_4}\right)$$

Unsurprisingly, the right sidewall angle is defined as,

$$\theta_R = \tan^{-1}\left(\frac{d_i}{span}\right) = \tan^{-1}\left(\frac{d_i}{x_8 - x_7}\right)$$

Continuing with the uncertainty analysis yields the general expression,

$$\sigma_\theta = \sqrt{\sigma_r^2 \left[\frac{span}{d^2 + span^2} \right]^2 + 2\sigma_z^2 \left[\frac{d}{d^2 + span^2} \right]^2}$$

Thus, the left and right sidewall angles are described by,

$$\sigma_{\theta,L} = \sqrt{\sigma_r^2 \left[\frac{x_5 - x_4}{d^2 + (x_5 - x_4)^2} \right]^2 + 2\sigma_z^2 \left[\frac{d}{d^2 + (x_5 - x_4)^2} \right]^2}$$

$$\sigma_{\theta,R} = \sqrt{\sigma_r^2 \left[\frac{x_8 - x_7}{d^2 + (x_8 - x_7)^2} \right]^2 + 2\sigma_z^2 \left[\frac{d}{d^2 + (x_8 - x_7)^2} \right]^2}$$

Simplifying the equations,

$$\sigma_{\theta,L} = \sqrt{\left[\frac{1}{d^2 + (x_5 - x_4)^2} \right]^2 [\sigma_r^2 (x_5 - x_4)^2 + 2\sigma_z^2 d^2]}$$

$$\sigma_{\theta,R} = \sqrt{\left[\frac{1}{d^2 + (x_8 - x_7)^2} \right]^2 [\sigma_r^2 (x_8 - x_7)^2 + 2\sigma_z^2 d^2]}$$

$$\sigma_{\theta,L} = \frac{1}{d^2 + (x_5 - x_4)^2} \sqrt{\sigma_r^2 (x_5 - x_4)^2 + 2\sigma_z^2 d^2} \text{ rad}$$

$$\sigma_{\theta,R} = \frac{1}{d^2 + (x_8 - x_7)^2} \sqrt{\sigma_r^2 (x_8 - x_7)^2 + 2\sigma_z^2 d^2} \text{ rad}$$

In degrees,

$$\sigma_{\theta,L} = \frac{180}{\pi} \frac{1}{d^2 + (x_5 - x_4)^2} \sqrt{\sigma_r^2 (x_5 - x_4)^2 + 2\sigma_z^2 d^2} \deg$$

$$\sigma_{\theta,R} = \frac{180}{\pi} \frac{1}{d^2 + (x_8 - x_7)^2} \sqrt{\sigma_r^2 (x_8 - x_7)^2 + 2\sigma_z^2 d^2} \deg$$

Noting that,

$$d_i = \frac{1}{2}(y_1 + y_9) - \frac{1}{2}(y_1 + y_6)$$

B.2.7 Indent Sidewall Angle (Average)

Sensitivity Analysis:

The average sidewall angle of a given trapezoidal element can be approximated by the following relation,

$$\theta_{avg} = \tan^{-1} \left[\frac{d_i}{\frac{1}{2}(l_i - l_b)} \right] = \tan^{-1} \left[\frac{d_i}{\frac{1}{2}[(x_8 - x_4) - (x_7 - x_5)]} \right]$$

Continuing with the uncertainty analysis yields the general expression,

$$\sigma_{\theta,avg} = \sqrt{\sigma_r^2 \left[\frac{2}{(l_i - l_b) \left[\frac{4d^2}{(l_i - l_b)^2} + 1 \right]} \right]^2 + 4\sigma_z^2 \left[\frac{2d}{(l_i - l_b)^2 \left[\frac{4d^2}{(l_i - l_b)^2} + 1 \right]} \right]^2}$$

This simplifies to,

$$\sigma_{\theta,avg} = \frac{2(l_i - l_b)}{4d^2 + (l_i - l_b)^2} \sqrt{\sigma_r^2 + 4\sigma_z^2 \left[\frac{d}{(l_i - l_b)} \right]^2} \text{ rad}$$

In degrees,

$$\sigma_{\theta,avg} = \frac{360}{\pi} \left[\frac{l_i - l_b}{4d^2 + (l_i - l_b)^2} \right] \sqrt{\sigma_r^2 + 4\sigma_z^2 \left[\frac{d}{(l_i - l_b)} \right]^2} \deg$$

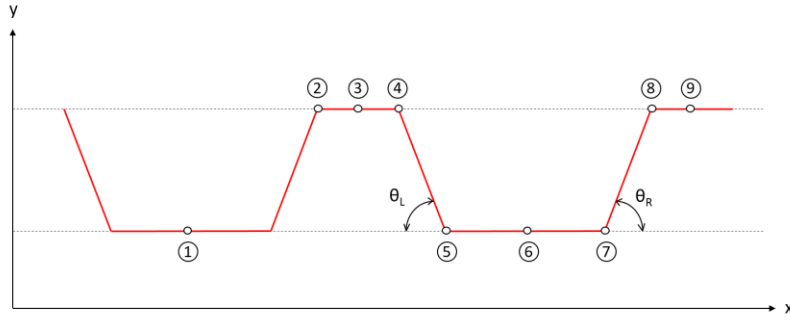
Noting that,

$$d = \frac{1}{2}(y_1 + y_9) - \frac{1}{2}(y_1 + y_6)$$

$$l_i = l_{indent} = x_8 - x_2$$

$$l_b = l_{basin} = x_7 - x_5$$

B.2.8 Indent Sidewall Length (Left/Right)



Sensitivity Analysis:

The sidewall length of a given trapezoidal element is given by the general relation,

$$L = \sqrt{d_i^2 + span^2} = \sqrt{d_i^2 + (x_5 - x_4)^2} = \sqrt{d_i^2 + (x_8 - x_7)^2}$$

Where “span” denotes the axial length of the sidewall. Referred to as “span” for the remainder of the analysis for conciseness.

From this general relation the left sidewall length is defined as,

$$L_L = \sqrt{d_i^2 + span^2} = \sqrt{d_i^2 + (x_5 - x_4)^2}$$

Unsurprisingly, the right sidewall length is defined as,

$$L_R = \sqrt{d_i^2 + span^2} = \sqrt{d_i^2 + (x_8 - x_7)^2}$$

Continuing with the uncertainty analysis yields the general expression,

$$\sigma_{length} = \sqrt{\left[\frac{1}{d^2 + span^2} \right] [\sigma_r^2 d^2 + 2\sigma_z^2 span^2]}$$

Thus, the left and right sidewall lengths are described by,

$$\sigma_{length,L} = [d^2 + (x_5 - x_4)^2]^{-0.5} \sqrt{\sigma_r^2 d^2 + 2\sigma_z^2 (x_5 - x_4)^2}$$

$$\sigma_{length,R} = [d^2 + (x_8 - x_7)^2]^{-0.5} \sqrt{\sigma_r^2 d^2 + 2\sigma_z^2 (x_8 - x_7)^2}$$

B.2.9 Indent Sidewall Length (Average)

Sensitivity Analysis:

The average sidewall length of a given trapezoidal element can be approximated by the following relation,

$$L_{avg} = \sqrt{d_i^2 + \left[\frac{1}{2}(l_i - l_b)\right]^2} = \sqrt{d_i^2 + \left[\frac{1}{2}((x_8 - x_4) - (x_7 - x_5))\right]^2}$$

Where,

$$d_i = \frac{1}{2}(y_1 + y_9) - \frac{1}{2}(y_1 + y_6)$$

$$l_i = l_{indent} = x_8 - x_2$$

$$l_b = l_{basin} = x_7 - x_5$$

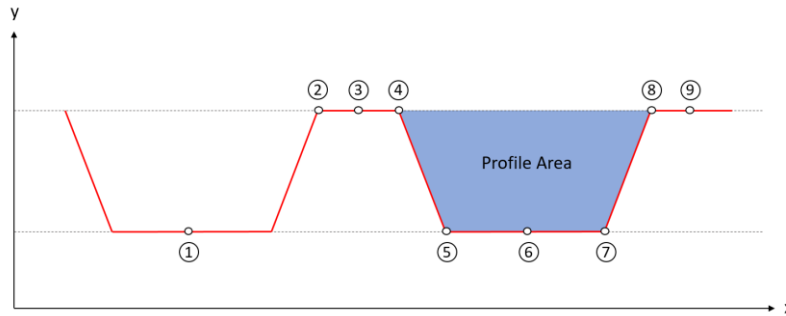
Continuing with the uncertainty analysis yields the general expression after applying some simplifications and removing insignificant terms,

$$\sigma_{L,avg} = 2\sigma_r d [4d^2 + (l_i - l_b)^2]^{-0.5}$$

Equivalently,

$$\sigma_{L,avg} = 2\sigma_r d \left[4d^2 + ((x_8 - x_4) - (x_7 - x_5))^2 \right]^{-0.5}$$

B.2.10 Indent Profile Area



Sensitivity Analysis:

The profile area of a given trapezoidal element is given by,

$$A = \frac{1}{2}(l_i + l_b)d_i$$

Where,

$$d_i = \frac{1}{2}(y_1 + y_9) - \frac{1}{2}(y_1 + y_6)$$

$$l_i = l_{indent} = x_8 - x_2$$

$$l_b = l_{basin} = x_7 - x_5$$

This is equivalent to,

$$A = \frac{1}{4}[(x_8 - x_4) + (x_7 - x_5)][(y_3 + y_9) - (y_1 + y_6)]$$

Continuing with the uncertainty analysis yields the general expression,

$$\sigma_A = \frac{1}{2} \sqrt{\sigma_r^2 (l_i + l_b)^2 + 4\sigma_z^2 d_i^2}$$

B.3 Monte-Carlo Verification

To verify the analytical results of the indent geometry measurement uncertainties a Monte Carlo simulation was performed. This represents a stochastic method for assessing the same parameters rather than a using deterministic one. To perform the Monte Carlo simulation the ideal indent profile indicated in Figure B.1 had its prescribed measurement points perturbed, accounting for the inaccuracies of the measurement system, σ_r and σ_z . From these perturbed points the two-dimensional indent geometry was computed using the formulas in the proposed ASTM standard. By running these calculations for a large number of histories, say $n=1000000$, it is possible to get an accurate assessment of the standard deviations of the indent geometry measurements seen in practice.

Histories = 1000000					
σ_r [μm] = 8.31					
σ_z [μm] = 10.00					
		IDEAL		SIMULATED	Predicted
				MEAN	STDEV
					STDEV
Depth	[μm]	: 100.0		99.99	8.300
Pitch	[μm]	: 5600.0		5599.99	14.133
Length	[μm]	: 4500.0		4500.00	14.146
Basin	[μm]	: 3950.5		3950.49	14.145
Plateau	[μm]	: 1100.0		1099.99	14.131
Angle_R	[deg]	: 20.0		20.03	1.803
Angle_L	[deg]	: 20.0		20.03	1.802
Angle_Avg	[deg]	: 20.0		20.00	1.669
Length_R	[μm]	: 292.4		292.51	13.583
Length_L	[μm]	: 292.4		292.54	13.596
Length_Avg	[μm]	: 292.4		292.48	2.839
Area	[μm^2]	: 422525.2		422488.40	35085.327
					35126.084

Figure B.2: Monte Carlo Verification of Analytical Solutions of Measurement Uncertainty

Such a Monte Carlo simulation was performed using the idealized profile outlined in Section B.2, the results of which can be seen in Figure B.2. The “IDEAL” column indicates the true measured indent geometry values if perfect measurements can be made, the “SIMULATED MEAN” column represents the same values but instead uses the perturbed data points. The “SIMULATED STDEV” column contains the standard deviations of the measurements using the

Monte Carlo simulation, whereas the “Predicted STDEV” column represents the analytical solutions for measurement uncertainty highlighted in the previous section. From this information it is clear that the analytical solutions are correct since the stochastic method (Monte Carlo) yields nearly identical results. If an infinite number of histories could be run the Monte Carlo simulation would converge to the analytical solution. The agreement between both methods can be clearly visualized in Figure B.3 which compares the Monte Carlo simulation (labeled as “Simulated”) for indent depth with the analytical solution (labeled as “Theory”) for the measurement uncertainty, showing perfect alignment between both methods.

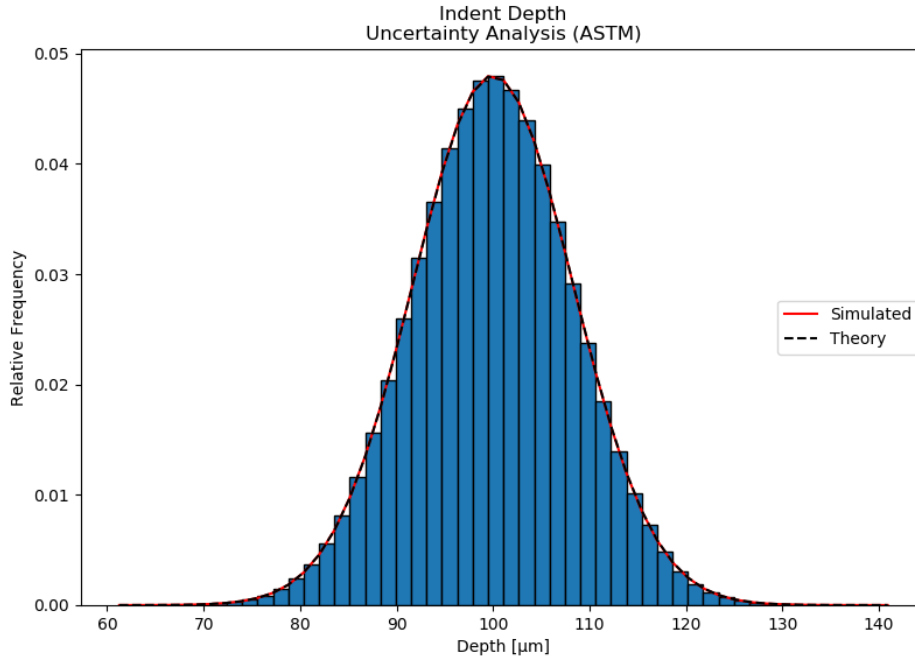


Figure B.3: Indent Depth (Monte-Carlo vs Analytical Solution)

B.4 Selecting the Required Number of Measured Samples

The ultimate goal of taking a set of measurements is to be confident in the values that are being measured. From the analytical and Monte Carlo solutions for indent geometry uncertainty it is clear that significant measurement uncertainties can exist for individual measurements, mandating the use of multiple measurements to get accurate results. Therefore, it is essential to choose an appropriate number of measurement samples that must be taken to ensure that the measurements fall within certain acceptable bounds. In statistics, this is described by the confidence interval, highlighted below, which indicates the range within a certain percentage of the measured values are expected to fall.

$$CI|_{\alpha} = \bar{x} \pm t_{\alpha/2, n-1} \frac{\sigma}{\sqrt{n}}$$

It is desirable to take the fewest number of samples to obtain the desired degree of confidence in the measurement. From the solutions, the standard deviations of the indent geometry measurements, σ , are well-known quantities that only depend on the points at which the measurements are performed and the uncertainty of the measurement system itself. The t-value is a statistic quantity related to the confidence desired and the number of samples taken. If a

confidence interval of 95% is desired, $\sigma_{\text{depth}} = 8.31\mu\text{m}$, and 6 independent samples are taken, this implies that 95% of the values will fall within $\pm 8.71\mu\text{m}$ of the mean. However, if 30 samples are taken instead this reduces to $3.03\mu\text{m}$. Figure B.4 visually indicates how sample size directly influences the confidence interval of the indent depth measurement.

$$6 \text{ Samples: } CI|_{\text{depth},95\%} = \pm t_{\frac{\alpha}{2},n-1} \frac{\sigma}{\sqrt{n}} = \pm 2.571 \frac{8.31\mu\text{m}}{\sqrt{6}} = \pm 8.72\mu\text{m}$$

$$30 \text{ Samples: } CI|_{\text{depth},95\%} = \pm t_{\frac{\alpha}{2},n-1} \frac{\sigma}{\sqrt{n}} = \pm 2.045 \frac{8.31\mu\text{m}}{\sqrt{30}} = \pm 3.10\mu\text{m}$$

Likewise, the inverse problem can be solved by specifying the desired confidence limit and determining the number of samples that must be taken to achieve that confidence. If it is desired for the measured values of depth to be within 5% of the true depth ($100\mu\text{m}$ for the idealized profile in this case) then approximately 12 samples of indent depth must be taken.

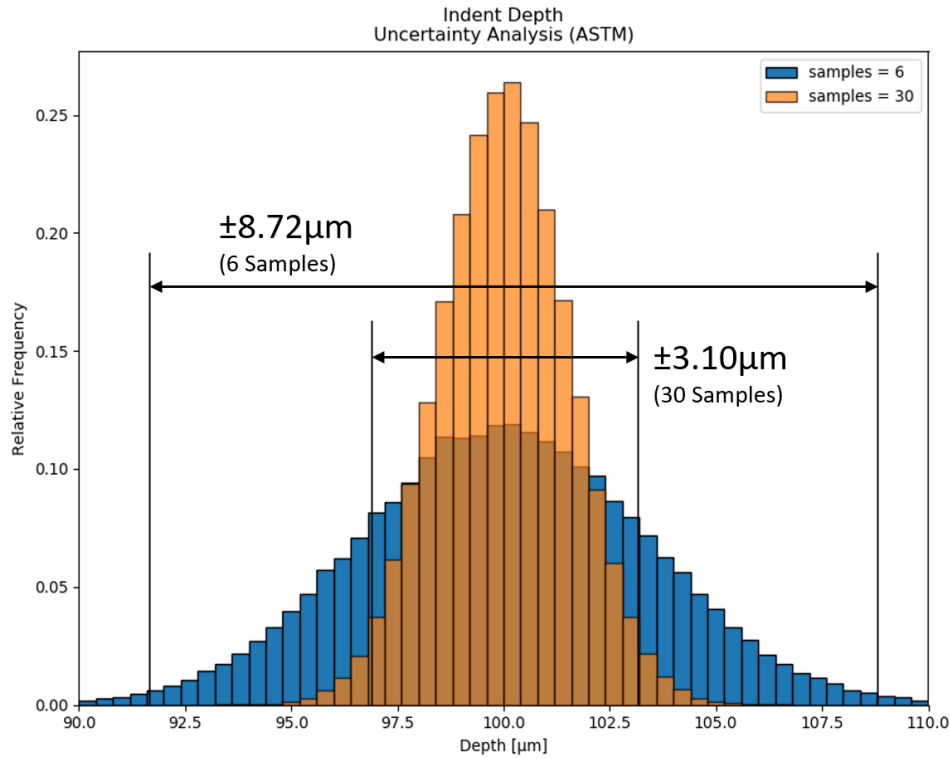


Figure B.4: 95% Confidence Interval of Indent Depth

Appendix C - Wire Report Summary

This Appendix contains the reports for the wires that were scanned and processed by the Indent Profiling System. Each report contains a general overview of the data and highlights some of the most important data from the analysis, along with an ASTM A881 and ISO 10138-2 report for each indented wire. A 2D representation of a single scan segment is also provided for each report to assist with data visualization. The reports appear in the following order indicated in the figure below.

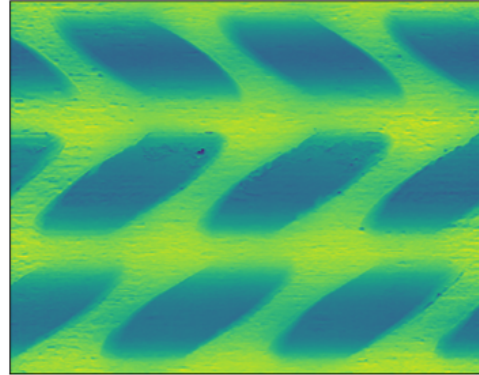
Cover Testing	Crosstie Wires	Machined Wires
WB	E-1	15
WD	F-1	15-.16-T1
WF	H-1	30-.16-T1
WG	J-1	45-.16-T2
WH	K-1	60-.16-T1
WI	L-1	75-.16-T1
WJ	M-1	90-.16-T3
WM		X1
WP		X2
WQ		X3
		X4
		X5

TEST REPORT: INDENT PROFILER

WIRE ID:WB

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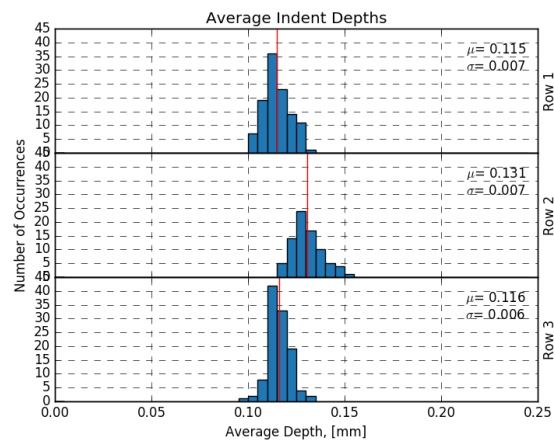
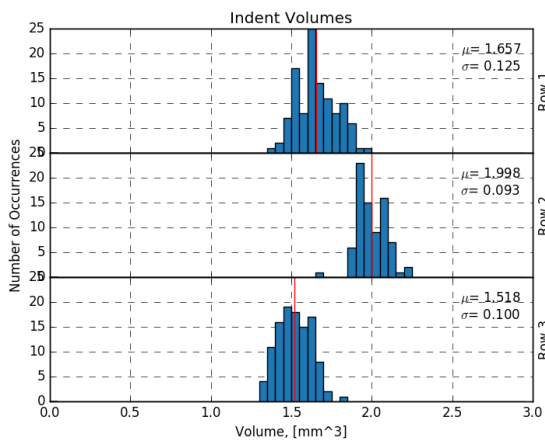
Scan Information				
Wire ID	WB_630mm_Trued_10.26.18			
Length [mm]	630			
Scan Date	10.26.18			
Proc Date	09.17.19			
Stat Date	09.17.19			
ID	Indents	Nominal Dia [mm]	Orientat-ion [deg]	Distance [mm]
Total	302	5.153	47.7	2.193
Row 1	111		47.1	1.996
Row 2	80		48.3	2.291
Row 3	111		-47.6	2.291



Indent Data								
ID	Indents	Volume [mm^3]	S.W. Area [mm^2]	Avg Depth [mm]	S.W. Angle [deg]	Avg Length [mm]	Width [mm]	Pitch [mm]
Total	302	1.696	2.922	0.119	16.45	4.060	4.009	5.580
Row 1	111	1.657	2.997	0.115	15.54	3.995	4.129	5.593
Row 2	80	1.998	3.263	0.131	18.28	3.934	4.494	5.581
Row 3	111	1.518	2.600	0.116	16.03	4.215	3.540	5.568

S.W. Area: The average sidewall area of the left and right side of the indents.

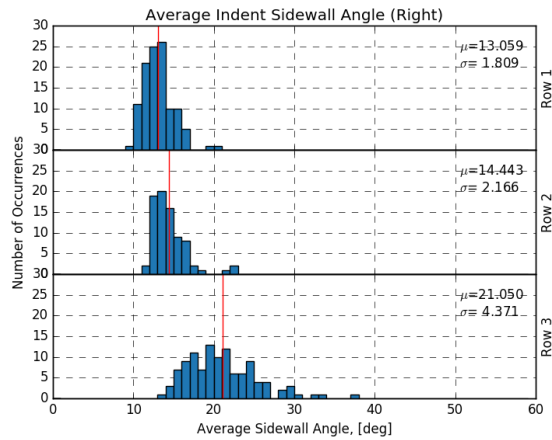
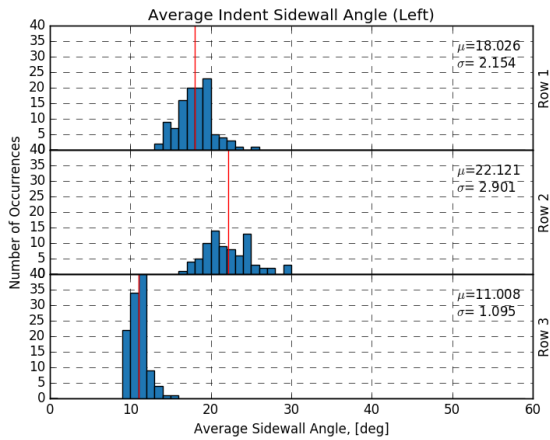
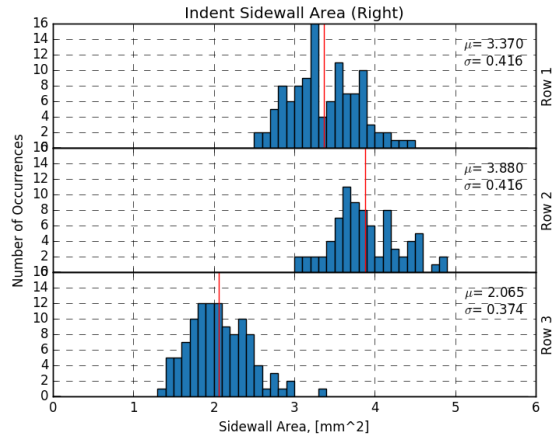
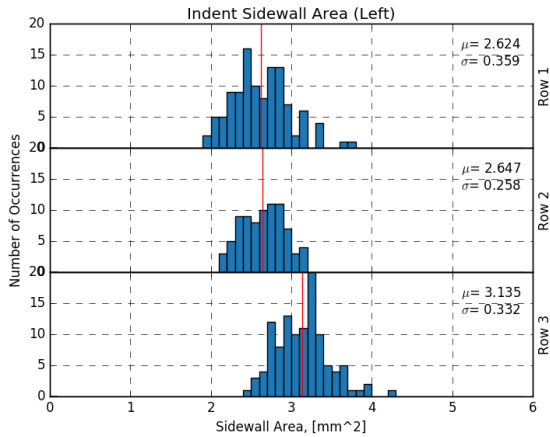
S.W. Angle: The average sidewall angle of the left and right side of the indents.



TEST REPORT: INDENT PROFILER

WIRE ID:WB

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TEST REPORT: ASTM A881

WIRE ID:WB

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SAMPLE ID		WB_630mm_Trued_10.26.18
SAMPLE LENGTH [MM]		630
NOMINAL DIAMETER [MM]		5.153
TEST ITEM	STANDARD VALUE	ACTUAL VALUE
INDENT DEPTH [MM]	0.115±0.035	0.119
SIDEWALL ANGLE [DEG]	In Contract	16.4
INDENT LENGTH [MM]	3.5±0.5	4.341
INDENT PITCH [MM]	5.46±0.29	5.58
ORIENTATION ANGLE [DEG]	≥45°	47.7
OUT OF ROUND [MM]	≤0.08	TBD

TEST REPORT: ISO 10138-2

WIRE ID:WB

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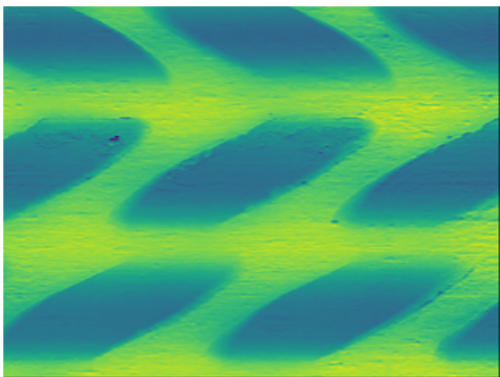
SAMPLE ID		WB_630mm_TrueD_10.26.18
SAMPLE LENGTH		630
NOMINAL DIAMETER		5.153
TEST ITEM	STANDARD VALUE	ACTUAL VALUE
INDENT LENGTH [MM]	3.5±0.5	4.341
INDENT DEPTH [MM]	0.15±0.05	0.119
INDENT SPACING [MM]	5.50±0.50	5.58
INDENT DISTANCE [MM]	$\Sigma e \leq 3.343$	2.00, 2.29, 2.29
AVG DIAMETER [MM]	-	TBD
OVALITY	$\leq 0.01 \times D$	TBD

TEST REPORT: INDENT PROFILER

WIRE ID:WD

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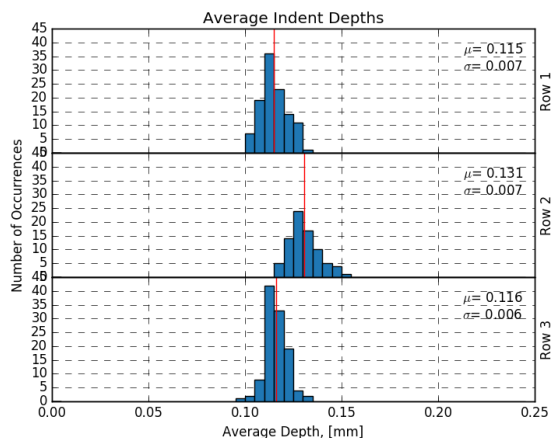
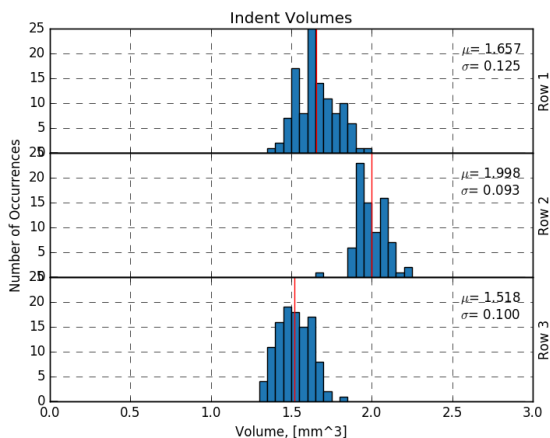
Scan Information					
Wire ID	WD_630mm_Trueid_10.26.18				
Length [mm]	630				
Scan Date	10.26.18				
Proc Date	9.17.19				
Stat Date	9.17.19				
ID	Indents	Nominal Dia [mm]	Orientat-ion [deg]	Distance [mm]	
Total	337	5.257	58.4	2.510	
Row 1	113		59.1	2.547	
Row 2	112		-56.0	2.491	
Row 3	112		57.8	2.491	



Indent Data								
ID	Indents	Volume [mm^3]	S.W. Area [mm^2]	Avg Depth [mm]	S.W. Angle [deg]	Avg Length [mm]	Width [mm]	Pitch [mm]
Total	337	1.600	2.744	0.141	17.22	3.512	3.854	5.548
Row 1	113	1.556	2.728	0.135	17.22	3.666	3.792	5.548
Row 2	112	1.558	2.577	0.140	17.55	3.392	3.867	5.548
Row 3	112	1.687	2.926	0.149	16.89	3.476	3.904	5.548

S.W. Area: The average sidewall area of the left and right side of the indents.

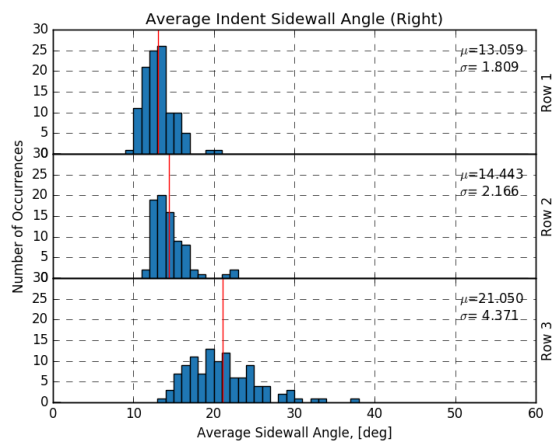
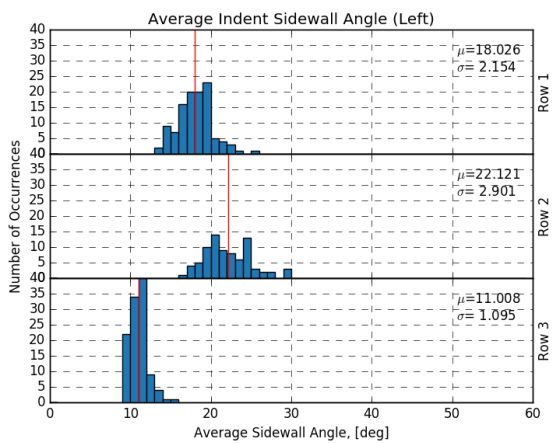
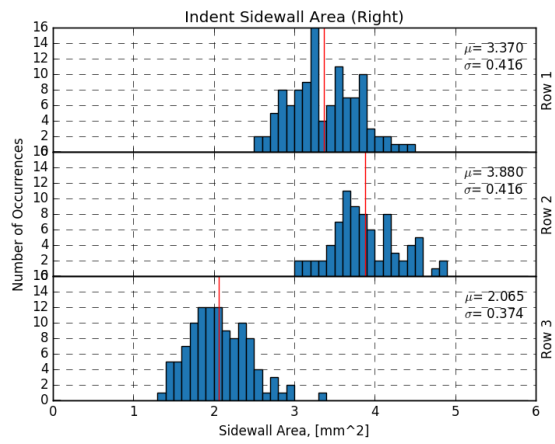
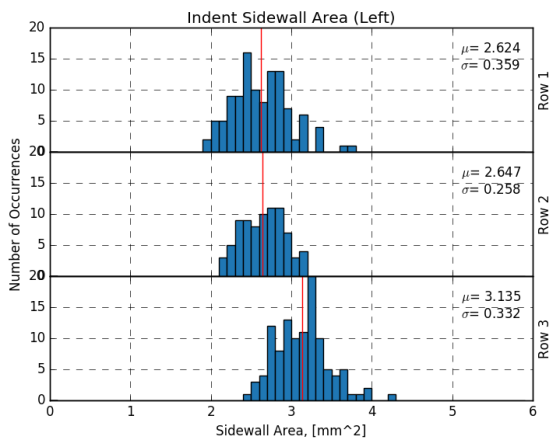
S.W. Angle: The average sidewall angle of the left and right side of the indents.



TEST REPORT: INDENT PROFILER

WIRE ID:WD

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TEST REPORT: ASTM A881

WIRE ID:WD

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SAMPLE ID		WD_630mm_Trued_10.26.18
SAMPLE LENGTH [MM]		630
NOMINAL DIAMETER [MM]		5.257
TEST ITEM	STANDARD VALUE	ACTUAL VALUE
INDENT DEPTH [MM]	0.115±0.035	0.141
SIDEWALL ANGLE [DEG]	In Contract	17.2
INDENT LENGTH [MM]	3.5±0.5	4.106
INDENT PITCH [MM]	5.46±0.29	5.55
ORIENTATION ANGLE [DEG]	≥45°	58.4
OUT OF ROUND [MM]	≤0.08	TBD

TEST REPORT: ISO 10138-2

WIRE ID:WD

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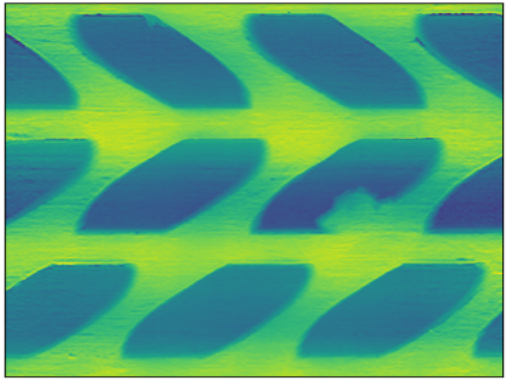
SAMPLE ID		WD_630mm_Trued_10.26.18
SAMPLE LENGTH		630
NOMINAL DIAMETER		5.257
TEST ITEM	STANDARD VALUE	ACTUAL VALUE
INDENT LENGTH [MM]	3.5±0.5	4.106
INDENT DEPTH [MM]	0.15±0.05	0.141
INDENT SPACING [MM]	5.50±0.50	5.55
INDENT DISTANCE [MM]	$\Sigma e \leq 3.343$	2.55, 2.49, 2.49
AVG DIAMETER [MM]	—	TBD
OVALITY	$\leq 0.01 \times D$	TBD

TEST REPORT: INDENT PROFILER

WIRE ID:WF

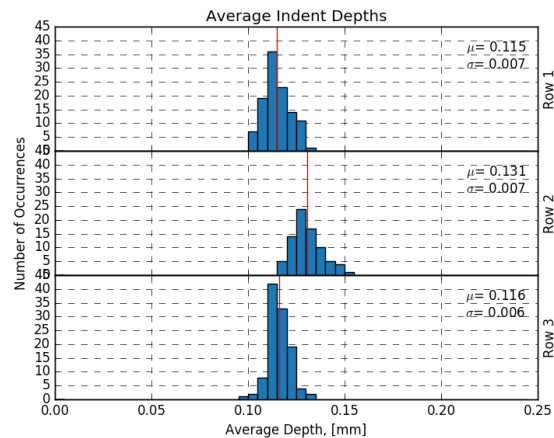
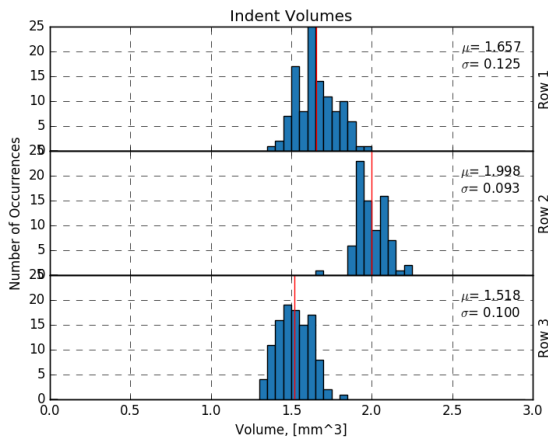
PAGE 1/4

Scan Information					
Wire ID		WF_630mm_TrueD_10.26.18			
Length [mm]		630			
Scan Date		10.26.18			
Proc Date		9.17.19			
Stat Date		9.17.19			
ID	Indents	Nominal Dia [mm]	Orientat-ion [deg]	Distance [mm]	
Total	333	5.195	48.4	2.143	
Row 1	111		50.0	2.129	
Row 2	111		47.3	2.150	
Row 3	111		-47.9	2.150	



Indent Data								
ID	Indents	Volume [mm^3]	S.W. Area [mm^2]	Avg Depth [mm]	S.W. Angle [deg]	Avg Length [mm]	Width [mm]	Pitch [mm]
Total	333	2.446	2.452	0.163	28.07	4.014	4.197	5.604
Row 1	111	2.362	2.269	0.155	27.23	4.034	4.198	5.617
Row 2	111	2.457	2.589	0.161	27.48	4.069	4.239	5.616
Row 3	111	2.518	2.498	0.174	29.52	3.939	4.155	5.577

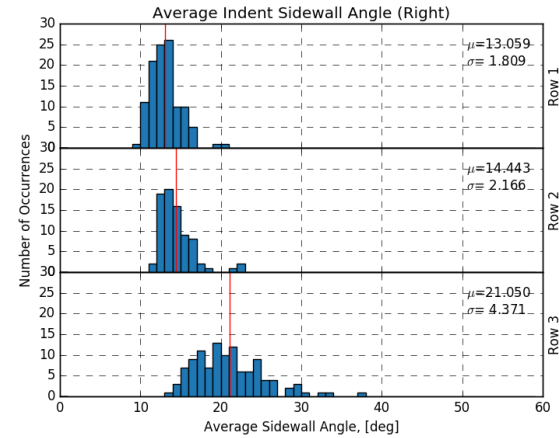
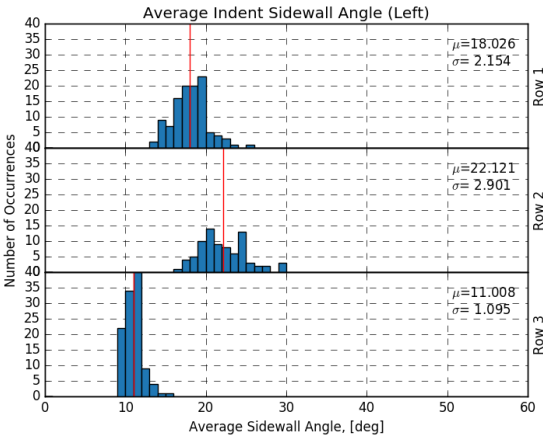
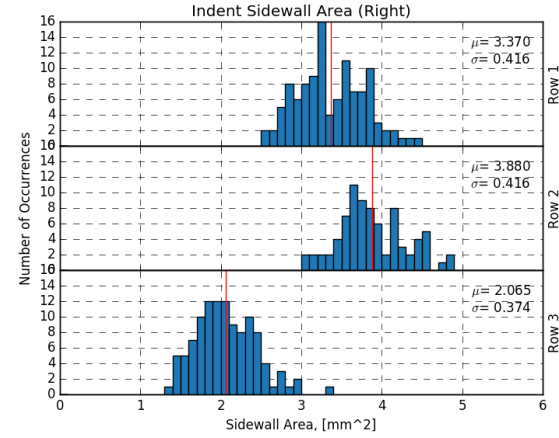
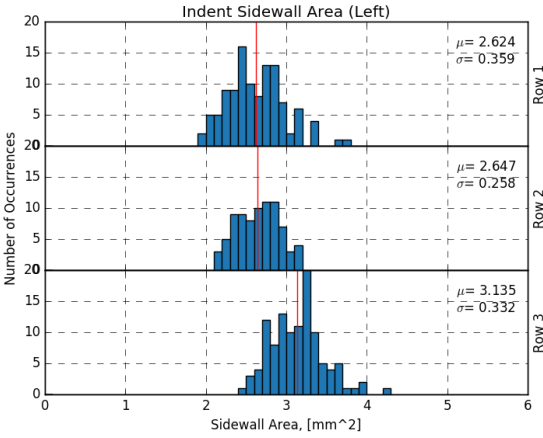
S.W. Area: The average sidewall area of the left and right side of the indents.
S.W. Angle: The average sidewall angle of the left and right side of the indents.



TEST REPORT: INDENT PROFILER

WIRE ID:WF

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TEST REPORT: ASTM A881

WIRE ID:WF

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SAMPLE ID		WB_630mm_Trued_10.26.18
SAMPLE LENGTH [MM]		630
NOMINAL DIAMETER [MM]		5.195
TEST ITEM	STANDARD VALUE	ACTUAL VALUE
INDENT DEPTH [MM]	0.115±0.035	0.163
SIDEWALL ANGLE [DEG]	In Contract	28.1
INDENT LENGTH [MM]	3.5±0.5	4.534
INDENT PITCH [MM]	5.46±0.29	5.60
ORIENTATION ANGLE [DEG]	≥45°	48.4
OUT OF ROUND [MM]	≤0.08	TBD

TEST REPORT: ISO 10138-2

WIRE ID:WF

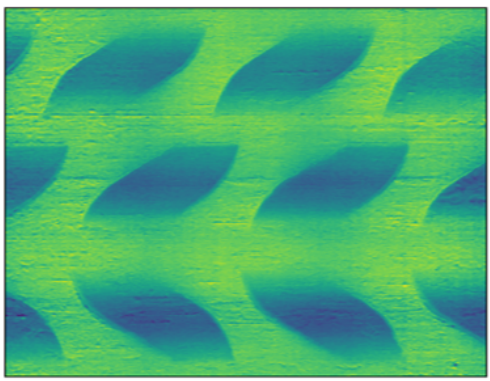
PAGE 4/4

SAMPLE ID		WB_630mm_Trued_10.26.18
SAMPLE LENGTH		630
NOMINAL DIAMETER		5.195
TEST ITEM	STANDARD VALUE	ACTUAL VALUE
INDENT LENGTH [MM]	3.5±0.5	4.534
INDENT DEPTH [MM]	0.15±0.05	0.163
INDENT SPACING [MM]	5.50±0.50	5.60
INDENT DISTANCE [MM]	$\Sigma e \leq 3.343$	2.13, 2.15, 2.15
AVG DIAMETER [MM]	-	TBD
OVALITY	$\leq 0.01 \times D$	TBD

TEST REPORT: INDENT PROFILER

WIRE ID:WG

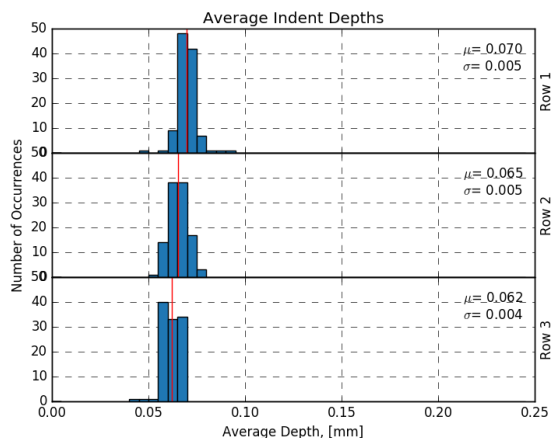
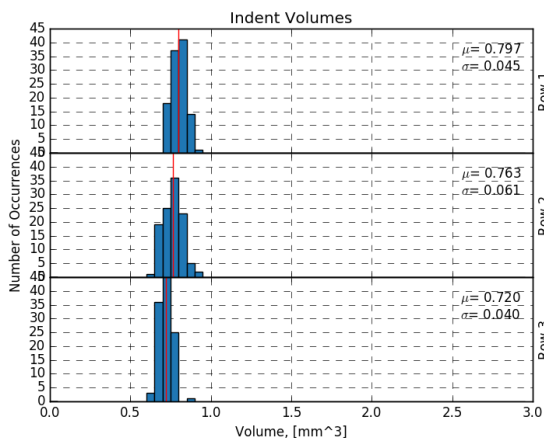
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Scan Information					
Wire ID	WG_630mm_Trued_11.05.18				
Length [mm]	630				
Scan Date	11.05.18				
Proc Date	09.17.19				
Stat Date	09.17.19				
ID	Indents	Nominal Dia [mm]	Orientat- ion [deg]	Distance [mm]	
Total	332	5.324	56.1	3.047	
Row 1	111		-57.9	3.031	
Row 2	111		56.0	3.054	
Row 3	110		54.3	3.054	

Indent Data								
ID	Indents	Volume [mm^3]	S.W. Area [mm^2]	Avg Depth [mm]	S.W. Angle [deg]	Avg Length [mm]	Width [mm]	Pitch [mm]
Total	332	0.760	2.317	0.066	10.56	3.885	3.502	5.644
Row 1	111	0.797	2.405	0.070	9.95	3.855	3.512	5.644
Row 2	111	0.763	2.308	0.065	10.66	3.895	3.527	5.644
Row 3	110	0.720	2.236	0.062	11.07	3.906	3.467	5.645

S.W. Area: The average sidewall area of the left and right side of the indents.

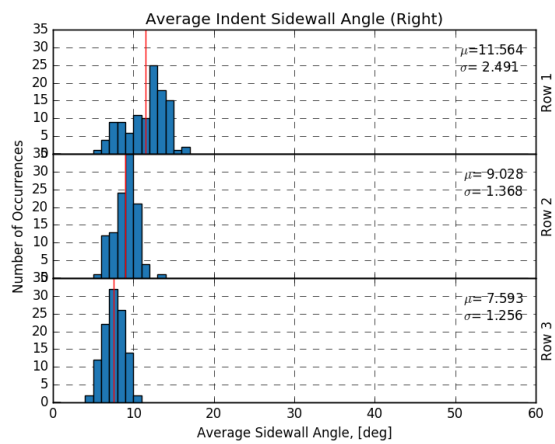
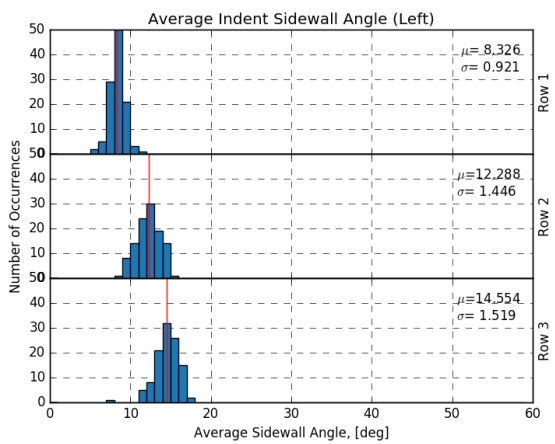
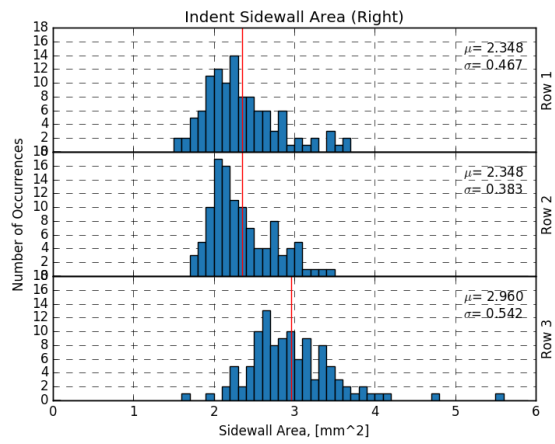
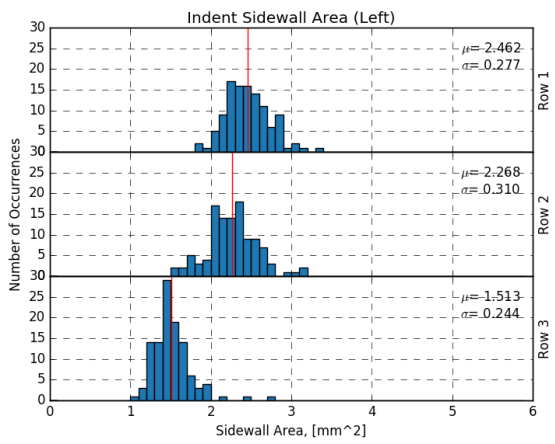
S.W. Angle: The average sidewall angle of the left and right side of the indents.



TEST REPORT: INDENT PROFILER

WIRE ID:WG

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TEST REPORT: ASTM A881

WIRE ID:WG

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SAMPLE ID		WG_630mm_Trued_11.05.18
SAMPLE LENGTH [MM]		630
NOMINAL DIAMETER [MM]		5.324
TEST ITEM	STANDARD VALUE	ACTUAL VALUE
INDENT DEPTH [MM]	0.115±0.035	0.066
SIDEWALL ANGLE [DEG]	In Contract	10.6
INDENT LENGTH [MM]	3.5±0.5	3.888
INDENT PITCH [MM]	5.46±0.29	5.64
ORIENTATION ANGLE [DEG]	≥45°	56.1
OUT OF ROUND [MM]	≤0.08	TBD

TEST REPORT: ISO 10138-2

WIRE ID:WG

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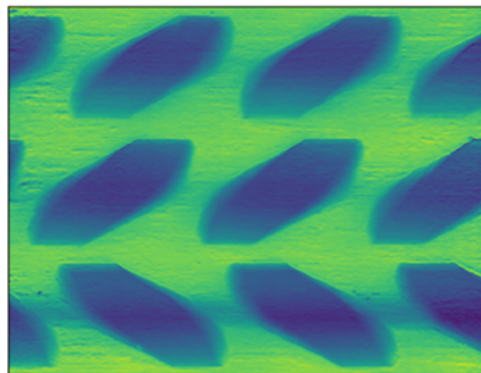
SAMPLE ID		WG_630mm_True_d_11.05.18
SAMPLE LENGTH		630
NOMINAL DIAMETER		5.324
TEST ITEM	STANDARD VALUE	ACTUAL VALUE
INDENT LENGTH [MM]	3.5±0.5	3.888
INDENT DEPTH [MM]	0.15±0.05	0.066
INDENT SPACING [MM]	5.50±0.50	5.64
INDENT DISTANCE [MM]	$\Sigma e \leq 3.343$	3.03, 3.05, 3.05
AVG DIAMETER [MM]	-	TBD
OVALITY	$\leq 0.01 \times D$	TBD

TEST REPORT: INDENT PROFILER

WIRE ID:WH

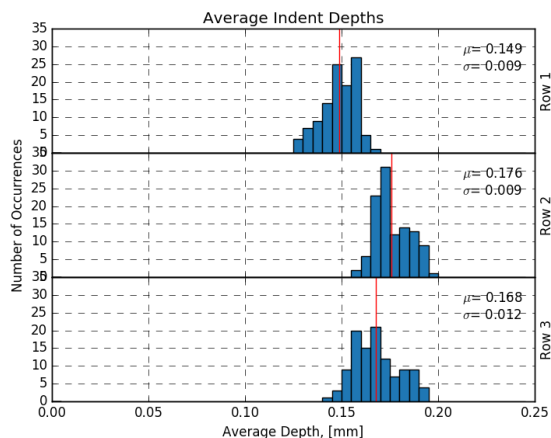
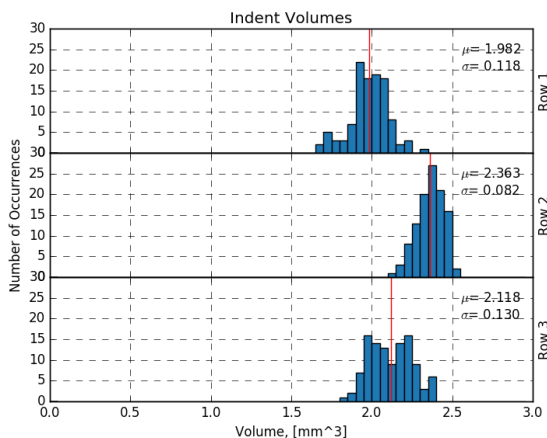
PAGE 1/4

Scan Information				
Wire ID	WH_630mm_Trued_10.26.18			
Length [mm]	630			
Scan Date	10.26.18			
Proc Date	09.17.19			
Stat Date	09.17.19			
ID	Indents	Nominal Dia [mm]	Orientat- ion [deg]	Distance [mm]
Total	332	5.107	51.0	1.873
Row 1	111		-50.6	1.765
Row 2	111		50.9	1.927
Row 3	110		51.4	1.927



Indent Data								
ID	Indents	Volume [mm^3]	S.W. Area [mm^2]	Avg Depth [mm]	S.W. Angle [deg]	Avg Length [mm]	Width [mm]	Pitch [mm]
Total	332	2.154	3.961	0.164	17.17	3.676	4.383	5.599
Row 1	111	1.982	3.852	0.149	14.33	3.639	4.523	5.599
Row 2	111	2.363	4.062	0.176	19.42	3.676	4.426	5.598
Row 3	110	2.118	3.970	0.168	17.75	3.713	4.198	5.599

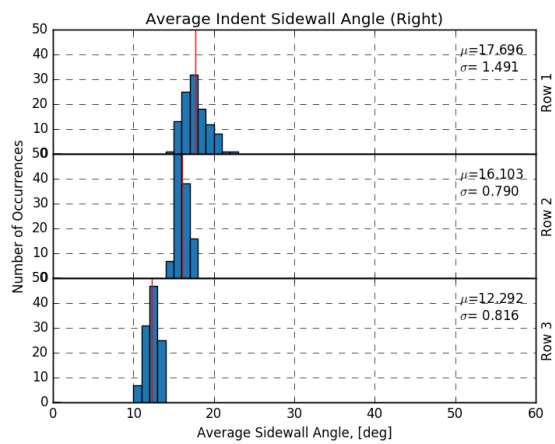
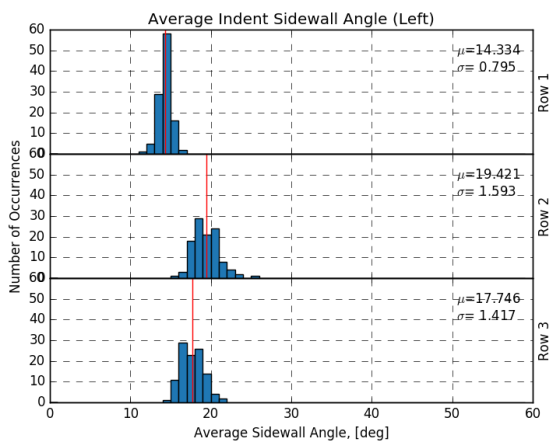
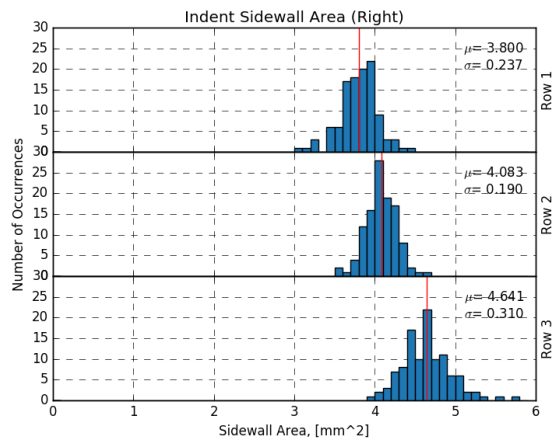
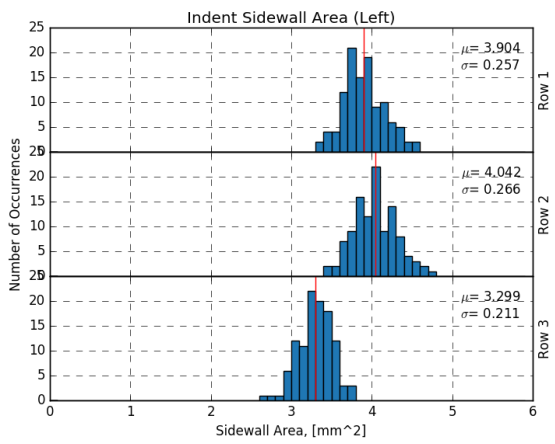
S.W. Area: The average sidewall area of the left and right side of the indents.
S.W. Angle: The average sidewall angle of the left and right side of the indents.



TEST REPORT: INDENT PROFILER

WIRE ID:WH

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TEST REPORT: ASTM A881

WIRE ID:WH

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SAMPLE ID		WH_630mm_Trued_10.26.18
SAMPLE LENGTH [MM]		630
NOMINAL DIAMETER [MM]		5.107
TEST ITEM	STANDARD VALUE	ACTUAL VALUE
INDENT DEPTH [MM]	0.115±0.035	0.164
SIDEWALL ANGLE [DEG]	In Contract	17.2
INDENT LENGTH [MM]	3.5±0.5	4.610
INDENT PITCH [MM]	5.46±0.29	5.60
ORIENTATION ANGLE [DEG]	≥45°	51.0
OUT OF ROUND [MM]	≤0.08	TBD

TEST REPORT: ISO 10138-2

WIRE ID:WH

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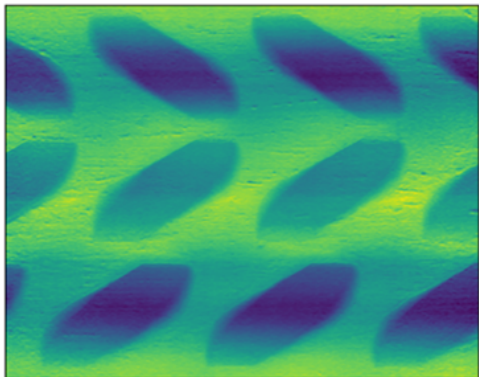
SAMPLE ID		WH_630mm_Trued_10.26.18
SAMPLE LENGTH		630
NOMINAL DIAMETER		5.107
TEST ITEM	STANDARD VALUE	ACTUAL VALUE
INDENT LENGTH [MM]	3.5±0.5	4.610
INDENT DEPTH [MM]	0.15±0.05	0.164
INDENT SPACING [MM]	5.50±0.50	5.60
INDENT DISTANCE [MM]	$\Sigma e \leq 3.343$	1.77, 1.93, 1.93
AVG DIAMETER [MM]	-	TBD
OVALITY	$\leq 0.01 \times D$	TBD

TEST REPORT: INDENT PROFILER

WIRE ID:WI

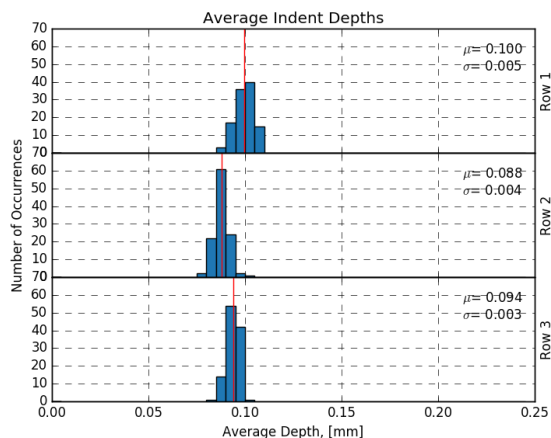
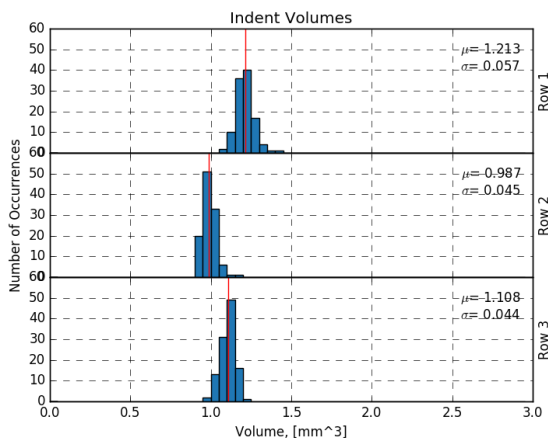
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Scan Information					
Wire ID	WI_630mm_TrueD_10.26.18				
Length [mm]	630				
Scan Date	10.26.18				
Proc Date	09.17.19				
Stat Date	09.17.19				
ID	Indents	Nominal Dia [mm]	Orientat-ion [deg]	Distance [mm]	
Total	335	5.208	50.1	2.445	
Row 1	111		51.0	2.350	
Row 2	112		50.1	2.493	
Row 3	112		-49.3	2.493	



Indent Data								
ID	Indents	Volume [mm^3]	S.W. Area [mm^2]	Avg Depth [mm]	S.W. Angle [deg]	Avg Length [mm]	Width [mm]	Pitch [mm]
Total	335	1.102	2.850	0.094	11.02	3.436	3.999	5.593
Row 1	111	1.213	3.101	0.100	11.16	3.410	4.258	5.604
Row 2	112	0.987	2.642	0.088	10.90	3.458	3.768	5.587
Row 3	112	1.108	2.808	0.094	11.01	3.441	3.972	5.588

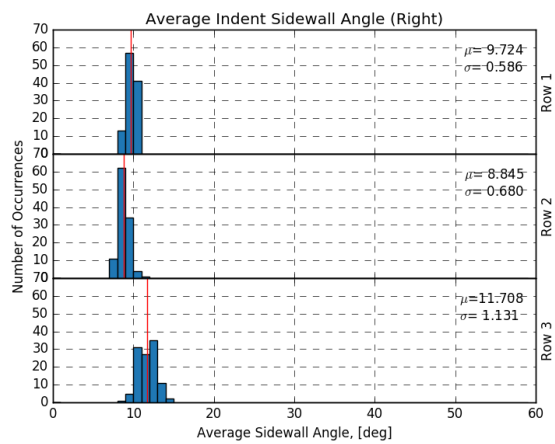
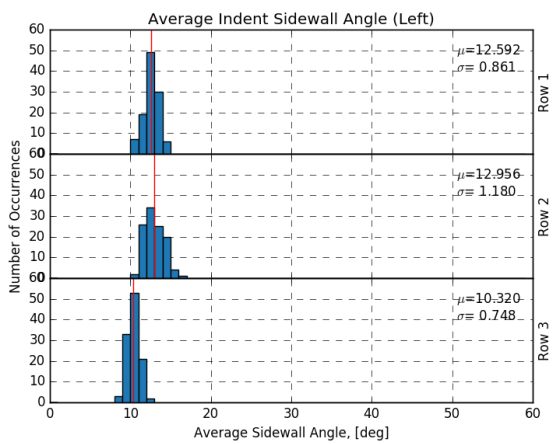
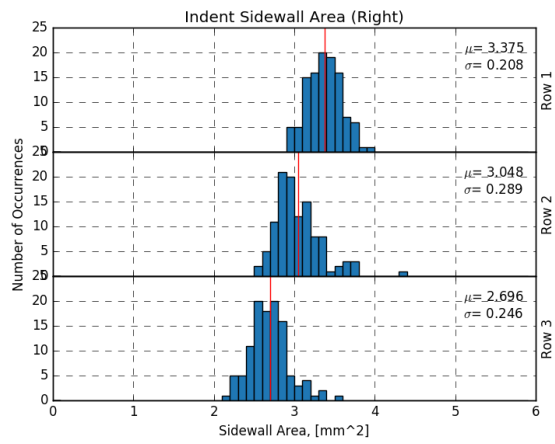
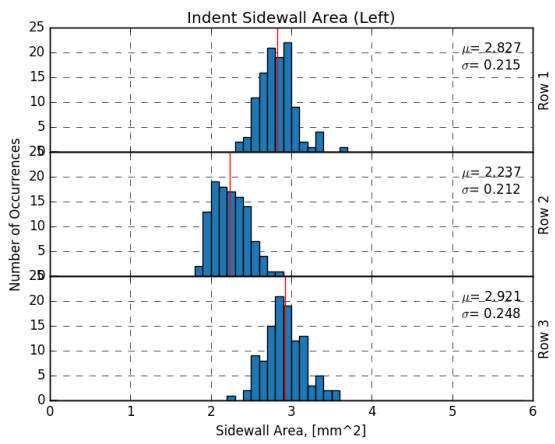
S.W. Area: The average sidewall area of the left and right side of the indents.
S.W. Angle: The average sidewall angle of the left and right side of the indents.



TEST REPORT: INDENT PROFILER

WIRE ID:WI

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TEST REPORT: ASTM A881

WIRE ID:WI

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SAMPLE ID		WI_630mm_Trued_10.26.18
SAMPLE LENGTH [MM]		630
NOMINAL DIAMETER [MM]		5.208
TEST ITEM	STANDARD VALUE	ACTUAL VALUE
INDENT DEPTH [MM]	0.115±0.035	0.094
SIDEWALL ANGLE [DEG]	In Contract	11.0
INDENT LENGTH [MM]	3.5±0.5	4.197
INDENT PITCH [MM]	5.46±0.29	5.59
ORIENTATION ANGLE [DEG]	≥45°	50.1
OUT OF ROUND [MM]	≤0.08	TBD

TEST REPORT: ISO 10138-2

WIRE ID:WI

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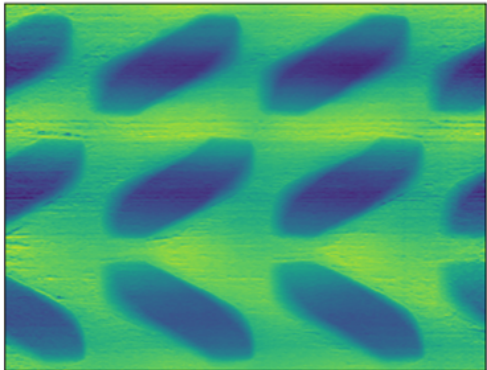
SAMPLE ID		WI_630mm_True_d_10.26.18
SAMPLE LENGTH		630
NOMINAL DIAMETER		5.208
TEST ITEM	STANDARD VALUE	ACTUAL VALUE
INDENT LENGTH [MM]	3.5±0.5	4.197
INDENT DEPTH [MM]	0.15±0.05	0.094
INDENT SPACING [MM]	5.50±0.50	5.59
INDENT DISTANCE [MM]	$\Sigma e \leq 3.343$	2.35, 2.49, 2.49
AVG DIAMETER [MM]	-	TBD
OVALITY	$\leq 0.01 \times D$	TBD

TEST REPORT: INDENT PROFILER

WIRE ID:WJ

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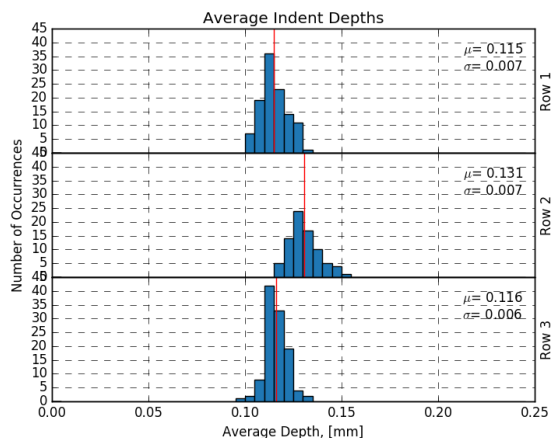
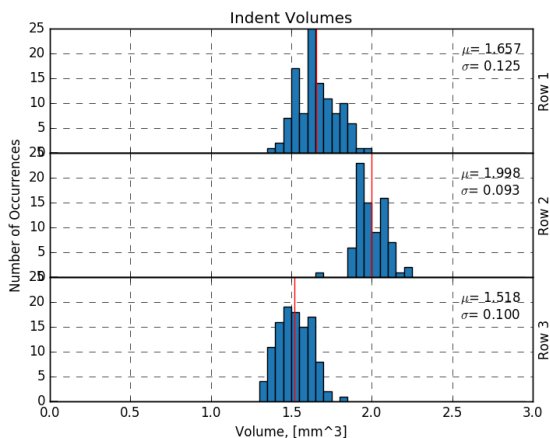
Scan Information				
Wire ID	WJ_630mm_TrueD_10.26.18			
Length [mm]	630			
Scan Date	10.26.18			
Proc Date	09.17.19			
Stat Date	09.17.19			
ID	Indents	Nominal Dia [mm]	Orientat-ion [deg]	Distance [mm]
Total	333	5.211	50.8	2.295
Row 1	111		-50.9	2.280
Row 2	111		51.0	2.302
Row 3	111		50.5	2.302



Indent Data								
ID	Indents	Volume [mm^3]	S.W. Area [mm^2]	Avg Depth [mm]	S.W. Angle [deg]	Avg Length [mm]	Width [mm]	Pitch [mm]
Total	333	1.428	3.638	0.123	11.52	3.411	4.134	5.609
Row 1	111	1.449	3.639	0.123	12.45	3.357	4.229	5.610
Row 2	111	1.337	3.425	0.116	10.69	3.478	3.990	5.608
Row 3	111	1.497	3.849	0.130	11.41	3.397	4.184	5.609

S.W. Area: The average sidewall area of the left and right side of the indents.

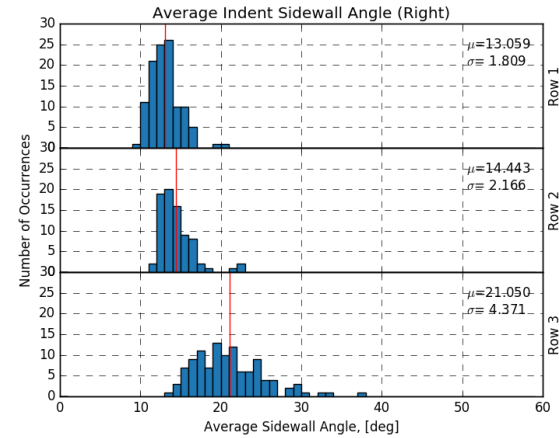
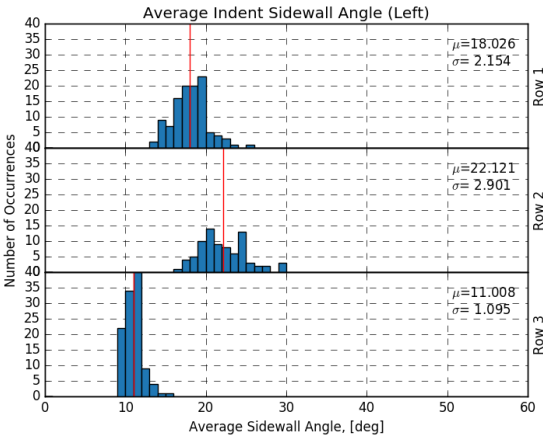
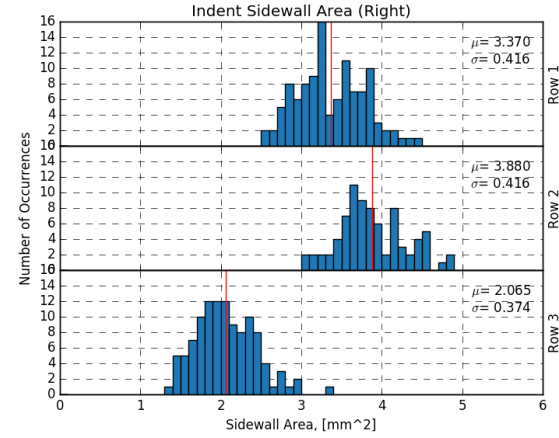
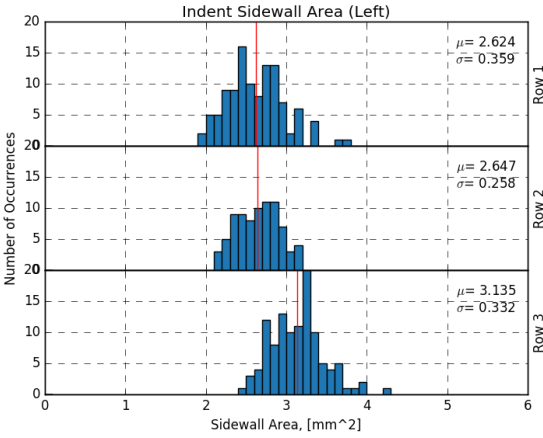
S.W. Angle: The average sidewall angle of the left and right side of the indents.



TEST REPORT: INDENT PROFILER

WIRE ID:WJ

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TEST REPORT: ASTM A881

WIRE ID:WJ

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SAMPLE ID		WJ_630mm_Trued_10.26.18
SAMPLE LENGTH [MM]		630
NOMINAL DIAMETER [MM]		5.211
TEST ITEM	STANDARD VALUE	ACTUAL VALUE
INDENT DEPTH [MM]	0.115±0.035	0.123
SIDEWALL ANGLE [DEG]	In Contract	11.5
INDENT LENGTH [MM]	3.5±0.5	4.453
INDENT PITCH [MM]	5.46±0.29	5.61
ORIENTATION ANGLE [DEG]	≥45°	50.8
OUT OF ROUND [MM]	≤0.08	TBD

TEST REPORT: ISO 10138-2

WIRE ID:WJ

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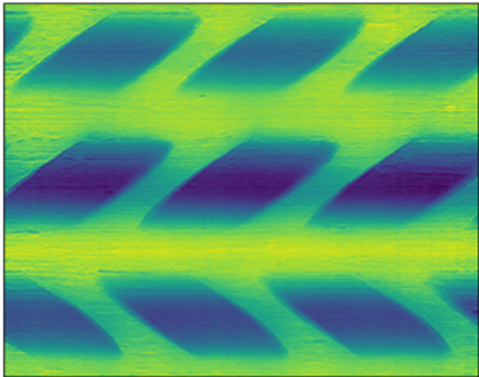
SAMPLE ID		WJ_630mm_True_d_10.26.18
SAMPLE LENGTH		630
NOMINAL DIAMETER		5.211
TEST ITEM	STANDARD VALUE	ACTUAL VALUE
INDENT LENGTH [MM]	3.5±0.5	4.453
INDENT DEPTH [MM]	0.15±0.05	0.123
INDENT SPACING [MM]	5.50±0.50	5.61
INDENT DISTANCE [MM]	$\Sigma e \leq 3.343$	2.28, 2.30, 2.30
AVG DIAMETER [MM]	-	TBD
OVALITY	$\leq 0.01 \times D$	TBD

TEST REPORT: INDENT PROFILER

WIRE ID:WM

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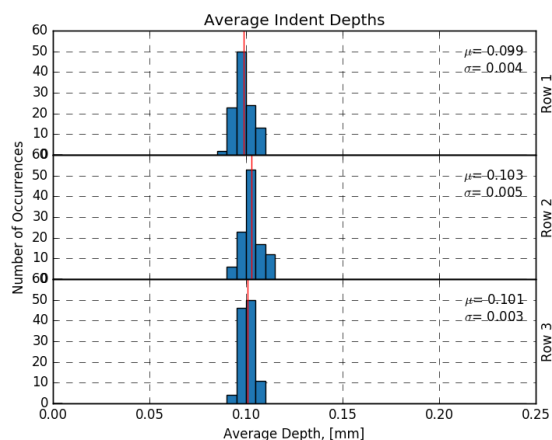
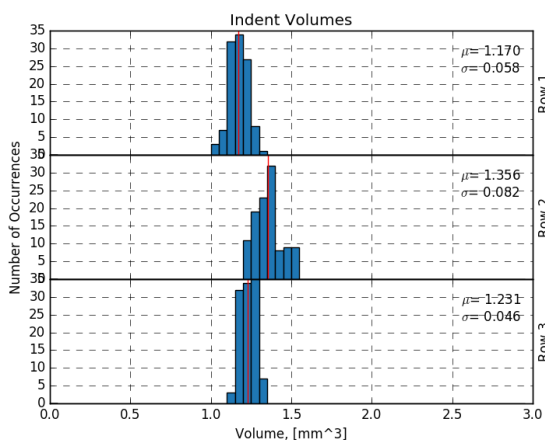
Scan Information					
Wire ID		WM_630mm_Trueid_10.26.18			
Length [mm]		630			
Scan Date		10.26.18			
Proc Date		09.17.19			
Stat Date		09.17.19			
ID	Indents	Nominal Dia [mm]	Orientat-ion [deg]	Distance [mm]	
Total	334	5.175	47.3	2.811	
Row 1	112		-47.6	2.811	
Row 2	111		46.4	2.811	
Row 3	111		48.0	2.811	



Indent Data								
ID	Indents	Volume [mm^3]	S.W. Area [mm^2]	Avg Depth [mm]	S.W. Angle [deg]	Avg Length [mm]	Width [mm]	Pitch [mm]
Total	334	1.252	2.062	0.101	16.41	4.085	3.411	5.564
Row 1	112	1.170	2.129	0.099	13.62	4.096	3.300	5.556
Row 2	111	1.356	2.185	0.103	17.19	4.099	3.631	5.566
Row 3	111	1.231	1.872	0.101	18.44	4.060	3.302	5.571

S.W. Area: The average sidewall area of the left and right side of the indents.

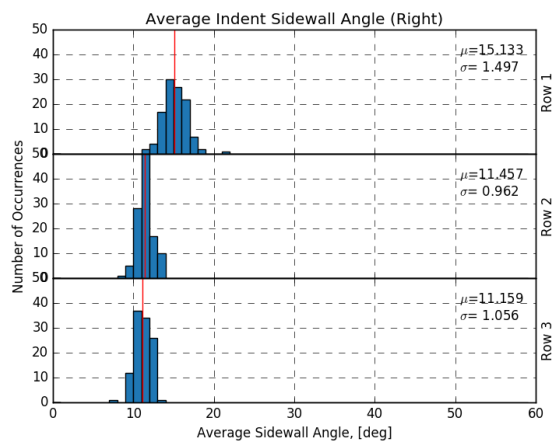
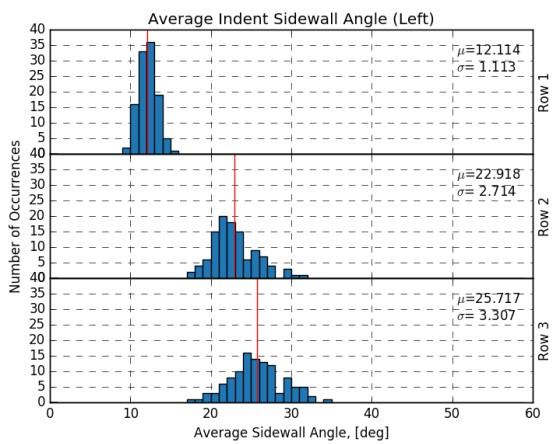
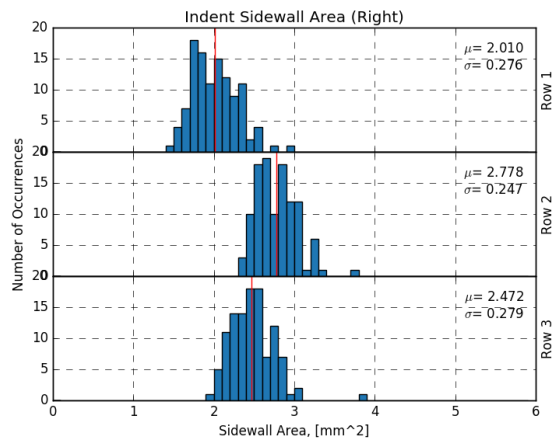
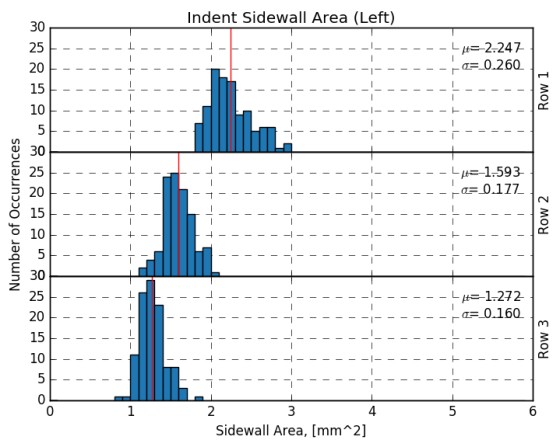
S.W. Angle: The average sidewall angle of the left and right side of the indents.



TEST REPORT: INDENT PROFILER

WIRE ID:WM

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TEST REPORT: ASTM A881

WIRE ID:WM

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SAMPLE ID		WM_630mm_Trued_10.26.18
SAMPLE LENGTH [MM]		630
NOMINAL DIAMETER [MM]		5.175
TEST ITEM	STANDARD VALUE	ACTUAL VALUE
INDENT DEPTH [MM]	0.115±0.035	0.101
SIDEWALL ANGLE [DEG]	In Contract	16.4
INDENT LENGTH [MM]	3.5±0.5	4.275
INDENT PITCH [MM]	5.46±0.29	5.56
ORIENTATION ANGLE [DEG]	≥45°	47.3
OUT OF ROUND [MM]	≤0.08	TBD

TEST REPORT: ISO 10138-2

WIRE ID:WM

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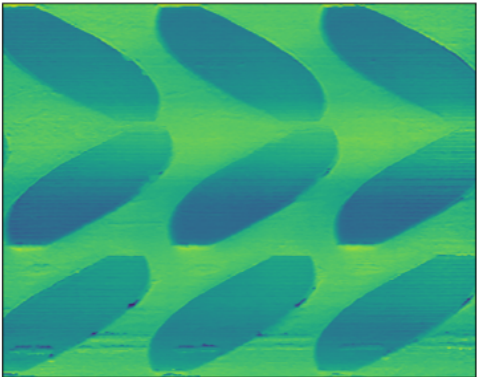
SAMPLE ID		WM_630mm_Trued_10.26.18
SAMPLE LENGTH		630
NOMINAL DIAMETER		5.175
TEST ITEM	STANDARD VALUE	ACTUAL VALUE
INDENT LENGTH [MM]	3.5±0.5	4.275
INDENT DEPTH [MM]	0.15±0.05	0.101
INDENT SPACING [MM]	5.50±0.50	5.56
INDENT DISTANCE [MM]	$\Sigma e \leq 3.343$	2.81, 2.81, 2.81
AVG DIAMETER [MM]	-	TBD
OVALITY	$\leq 0.01 \times D$	TBD

TEST REPORT: INDENT PROFILER

WIRE ID:WP

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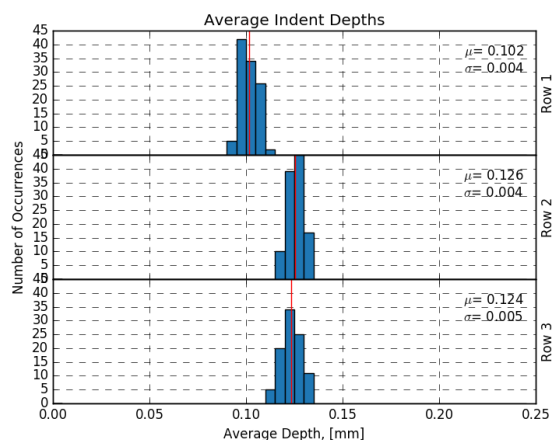
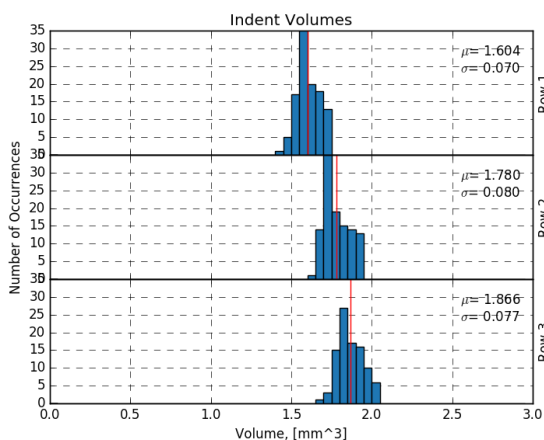
Scan Information				
Wire ID	WP_630mm_Trued_10.26.18			
Length [mm]	630			
Scan Date	10.26.18			
Proc Date	09.17.19			
Stat Date	09.17.19			
ID	Indents	Nominal Dia [mm]	Orientat-ion [deg]	Distance [mm]
Total	315	5.283	50.3	1.689
Row 1	109		52.5	1.599
Row 2	111		50.6	1.734
Row 3	95		-47.9	1.734



Indent Data								
ID	Indents	Volume [mm^3]	S.W. Area [mm^2]	Avg Depth [mm]	S.W. Angle [deg]	Avg Length [mm]	Width [mm]	Pitch [mm]
Total	315	1.745	1.803	0.117	29.00	3.444	4.817	5.581
Row 1	109	1.604	1.711	0.102	26.49	3.323	5.087	5.581
Row 2	111	1.780	1.797	0.126	27.22	3.497	4.576	5.581
Row 3	95	1.866	1.915	0.124	33.97	3.521	4.790	5.581

S.W. Area: The average sidewall area of the left and right side of the indents.

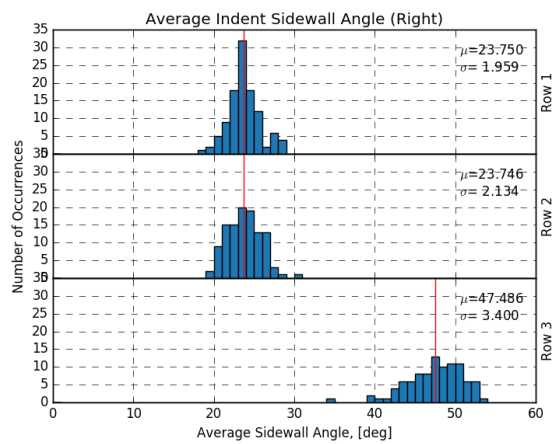
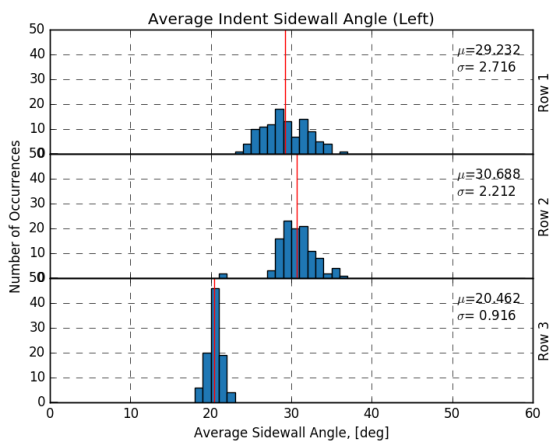
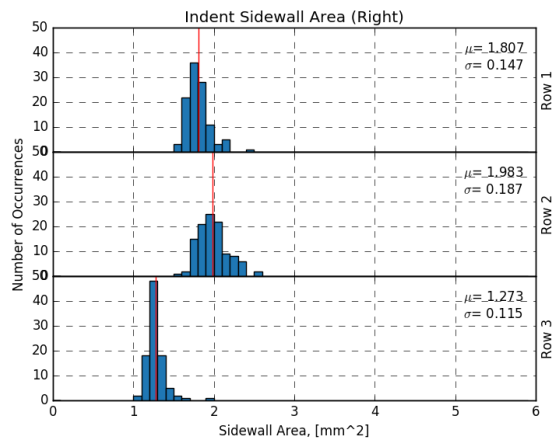
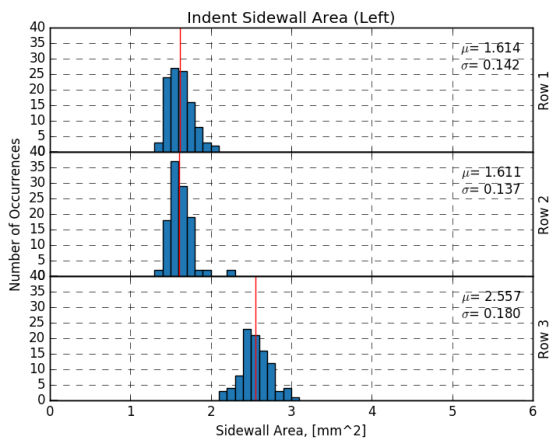
S.W. Angle: The average sidewall angle of the left and right side of the indents.



TEST REPORT: INDENT PROFILER

WIRE ID:WP

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TEST REPORT: ASTM A881

WIRE ID:WP

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SAMPLE ID		WP_630mm_Trued_10.26.18
SAMPLE LENGTH [MM]		630
NOMINAL DIAMETER [MM]		5.283
TEST ITEM	STANDARD VALUE	ACTUAL VALUE
INDENT DEPTH [MM]	0.115±0.035	0.117
SIDEWALL ANGLE [DEG]	In Contract	29.0
INDENT LENGTH [MM]	3.5±0.5	4.134
INDENT PITCH [MM]	5.46±0.29	5.58
ORIENTATION ANGLE [DEG]	≥45°	50.3
OUT OF ROUND [MM]	≤0.08	TBD

TEST REPORT: ISO 10138-2

WIRE ID:WP

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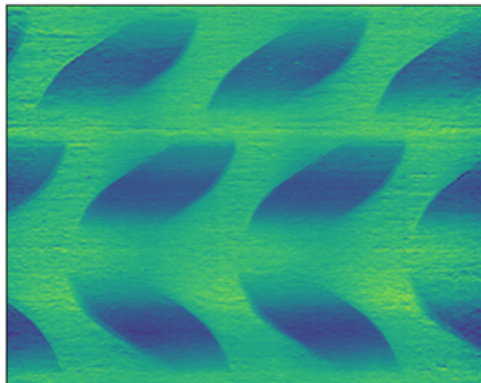
SAMPLE ID		WP_630mm_True_d_10.26.18
SAMPLE LENGTH		630
NOMINAL DIAMETER		5.283
TEST ITEM	STANDARD VALUE	ACTUAL VALUE
INDENT LENGTH [MM]	3.5±0.5	4.134
INDENT DEPTH [MM]	0.15±0.05	0.117
INDENT SPACING [MM]	5.50±0.50	5.58
INDENT DISTANCE [MM]	$\Sigma e \leq 3.343$	1.60, 1.77, 1.77
AVG DIAMETER [MM]	-	TBD
OVALITY	$\leq 0.01 \times D$	TBD

TEST REPORT: INDENT PROFILER

WIRE ID:WQ

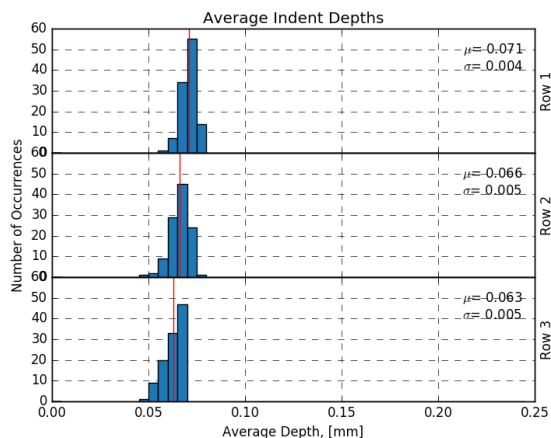
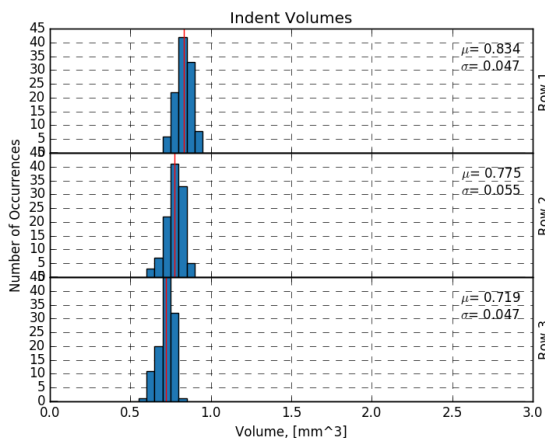
PAGE 1/4

Scan Information				
Wire ID	WQ_630mm_Trued_10.26.18			
Length [mm]	630			
Scan Date	10.26.18			
Proc Date	09.17.19			
Stat Date	09.17.19			
ID	Indents	Nominal Dia [mm]	Orientat-ion [deg]	Distance [mm]
Total	332	5.288	55.8	3.052
Row 1	111		-55.9	3.000
Row 2	111		58.6	3.078
Row 3	110		52.7	3.078



Indent Data								
ID	Indents	Volume [mm^3]	S.W. Area [mm^2]	Avg Depth [mm]	S.W. Angle [deg]	Avg Length [mm]	Width [mm]	Pitch [mm]
Total	332	0.776	2.149	0.067	11.58	3.878	3.482	5.645
Row 1	111	0.834	2.196	0.071	11.48	3.844	3.541	5.643
Row 2	111	0.775	2.180	0.066	11.36	3.907	3.518	5.645
Row 3	110	0.719	2.070	0.063	11.90	3.883	3.385	5.645

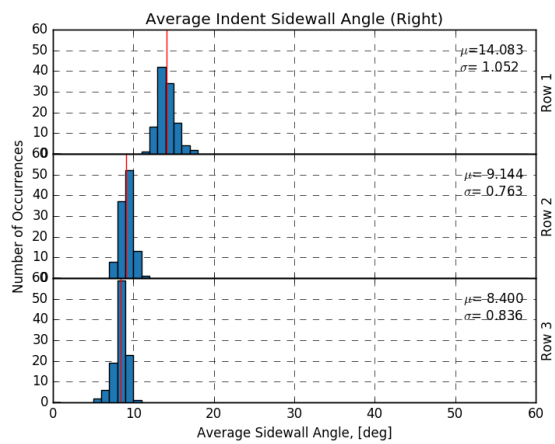
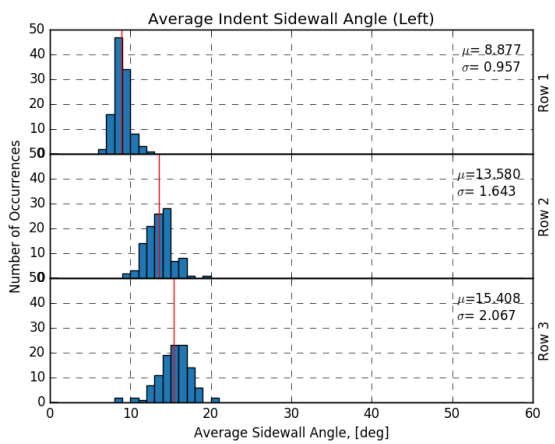
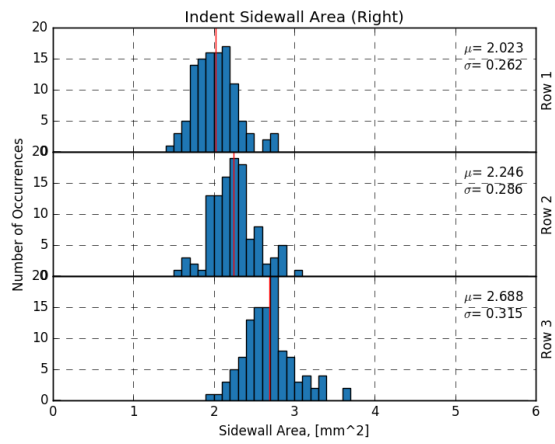
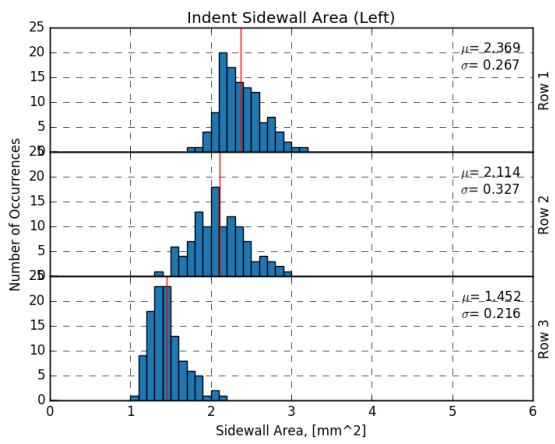
S.W. Area: The average sidewall area of the left and right side of the indents.
S.W. Angle: The average sidewall angle of the left and right side of the indents.



TEST REPORT: INDENT PROFILER

WIRE ID:WQ

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TEST REPORT: ASTM A881

WIRE ID:WQ

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SAMPLE ID		WQ_630mm_Trued_10.26.18
SAMPLE LENGTH [MM]		630
NOMINAL DIAMETER [MM]		5.288
TEST ITEM	STANDARD VALUE	ACTUAL VALUE
INDENT DEPTH [MM]	0.115±0.035	0.067
SIDEWALL ANGLE [DEG]	In Contract	11.6
INDENT LENGTH [MM]	3.5±0.5	3.907
INDENT PITCH [MM]	5.46±0.29	5.65
ORIENTATION ANGLE [DEG]	≥45°	55.8
OUT OF ROUND [MM]	≤0.08	TBD

TEST REPORT: ISO 10138-2

WIRE ID:WQ

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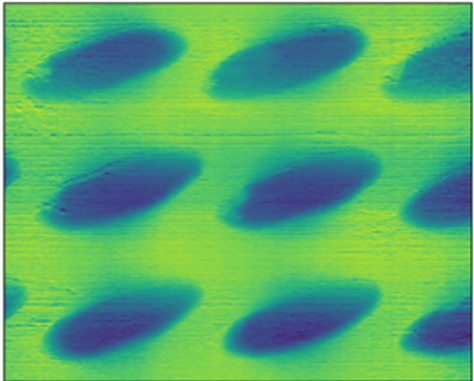
SAMPLE ID		WQ_630mm_True_d_10.26.18
SAMPLE LENGTH		630
NOMINAL DIAMETER		5.288
TEST ITEM	STANDARD VALUE	ACTUAL VALUE
INDENT LENGTH [MM]	3.5±0.5	3.907
INDENT DEPTH [MM]	0.15±0.05	0.067
INDENT SPACING [MM]	5.50±0.50	5.65
INDENT DISTANCE [MM]	$\Sigma e \leq 3.343$	3.00, 3.08, 3.08
AVG DIAMETER [MM]	-	TBD
OVALITY	$\leq 0.01 \times D$	TBD

TEST REPORT: INDENT PROFILER

WIRE ID:E-1

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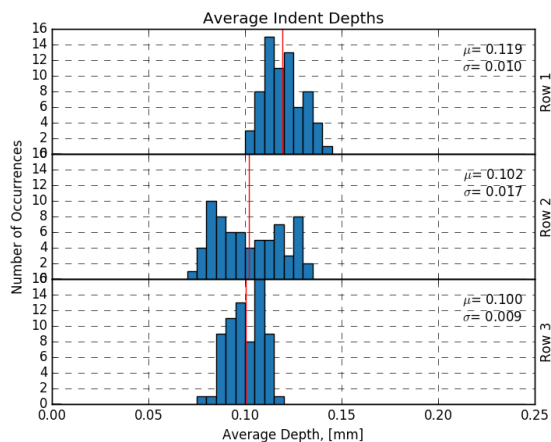
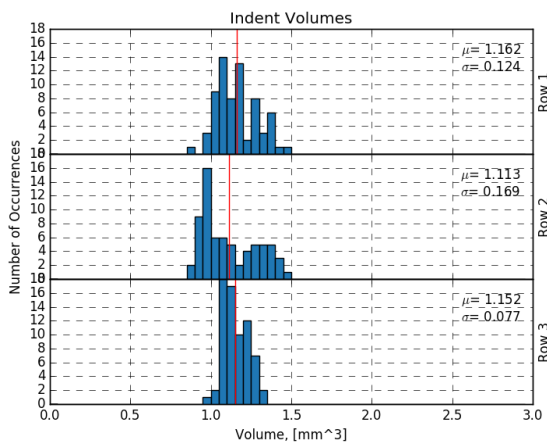
Scan Information					
Wire ID		E1_435mm_Trued_12.18.18			
Length [mm]		435			
Scan Date		12.18.18			
Proc Date		09.17.19			
Stat Date		09.17.19			
ID	Indents	Nominal Dia [mm]	Orientat-ion [deg]	Distance [mm]	
Total	207	5.216	49.1	3.646	
Row 1	69		49.7	3.764	
Row 2	69		51.6	3.587	
Row 3	69		46.2	3.587	



Indent Data								
ID	Indents	Volume [mm^3]	S.W. Area [mm^2]	Avg Depth [mm]	S.W. Angle [deg]	Avg Length [mm]	Width [mm]	Pitch [mm]
Total	207	1.142	3.408	0.107	9.46	4.133	3.240	6.129
Row 1	69	1.162	3.219	0.119	9.99	4.126	3.007	6.109
Row 2	69	1.113	3.375	0.102	9.02	4.079	3.349	6.162
Row 3	69	1.152	3.629	0.100	9.37	4.195	3.363	6.117

S.W. Area: The average sidewall area of the left and right side of the indents.

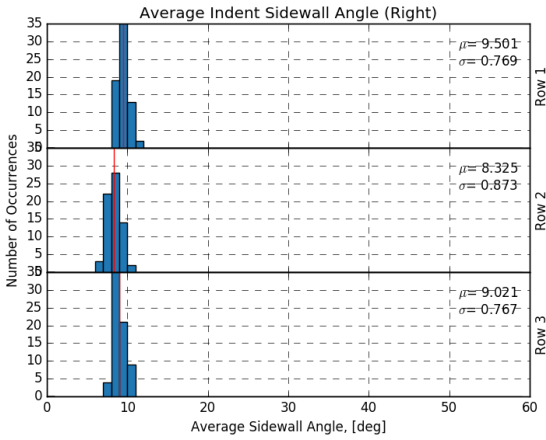
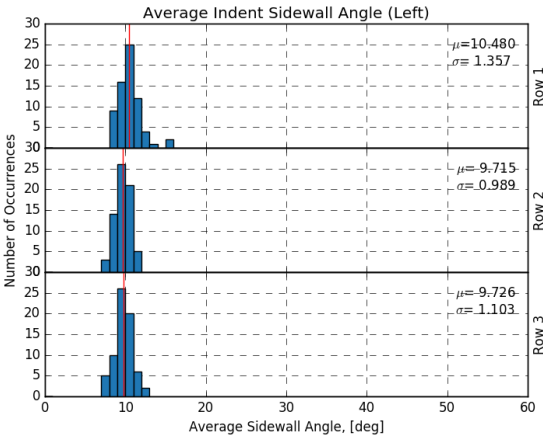
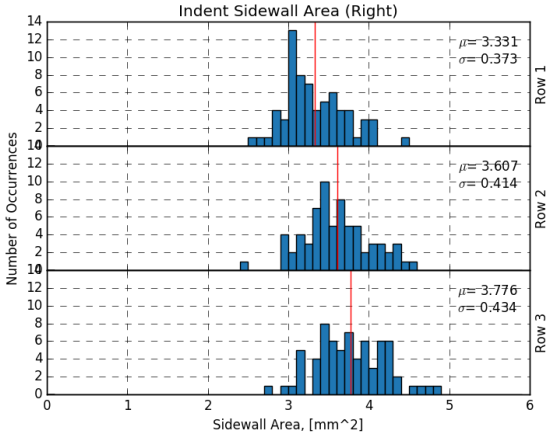
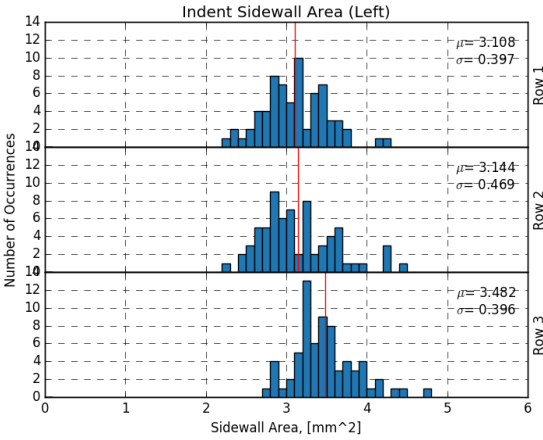
S.W. Angle: The average sidewall angle of the left and right side of the indents.



TEST REPORT: INDENT PROFILER

WIRE ID:E-1

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TEST REPORT: ASTM A881

WIRE ID:E-1

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SAMPLE ID		E1_435mm_Trued_12.18.18
SAMPLE LENGTH [MM]		435
NOMINAL DIAMETER [MM]		5.216
TEST ITEM	STANDARD VALUE	ACTUAL VALUE
INDENT DEPTH [MM]	0.115±0.035	0.107
SIDEWALL ANGLE [DEG]	In Contract	9.5
INDENT LENGTH [MM]	3.5±0.5	4.570
INDENT PITCH [MM]	5.46±0.29	6.13
ORIENTATION ANGLE [DEG]	≥45°	49.1
OUT OF ROUND [MM]	≤0.08	TBD

TEST REPORT: ISO 10138-2

WIRE ID:E-1

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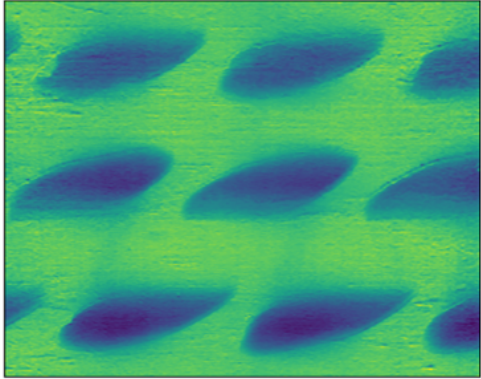
SAMPLE ID		E1_435mm_Trued_12.18.18
SAMPLE LENGTH		435
NOMINAL DIAMETER		5.216
TEST ITEM	STANDARD VALUE	ACTUAL VALUE
INDENT LENGTH [MM]	3.5±0.5	4.570
INDENT DEPTH [MM]	0.15±0.05	0.107
INDENT SPACING [MM]	5.50±0.50	6.13
INDENT DISTANCE [MM]	$\Sigma e \leq 3.343$	3.76, 3.59, 3.59
AVG DIAMETER [MM]	-	TBD
OVALITY	$\leq 0.01 \times D$	TBD

TEST REPORT: INDENT PROFILER

WIRE ID:H-1

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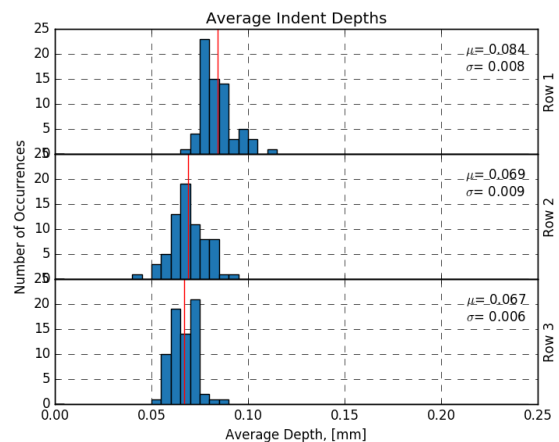
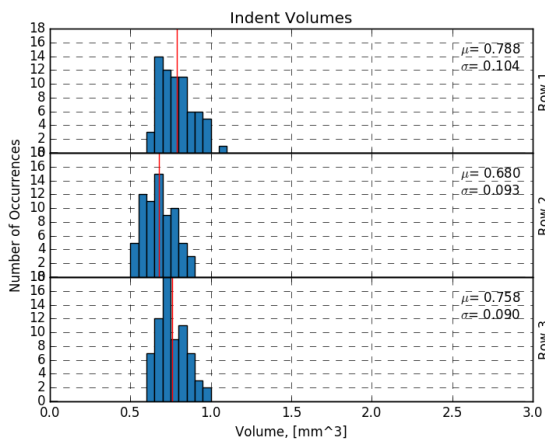
Scan Information				
Wire ID	H1_435mm_Trued_12.18.18			
Length [mm]	435			
Scan Date	12.18.18			
Proc Date	09.17.19			
Stat Date	09.17.19			
ID	Indents	Nominal Dia [mm]	Orientat- ion [deg]	Distance [mm]
Total	208	4.981	44.9	3.819
Row 1	69		46.1	3.941
Row 2	70		42.1	3.757
Row 3	69		46.5	3.757



Indent Data								
ID	Indents	Volume [mm^3]	S.W. Area [mm^2]	Avg Depth [mm]	S.W. Angle [deg]	Avg Length [mm]	Width [mm]	Pitch [mm]
Total	208	0.742	3.079	0.073	7.18	4.470	2.797	6.103
Row 1	69	0.788	2.847	0.084	8.17	4.411	2.651	6.100
Row 2	70	0.680	3.160	0.069	6.79	4.485	2.725	6.105
Row 3	69	0.758	3.228	0.067	6.60	4.514	3.017	6.104

S.W. Area: The average sidewall area of the left and right side of the indents.

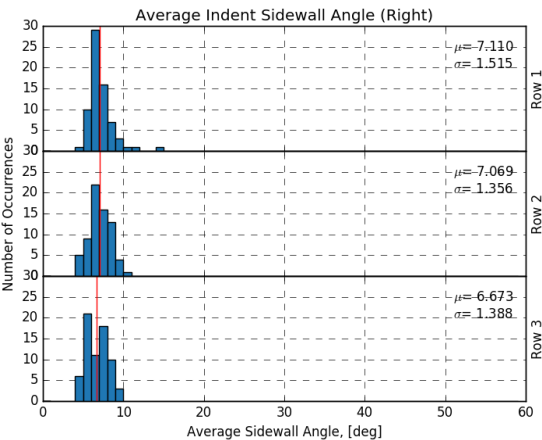
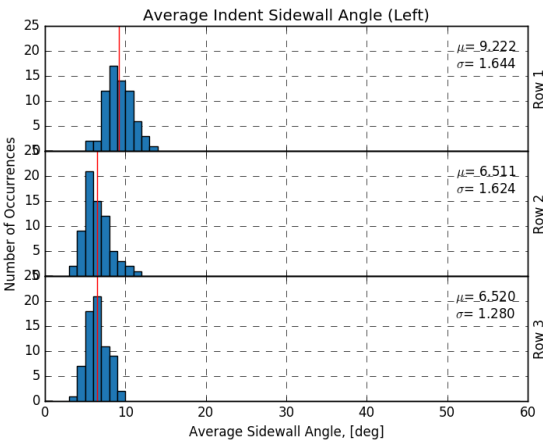
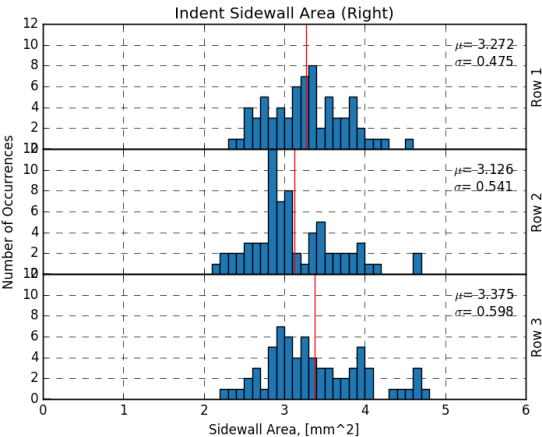
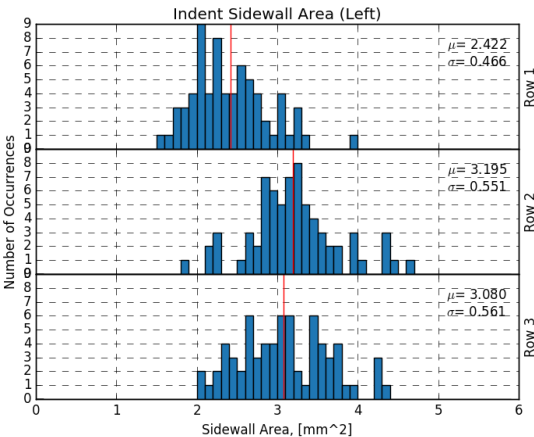
S.W. Angle: The average sidewall angle of the left and right side of the indents.



TEST REPORT: INDENT PROFILER

WIRE ID:H-1

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TEST REPORT: ASTM A881

WIRE ID:H-1

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SAMPLE ID		H1_435mm_Trued_12.18.18
SAMPLE LENGTH [MM]		435
NOMINAL DIAMETER [MM]		4.981
TEST ITEM	STANDARD VALUE	ACTUAL VALUE
INDENT DEPTH [MM]	0.115±0.035	0.073
SIDEWALL ANGLE [DEG]	In Contract	7.2
INDENT LENGTH [MM]	3.5±0.5	4.647
INDENT PITCH [MM]	5.46±0.29	6.10
ORIENTATION ANGLE [DEG]	≥45°	44.9
OUT OF ROUND [MM]	≤0.08	TBD

TEST REPORT: ISO 10138-2

WIRE ID:H-1

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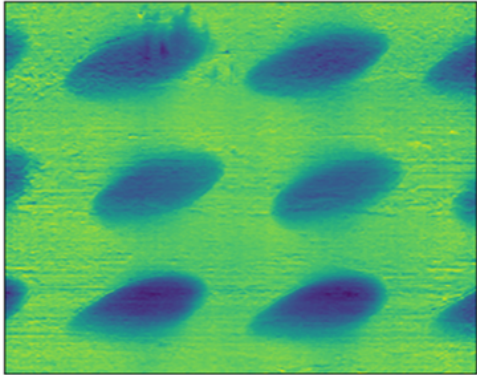
SAMPLE ID		H1_435mm_TrueD_12.18.18
SAMPLE LENGTH		435
NOMINAL DIAMETER		4.981
TEST ITEM	STANDARD VALUE	ACTUAL VALUE
INDENT LENGTH [MM]	3.5±0.5	4.647
INDENT DEPTH [MM]	0.15±0.05	0.073
INDENT SPACING [MM]	5.50±0.50	6.10
INDENT DISTANCE [MM]	$\Sigma e \leq 3.343$	3.94, 3.76, 3.76
AVG DIAMETER [MM]	-	TBD
OVALITY	$\leq 0.01 \times D$	TBD

TEST REPORT: INDENT PROFILER

WIRE ID: J-1

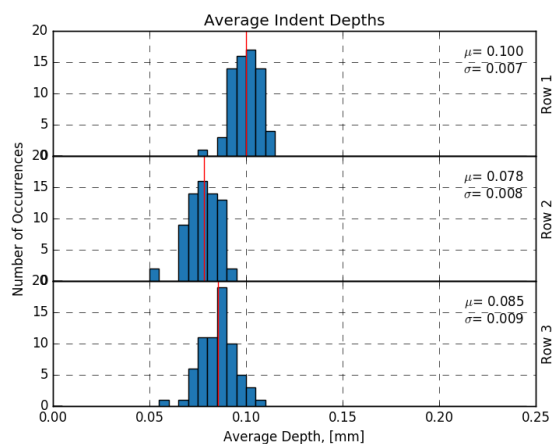
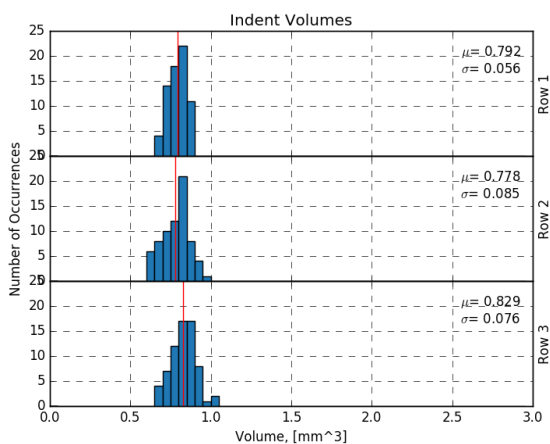
PAGE 1/4

Scan Information				
Wire ID	J1_435mm_Truead_12.18.18			
Length [mm]	435			
Scan Date	12.18.18			
Proc Date	09.17.19			
Stat Date	09.17.19			
ID	Indents	Nominal Dia [mm]	Orientat-ion [deg]	Distance [mm]
Total	207	4.960	55.9	3.519
Row 1	69		52.1	3.657
Row 2	70		58.9	3.450
Row 3	68		56.6	3.450



Indent Data								
ID	Indents	Volume [mm^3]	S.W. Area [mm^2]	Avg Depth [mm]	S.W. Angle [deg]	Avg Length [mm]	Width [mm]	Pitch [mm]
Total	207	0.800	3.032	0.088	7.26	3.969	2.984	6.101
Row 1	69	0.792	2.961	0.100	7.55	3.889	2.662	6.103
Row 2	70	0.778	3.181	0.078	6.54	3.968	3.225	6.102
Row 3	68	0.829	2.950	0.085	7.71	4.052	3.063	6.098

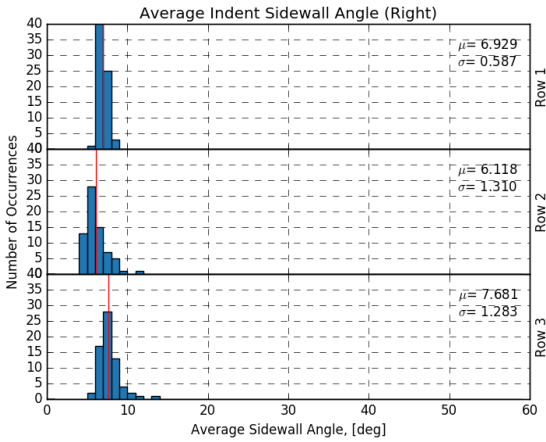
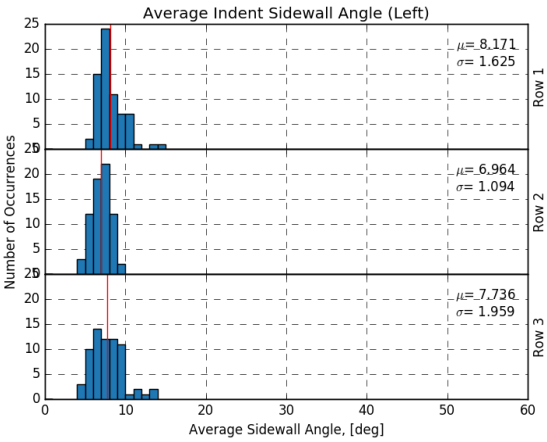
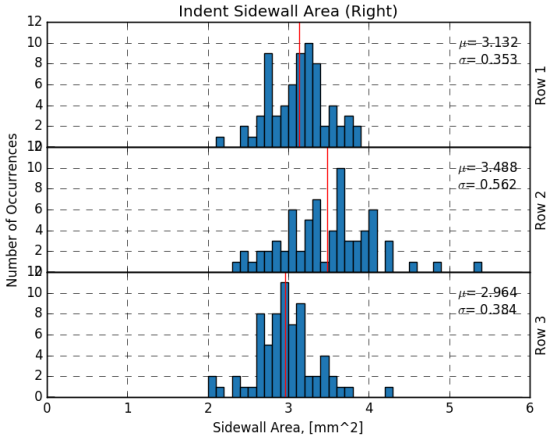
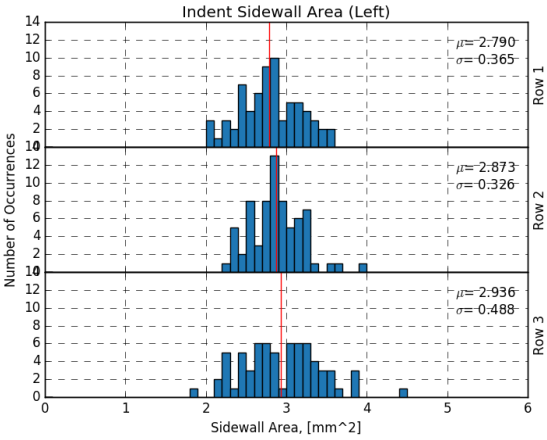
S.W. Area: The average sidewall area of the left and right side of the indents.
S.W. Angle: The average sidewall angle of the left and right side of the indents.



TEST REPORT: INDENT PROFILER

WIRE ID: J-1

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TEST REPORT: ASTM A881

WIRE ID: J-1

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SAMPLE ID		J1_435mm_Trued_12.18.18
SAMPLE LENGTH [MM]		435
NOMINAL DIAMETER [MM]		4.960
TEST ITEM	STANDARD VALUE	ACTUAL VALUE
INDENT DEPTH [MM]	0.115±0.035	0.088
SIDEWALL ANGLE [DEG]	In Contract	7.3
INDENT LENGTH [MM]	3.5±0.5	4.180
INDENT PITCH [MM]	5.46±0.29	6.10
ORIENTATION ANGLE [DEG]	≥45°	55.9
OUT OF ROUND [MM]	≤0.08	TBD

TEST REPORT: ISO 10138-2

WIRE ID: J-1

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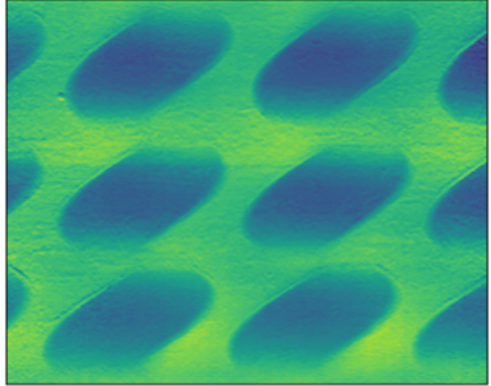
SAMPLE ID		J1_435mm_True_d_12.18.18
SAMPLE LENGTH		435
NOMINAL DIAMETER		4.960
TEST ITEM	STANDARD VALUE	ACTUAL VALUE
INDENT LENGTH [MM]	3.5±0.5	4.180
INDENT DEPTH [MM]	0.15±0.05	0.088
INDENT SPACING [MM]	5.50±0.50	6.10
INDENT DISTANCE [MM]	$\Sigma e \leq 3.343$	3.66, 3.45, 3.45
AVG DIAMETER [MM]	-	TBD
OVALITY	$\leq 0.01 \times D$	TBD

TEST REPORT: INDENT PROFILER

WIRE ID:K-1

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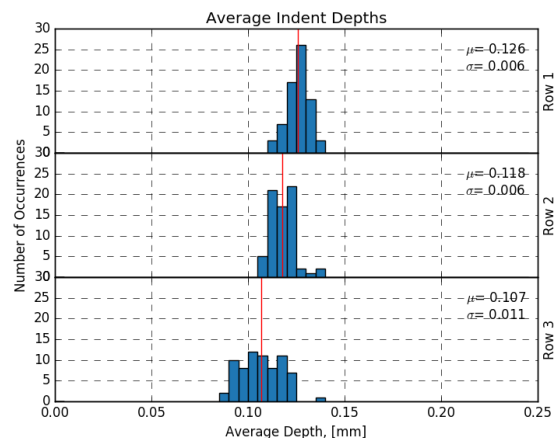
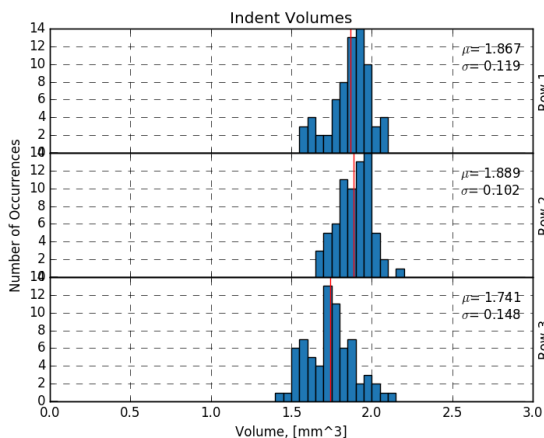
Scan Information					
Wire ID	K1_435mm_Trued_12.18.18				
Length [mm]	435				
Scan Date	12.18.18				
Proc Date	09.17.19				
Stat Date	09.17.19				
ID	Indents	Nominal Dia [mm]	Orientat-ion [deg]	Distance [mm]	
Total	209	5.124	60.1	2.789	
Row 1	69		61.7	2.878	
Row 2	70		57.3	2.744	
Row 3	70		61.3	2.744	



Indent Data								
ID	Indents	Volume [mm^3]	S.W. Area [mm^2]	Avg Depth [mm]	S.W. Angle [deg]	Avg Length [mm]	Width [mm]	Pitch [mm]
Total	209	1.832	2.443	0.117	15.79	4.391	4.001	6.136
Row 1	69	1.867	2.420	0.126	15.78	4.362	3.806	6.119
Row 2	70	1.889	2.330	0.118	16.96	4.290	4.120	6.119
Row 3	70	1.741	2.577	0.107	14.63	4.522	4.074	6.169

S.W. Area: The average sidewall area of the left and right side of the indents.

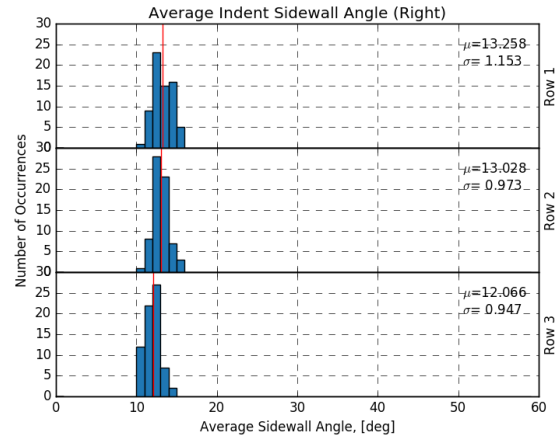
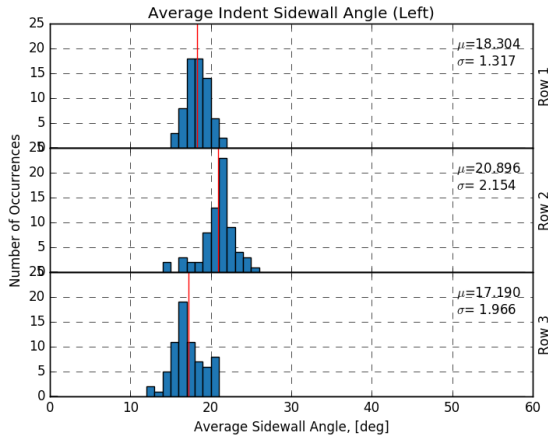
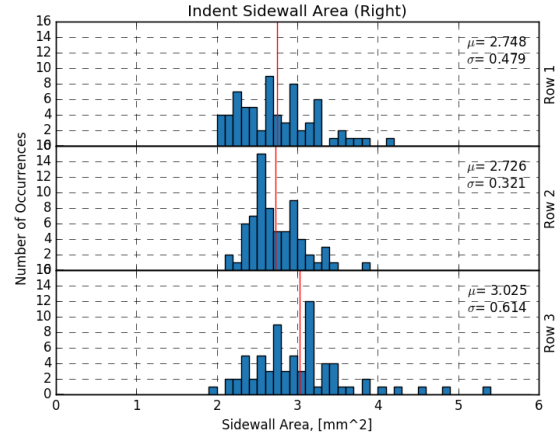
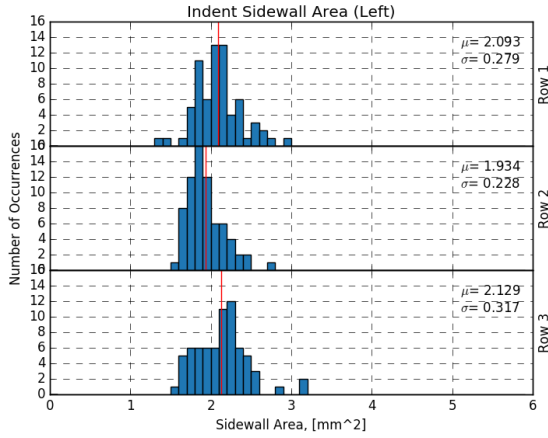
S.W. Angle: The average sidewall angle of the left and right side of the indents.



TEST REPORT: INDENT PROFILER

WIRE ID:K-1

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TEST REPORT: ASTM A881

WIRE ID:K-1

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SAMPLE ID		K1_435mm_Trued_12.18.18
SAMPLE LENGTH [MM]		435
NOMINAL DIAMETER [MM]		5.124
TEST ITEM	STANDARD VALUE	ACTUAL VALUE
INDENT DEPTH [MM]	0.115±0.035	0.117
SIDEWALL ANGLE [DEG]	In Contract	15.8
INDENT LENGTH [MM]	3.5±0.5	4.857
INDENT PITCH [MM]	5.46±0.29	6.14
ORIENTATION ANGLE [DEG]	≥45°	60.1
OUT OF ROUND [MM]	≤0.08	TBD

TEST REPORT: ISO 10138-2

WIRE ID:K-1

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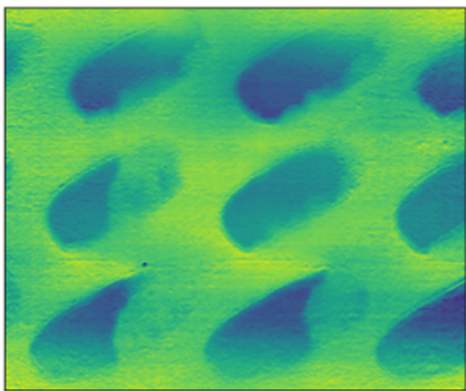
SAMPLE ID		K1_435mm_TrueD_12.18.18
SAMPLE LENGTH		435
NOMINAL DIAMETER		5.124
TEST ITEM	STANDARD VALUE	ACTUAL VALUE
INDENT LENGTH [MM]	3.5±0.5	4.857
INDENT DEPTH [MM]	0.15±0.05	0.117
INDENT SPACING [MM]	5.50±0.50	6.14
INDENT DISTANCE [MM]	$\Sigma e \leq 3.343$	2.88, 2.74, 2.74
AVG DIAMETER [MM]	-	TBD
OVALITY	$\leq 0.01 \times D$	TBD

TEST REPORT: INDENT PROFILER

WIRE ID:L-1

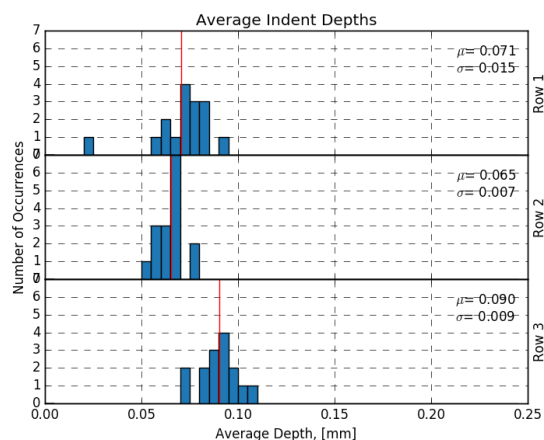
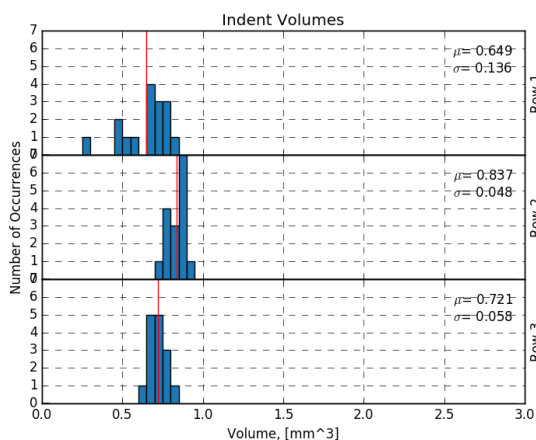
PAGE 1/4

Scan Information				
Wire ID	L1_435mm_Trueed_12.18.18			
Length [mm]	435			
Scan Date	12.18.18			
Proc Date	09.17.19			
Stat Date	09.17.19			
ID	Indents	Nominal Dia [mm]	Orientat-ion [deg]	Distance [mm]
Total	47	4.936	56.3	2.727
Row 1	16		64.5	2.422
Row 2	16		52.1	2.879
Row 3	15		52.4	2.879



Indent Data								
ID	Indents	Volume [mm^3]	S.W. Area [mm^2]	Avg Depth [mm]	S.W. Angle [deg]	Avg Length [mm]	Width [mm]	Pitch [mm]
Total	47	0.736	3.167	0.075	9.22	3.559	3.845	6.065
Row 1	16	0.649	2.285	0.071	10.70	3.300	4.037	6.082
Row 2	16	0.837	3.931	0.065	7.99	3.713	4.341	6.052
Row 3	15	0.721	3.294	0.090	8.96	3.672	3.110	6.061

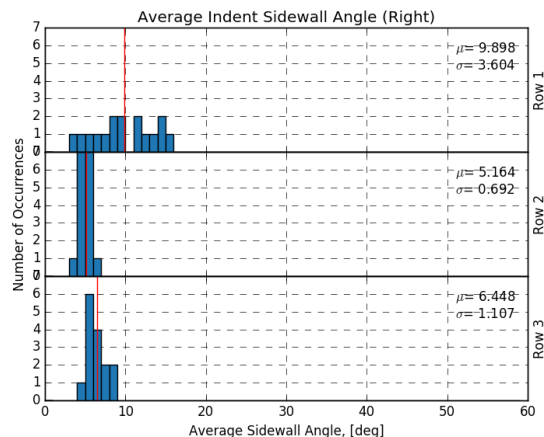
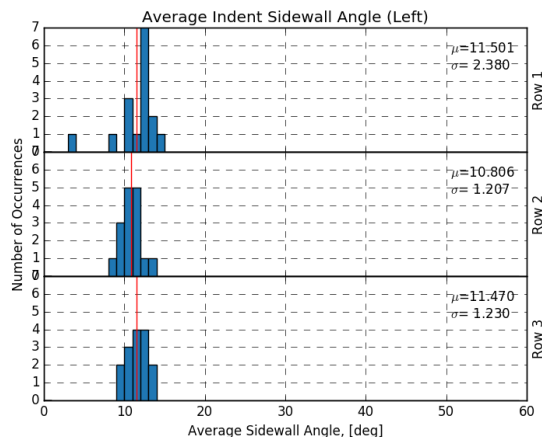
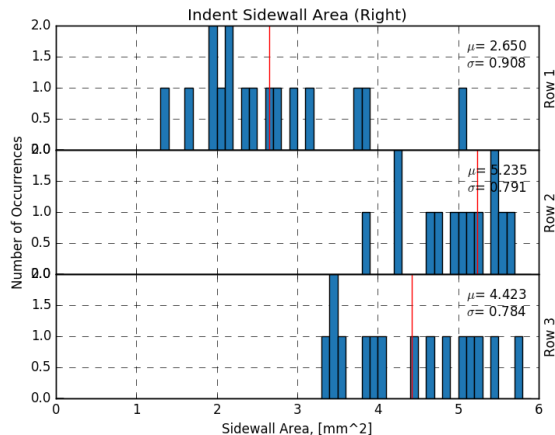
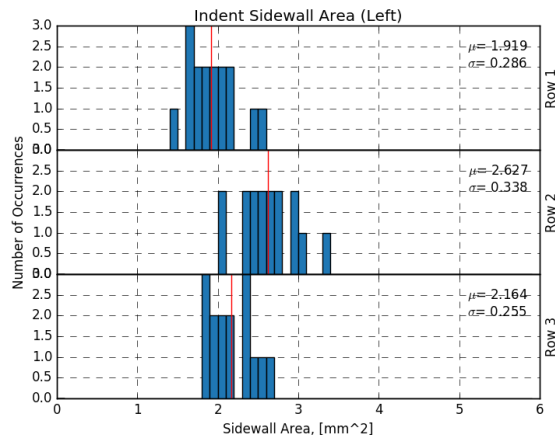
S.W. Area: The average sidewall area of the left and right side of the indents.
S.W. Angle: The average sidewall angle of the left and right side of the indents.



TEST REPORT: INDENT PROFILER

WIRE ID:L-1

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TEST REPORT: ASTM A881

WIRE ID:L-1

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SAMPLE ID		L1_435mm_Trued_12.18.18
SAMPLE LENGTH [MM]		435
NOMINAL DIAMETER [MM]		4.936
TEST ITEM	STANDARD VALUE	ACTUAL VALUE
INDENT DEPTH [MM]	0.115±0.035	0.075
SIDEWALL ANGLE [DEG]	In Contract	9.2
INDENT LENGTH [MM]	3.5±0.5	3.880
INDENT PITCH [MM]	5.46±0.29	6.07
ORIENTATION ANGLE [DEG]	≥45°	56.3
OUT OF ROUND [MM]	≤0.08	TBD

TEST REPORT: ISO 10138-2

WIRE ID:L-1

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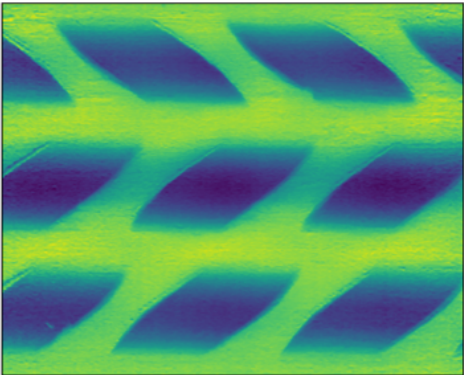
SAMPLE ID		L1_435mm_Trued_12.18.18
SAMPLE LENGTH		435
NOMINAL DIAMETER		4.936
TEST ITEM	STANDARD VALUE	ACTUAL VALUE
INDENT LENGTH [MM]	3.5±0.5	3.880
INDENT DEPTH [MM]	0.15±0.05	0.075
INDENT SPACING [MM]	5.50±0.50	6.07
INDENT DISTANCE [MM]	$\Sigma e \leq 3.343$	2.42, 2.88, 2.88
AVG DIAMETER [MM]	-	TBD
OVALITY	$\leq 0.01 \times D$	TBD

TEST REPORT: INDENT PROFILER

WIRE ID:M-1

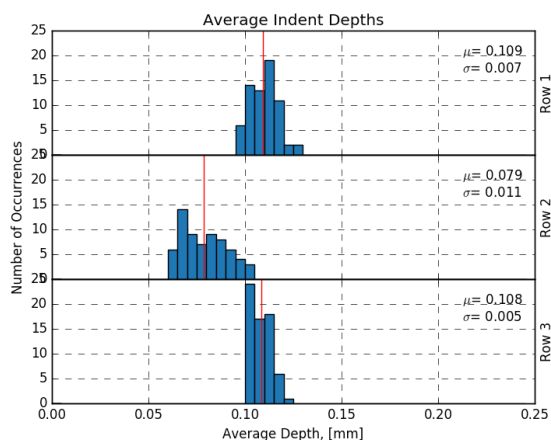
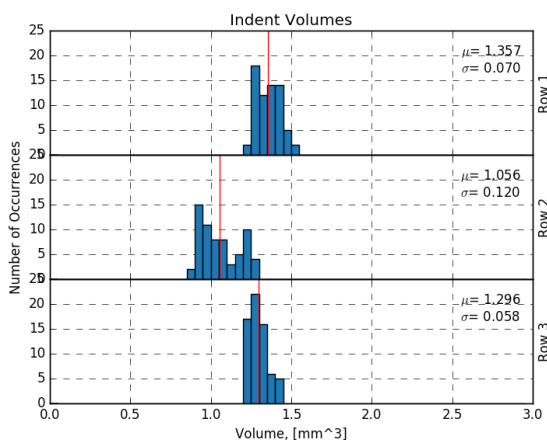
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Scan Information				
Wire ID	M1_435mm_TrueD_12.18.18			
Length [mm]	435			
Scan Date	12.18.18			
Proc Date	09.17.19			
Stat Date	09.17.19			
ID	Indents	Nominal Dia [mm]	Orientation [deg]	Distance [mm]
Total	199	4.954	47.2	3.062
Row 1	67		46.5	3.000
Row 2	66		51.6	3.092
Row 3	66		-43.4	3.092



Indent Data								
ID	Indents	Volume [mm ³]	S.W. Area [mm ²]	Avg Depth [mm]	S.W. Angle [deg]	Avg Length [mm]	Width [mm]	Pitch [mm]
Total	199	1.237	1.937	0.099	16.36	4.302	3.288	5.965
Row 1	67	1.357	1.808	0.109	17.34	4.282	3.211	5.949
Row 2	66	1.056	2.386	0.079	11.55	4.333	3.630	5.996
Row 3	66	1.296	1.617	0.108	20.18	4.292	3.023	5.952

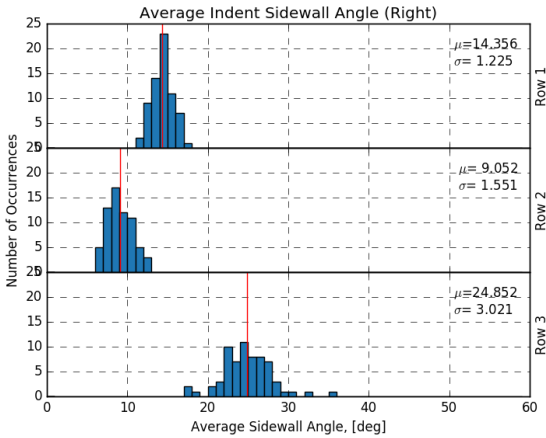
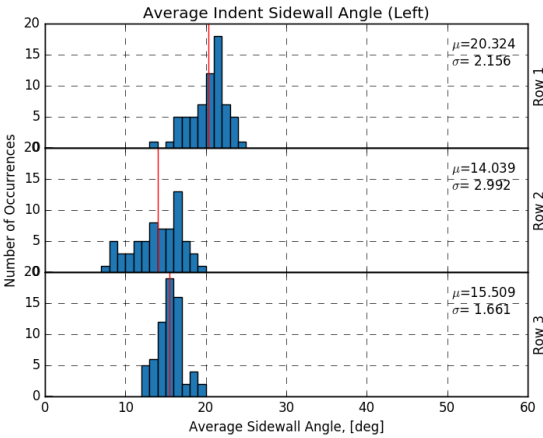
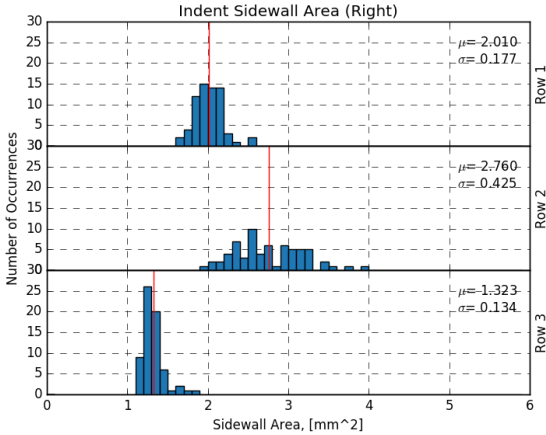
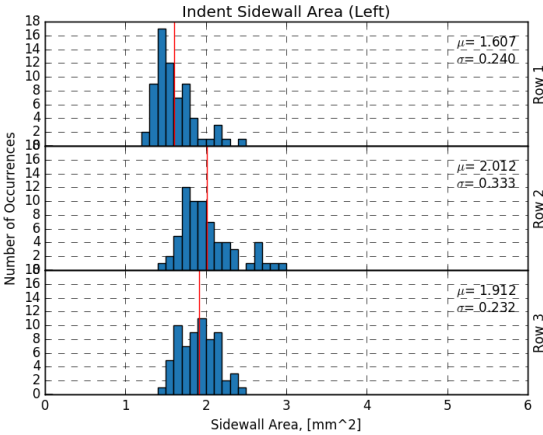
S.W. Area: The average sidewall area of the left and right side of the indents.
S.W. Angle: The average sidewall angle of the left and right side of the indents.



TEST REPORT: INDENT PROFILER

WIRE ID:M-1

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TEST REPORT: ASTM A881

WIRE ID:M-1

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SAMPLE ID		M1_435mm_Trued_12.18.18
SAMPLE LENGTH [MM]		435
NOMINAL DIAMETER [MM]		4.954
TEST ITEM	STANDARD VALUE	ACTUAL VALUE
INDENT DEPTH [MM]	0.115±0.035	0.099
SIDEWALL ANGLE [DEG]	In Contract	16.4
INDENT LENGTH [MM]	3.5±0.5	4.491
INDENT PITCH [MM]	5.46±0.29	5.97
ORIENTATION ANGLE [DEG]	≥45°	47.2
OUT OF ROUND [MM]	≤0.08	TBD

TEST REPORT: ISO 10138-2

WIRE ID:M-1

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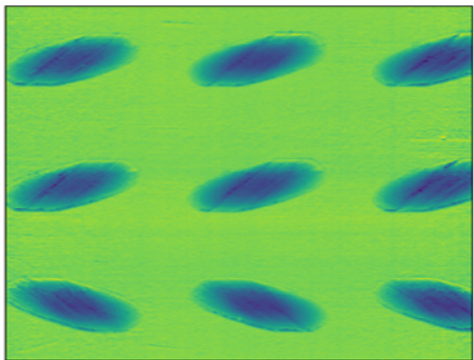
SAMPLE ID		M1_435mm_Trued_12.18.18
SAMPLE LENGTH		435
NOMINAL DIAMETER		4.954
TEST ITEM	STANDARD VALUE	ACTUAL VALUE
INDENT LENGTH [MM]	3.5±0.5	4.491
INDENT DEPTH [MM]	0.15±0.05	0.099
INDENT SPACING [MM]	5.50±0.50	5.97
INDENT DISTANCE [MM]	$\Sigma e \leq 3.343$	3.00, 3.09, 3.09
AVG DIAMETER [MM]	-	TBD
OVALITY	$\leq 0.01 \times D$	TBD

TEST REPORT: INDENT PROFILER

WIRE ID:15-S

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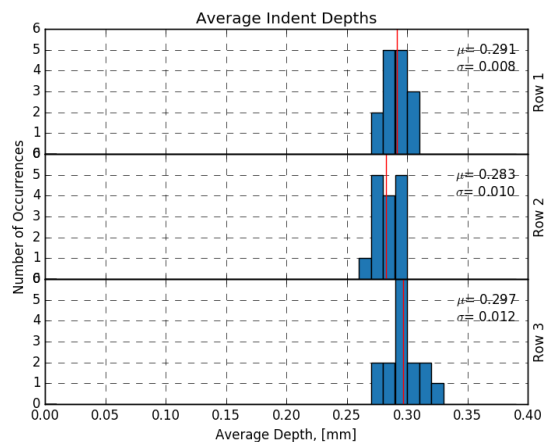
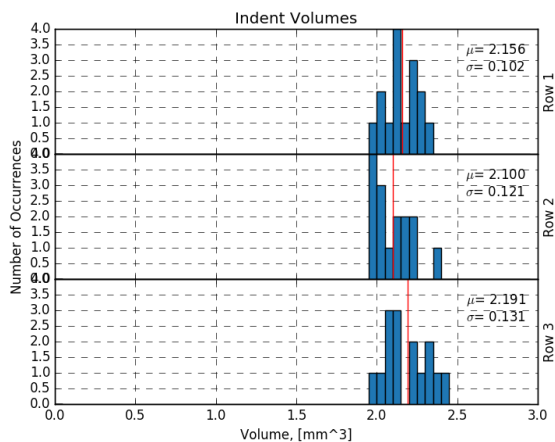
Scan Information				
Wire ID	15-16-T1_105mm_TrueD_11.15.18			
Length [mm]	105			
Scan Date	11.15.18			
Proc Date	09.17.19			
Stat Date	09.17.19			
ID	Indents	Nominal Dia [mm]	Orientat-ion [deg]	Distance [mm]
Total	45	5.176	46.8	4.550
Row 1	15		42.7	4.576
Row 2	15		44.9	4.537
Row 3	15		-52.7	4.537



Indent Data								
ID	Indents	Volume [mm^3]	S.W. Area [mm^2]	Avg Depth [mm]	S.W. Angle [deg]	Avg Length [mm]	Width [mm]	Pitch [mm]
Total	45	2.149	5.046	0.290	13.18	4.190	2.604	6.344
Row 1	15	2.156	5.293	0.291	13.32	4.210	2.572	6.329
Row 2	15	2.100	5.159	0.283	12.63	4.207	2.595	6.336
Row 3	15	2.191	4.684	0.297	13.59	4.154	2.647	6.367

S.W. Area: The average sidewall area of the left and right side of the indents.

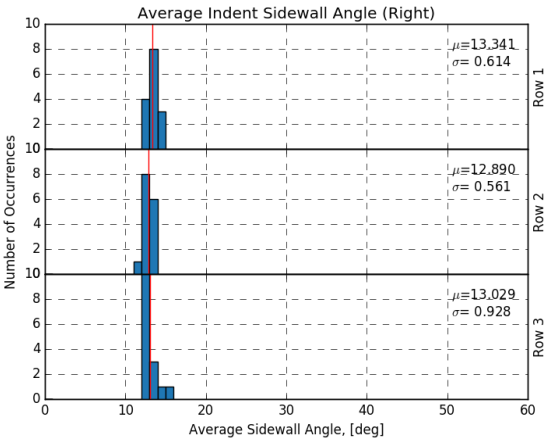
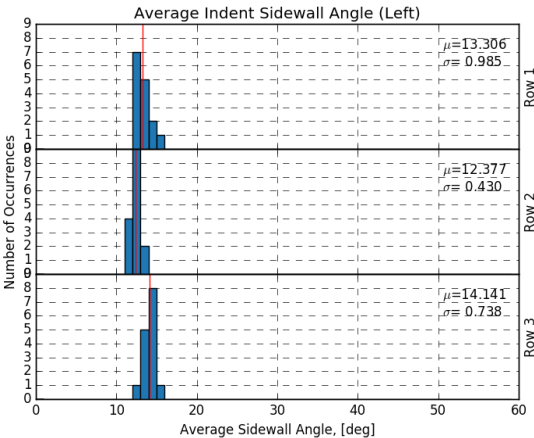
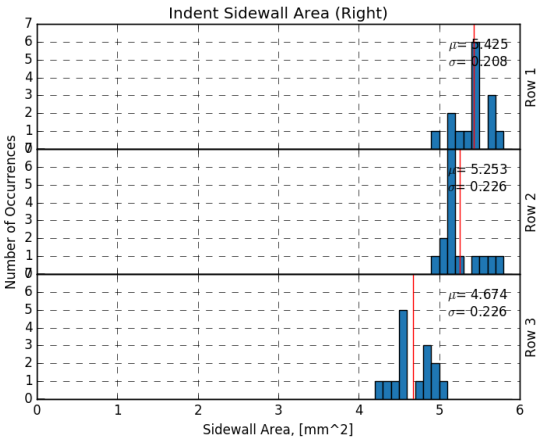
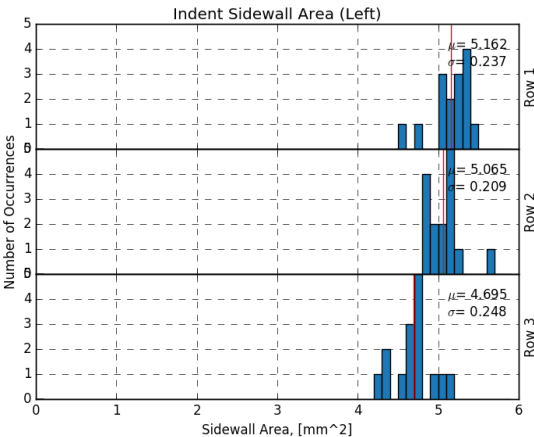
S.W. Angle: The average sidewall angle of the left and right side of the indents.



TEST REPORT: INDENT PROFILER

WIRE ID:15-S

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TEST REPORT: ASTM A881

WIRE ID:15-S

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SAMPLE ID		15-.16-T1_105mm_True
SAMPLE LENGTH [MM]		105
NOMINAL DIAMETER [MM]		5.176
TEST ITEM	STANDARD VALUE	ACTUAL VALUE
INDENT DEPTH [MM]	0.115±0.035	0.290
SIDEWALL ANGLE [DEG]	In Contract	13.2
INDENT LENGTH [MM]	3.5±0.5	4.503
INDENT PITCH [MM]	5.46±0.29	6.34
ORIENTATION ANGLE [DEG]	≥45°	46.8
OUT OF ROUND [MM]	≤0.08	TBD

TEST REPORT: ISO 10138-2

WIRE ID:15-S

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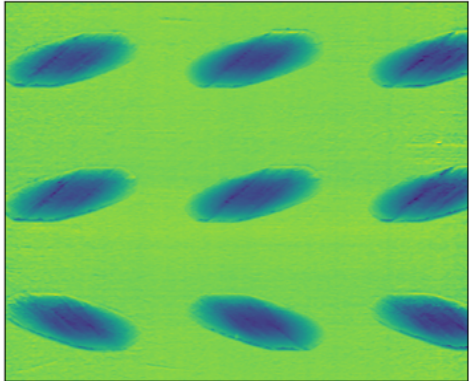
SAMPLE ID		15-.16-T1_105mm_True
SAMPLE LENGTH		105
NOMINAL DIAMETER		5.176
TEST ITEM	STANDARD VALUE	ACTUAL VALUE
INDENT LENGTH [MM]	3.5 ± 0.5	4.503
INDENT DEPTH [MM]	0.15 ± 0.05	0.290
INDENT SPACING [MM]	5.50 ± 0.50	6.34
INDENT DISTANCE [MM]	$\Sigma e \leq 3.343$	4.58, 4.54, 4.54
AVG DIAMETER [MM]	-	TBD
OVALITY	$\leq 0.01 \times D$	TBD

TEST REPORT: INDENT PROFILER

WIRE ID:15-D

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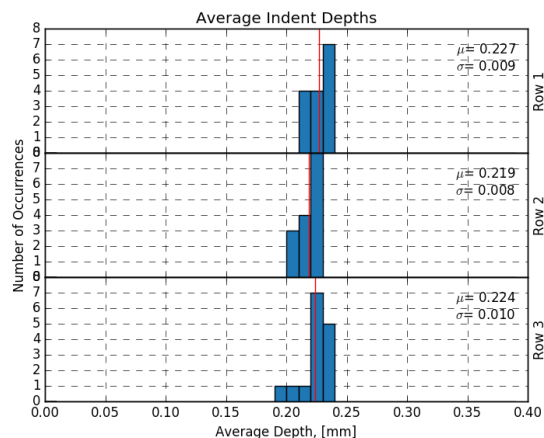
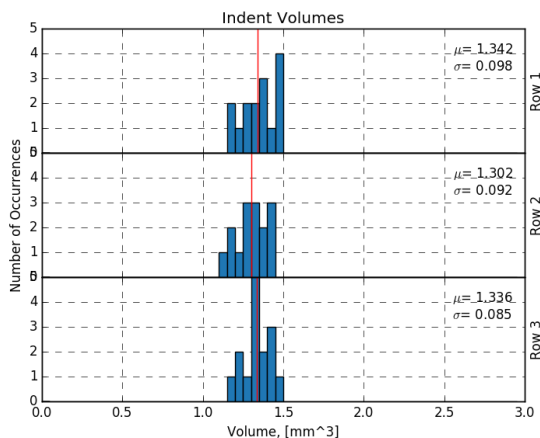
Scan Information					
Wire ID	15_105mm_Trued_11.16.18				
Length [mm]	105				
Scan Date	11.16.18				
Proc Date	09.17.19				
Stat Date	09.17.19				
ID	Indents	Nominal Dia [mm]	Orientat-ion [deg]	Distance [mm]	
Total	45	5.257	47.4	4.947	
Row 1	15		-44.3	4.942	
Row 2	15		50.2	4.949	
Row 3	15		47.8	4.949	



Indent Data								
ID	Indents	Volume [mm^3]	S.W. Area [mm^2]	Avg Depth [mm]	S.W. Angle [deg]	Avg Length [mm]	Width [mm]	Pitch [mm]
Total	45	1.327	3.686	0.223	12.67	3.645	2.352	6.344
Row 1	15	1.342	3.918	0.227	13.35	3.627	2.363	6.368
Row 2	15	1.302	3.432	0.219	12.56	3.625	2.339	6.336
Row 3	15	1.336	3.708	0.224	12.09	3.684	2.353	6.329

S.W. Area: The average sidewall area of the left and right side of the indents.

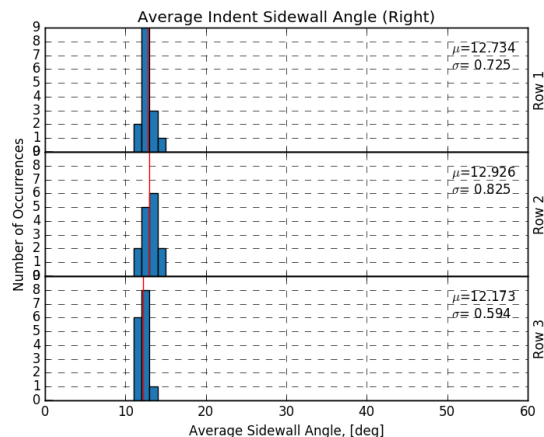
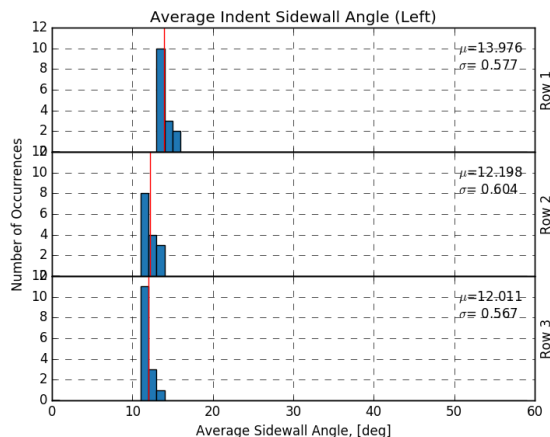
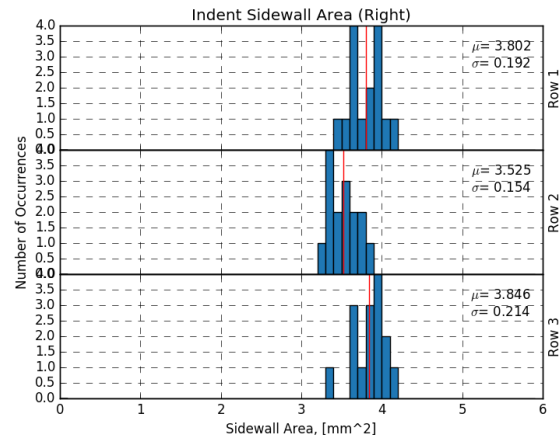
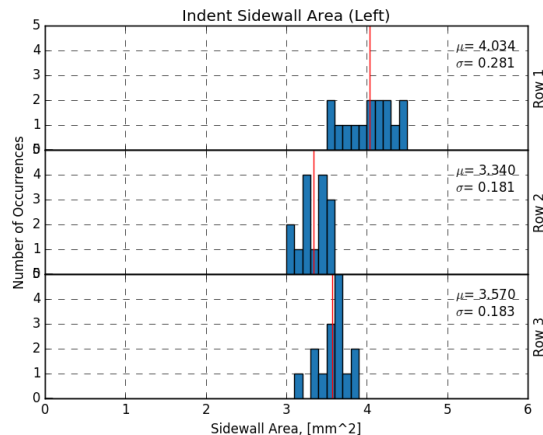
S.W. Angle: The average sidewall angle of the left and right side of the indents.



TEST REPORT: INDENT PROFILER

WIRE ID:15-D

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TEST REPORT: ASTM A881

WIRE ID:15-D

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SAMPLE ID		15_105mm_Trued_11.16.18
SAMPLE LENGTH [MM]		105
NOMINAL DIAMETER [MM]		5.257
TEST ITEM	STANDARD VALUE	ACTUAL VALUE
INDENT DEPTH [MM]	0.115±0.035	0.223
SIDEWALL ANGLE [DEG]	In Contract	12.7
INDENT LENGTH [MM]	3.5±0.5	5.059
INDENT PITCH [MM]	5.46±0.29	6.34
ORIENTATION ANGLE [DEG]	≥45°	47.4
OUT OF ROUND [MM]	≤0.08	TBD

TEST REPORT: ISO 10138-2

WIRE ID:15-D

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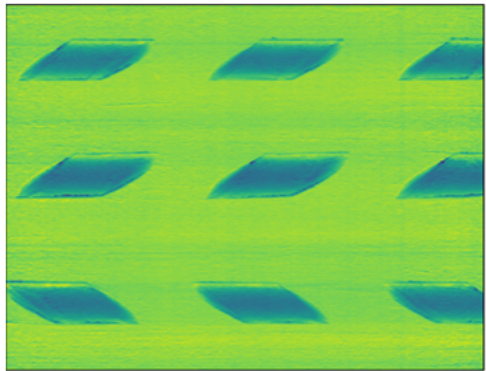
SAMPLE ID		15_105mm_TrueD_11.16.18
SAMPLE LENGTH		105
NOMINAL DIAMETER		5.257
TEST ITEM	STANDARD VALUE	ACTUAL VALUE
INDENT LENGTH [MM]	3.5±0.5	5.059
INDENT DEPTH [MM]	0.15±0.05	0.223
INDENT SPACING [MM]	5.50±0.50	6.34
INDENT DISTANCE [MM]	$\Sigma e \leq 3.343$	4.94, 4.95, 4.95
AVG DIAMETER [MM]	-	TBD
OVALITY	$\leq 0.01 \times D$	TBD

TEST REPORT: INDENT PROFILER

WIRE ID:30-S

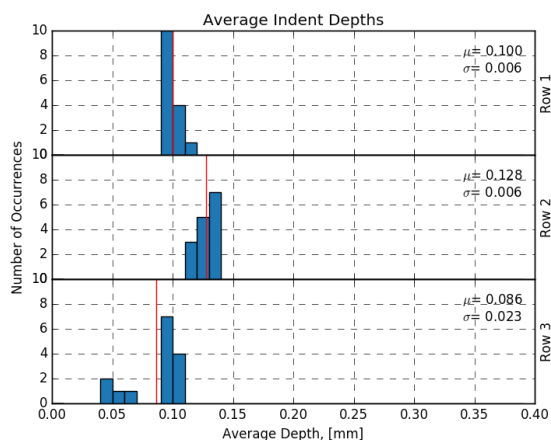
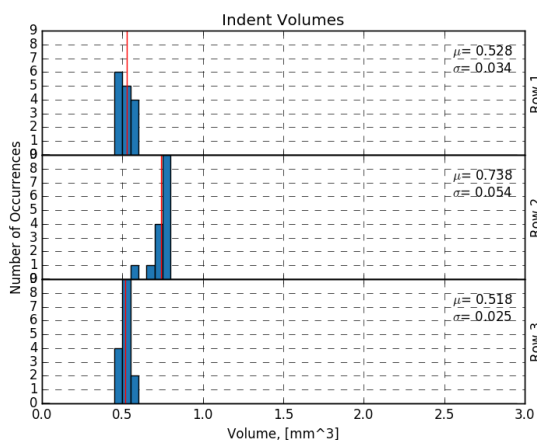
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Scan Information				
Wire ID	X3_105mm_Trued_11.16.18			
Length [mm]	105			
Scan Date	11.16.18			
Proc Date	09.17.19			
Stat Date	09.17.19			
ID	Indents	Nominal Dia [mm]	Orientation [deg]	Distance [mm]
Total	45	5.303	47.6	5.455
Row 1	15		-45.1	5.557
Row 2	15		45.8	5.404
Row 3	15		51.9	5.404



Indent Data								
ID	Indents	Volume [mm^3]	S.W. Area [mm^2]	Avg Depth [mm]	S.W. Angle [deg]	Avg Length [mm]	Width [mm]	Pitch [mm]
Total	45	0.595	1.050	0.105	19.93	3.599	1.945	6.345
Row 1	15	0.528	0.928	0.100	19.42	3.553	1.760	6.370
Row 2	15	0.738	1.069	0.128	22.50	3.567	1.889	6.330
Row 3	15	0.518	1.153	0.086	17.88	3.678	2.187	6.333

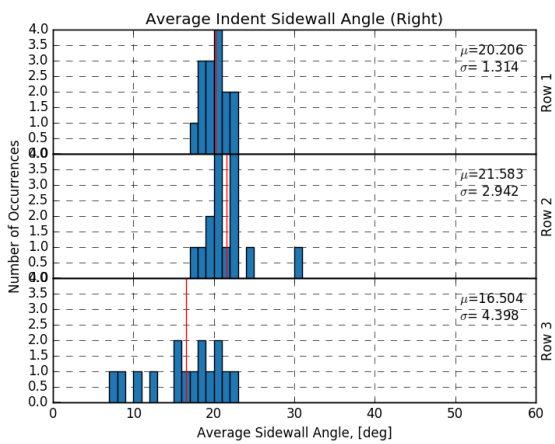
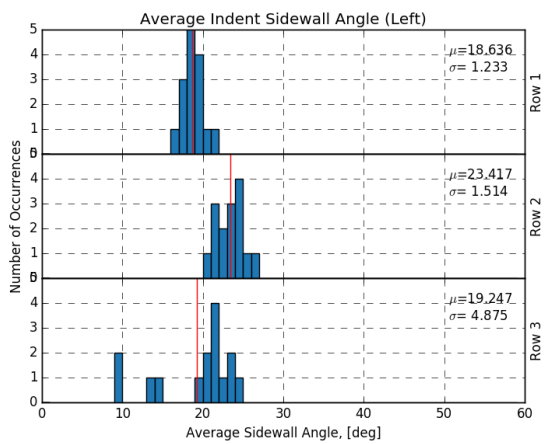
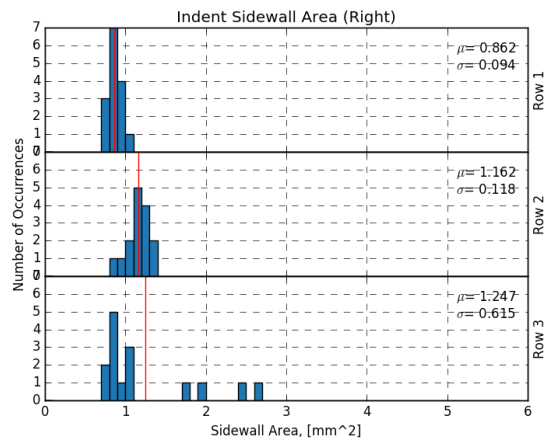
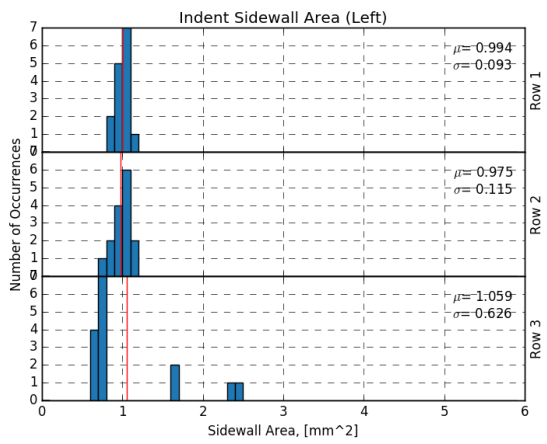
S.W. Area: The average sidewall area of the left and right side of the indents.
S.W. Angle: The average sidewall angle of the left and right side of the indents.



TEST REPORT: INDENT PROFILER

WIRE ID:30-S

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TEST REPORT: ASTM A881

WIRE ID:30-S

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SAMPLE ID		X3_105mm_Trued_11.16.18
SAMPLE LENGTH [MM]		105
NOMINAL DIAMETER [MM]		5.303
TEST ITEM	STANDARD VALUE	ACTUAL VALUE
INDENT DEPTH [MM]	0.115±0.035	0.105
SIDEWALL ANGLE [DEG]	In Contract	19.9
INDENT LENGTH [MM]	3.5±0.5	3.609
INDENT PITCH [MM]	5.46±0.29	6.35
ORIENTATION ANGLE [DEG]	≥45°	47.6
OUT OF ROUND [MM]	≤0.08	TBD

TEST REPORT: ISO 10138-2

WIRE ID:30-S

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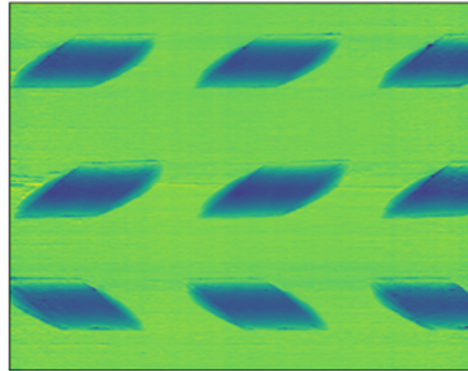
SAMPLE ID		X3_105mm_TrueD_11.16.18
SAMPLE LENGTH		105
NOMINAL DIAMETER		5.303
TEST ITEM	STANDARD VALUE	ACTUAL VALUE
INDENT LENGTH [MM]	3.5±0.5	3.609
INDENT DEPTH [MM]	0.15±0.05	0.105
INDENT SPACING [MM]	5.50±0.50	6.35
INDENT DISTANCE [MM]	$\Sigma e \leq 3.343$	5.56, 5.40, 5.40
AVG DIAMETER [MM]	-	TBD
OVALITY	$\leq 0.01 \times D$	TBD

TEST REPORT: INDENT PROFILER

WIRE ID: 30-D

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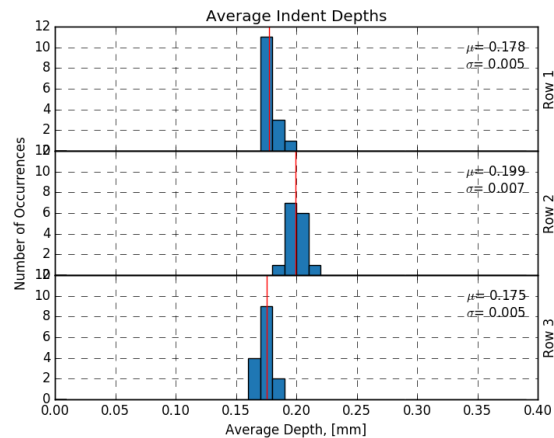
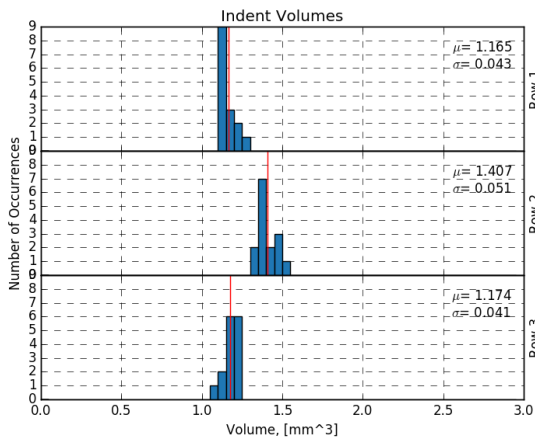
Scan Information				
Wire ID	30-16-T1_105mm_TrueD_11.15.18			
Length [mm]	105			
Scan Date	11.15.18			
Proc Date	09.17.19			
Stat Date	09.17.19			
ID	Indents	Nominal Dia [mm]	Orientation [deg]	Distance [mm]
Total	45	5.254	47.4	5.120
Row 1	15		-49.2	5.135
Row 2	15		44.3	5.112
Row 3	15		48.7	5.112



Indent Data								
ID	Indents	Volume [mm^3]	S.W. Area [mm^2]	Avg Depth [mm]	S.W. Angle [deg]	Avg Length [mm]	Width [mm]	Pitch [mm]
Total	45	1.249	1.582	0.184	21.84	3.730	2.145	6.343
Row 1	15	1.165	1.475	0.178	21.91	3.705	2.091	6.364
Row 2	15	1.407	1.817	0.199	21.82	3.788	2.219	6.329
Row 3	15	1.174	1.453	0.175	21.79	3.696	2.126	6.336

S.W. Area: The average sidewall area of the left and right side of the indents.

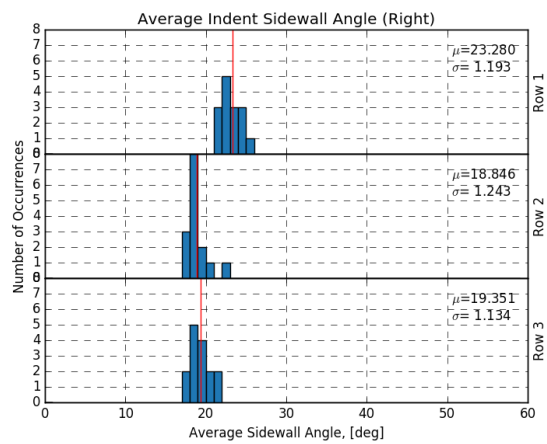
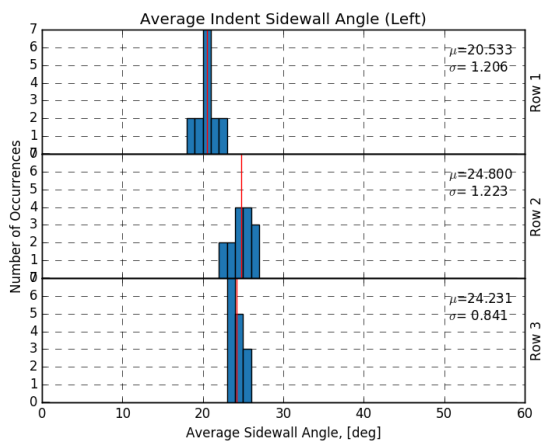
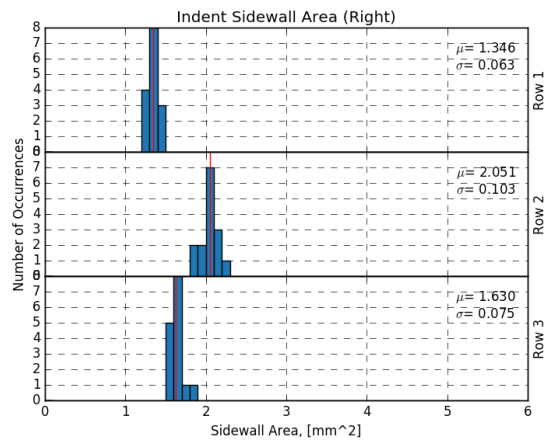
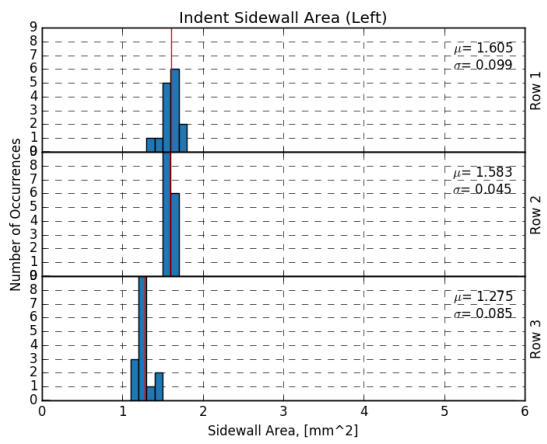
S.W. Angle: The average sidewall angle of the left and right side of the indents.



TEST REPORT: INDENT PROFILER

WIRE ID:30-D

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TEST REPORT: ASTM A881

WIRE ID:30-D

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SAMPLE ID		30-.16- T1_105mm_Trued_11.15.18
SAMPLE LENGTH [MM]		105
NOMINAL DIAMETER [MM]		5.254
TEST ITEM	STANDARD VALUE	ACTUAL VALUE
INDENT DEPTH [MM]	0.115±0.035	0.184
SIDEWALL ANGLE [DEG]	In Contract	21.8
INDENT LENGTH [MM]	3.5±0.5	4.062
INDENT PITCH [MM]	5.46±0.29	6.34
ORIENTATION ANGLE [DEG]	≥45°	47.4
OUT OF ROUND [MM]	≤0.08	TBD

TEST REPORT: ISO 10138-2

WIRE ID:30-D

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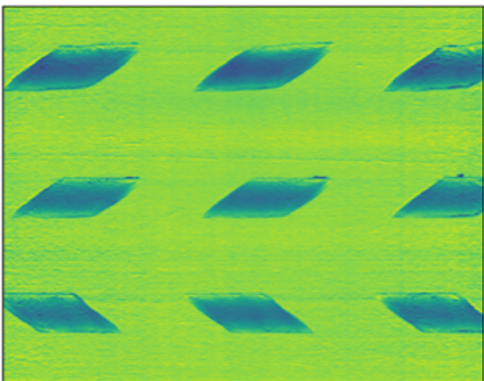
SAMPLE ID		30-.16- T1_105mm_TrueD_11.15.18
SAMPLE LENGTH		105
NOMINAL DIAMETER		5.254
TEST ITEM	STANDARD VALUE	ACTUAL VALUE
INDENT LENGTH [MM]	3.5±0.5	4.062
INDENT DEPTH [MM]	0.15±0.05	0.184
INDENT SPACING [MM]	5.50±0.50	6.34
INDENT DISTANCE [MM]	$\Sigma e \leq 3.343$	5.14, 5.11, 5.11
AVG DIAMETER [MM]	-	TBD
OVALITY	$\leq 0.01 \times D$	TBD

TEST REPORT: INDENT PROFILER

WIRE ID:45-S

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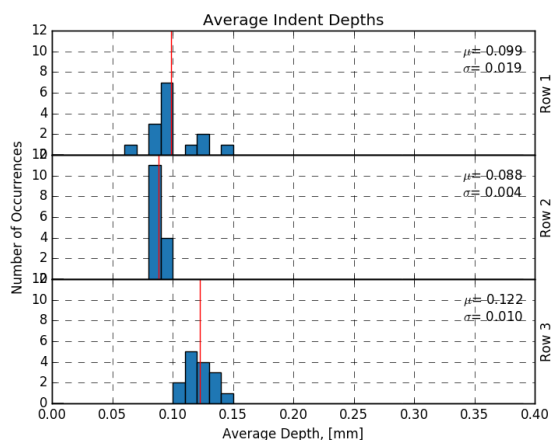
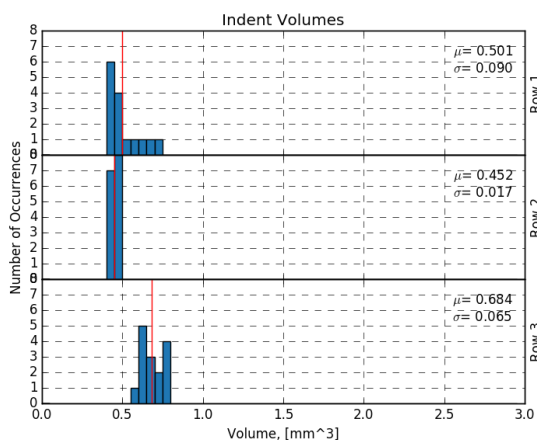
Scan Information					
Wire ID	X5_105mm_Trued_11.16.18				
Length [mm]	105				
Scan Date	11.16.18				
Proc Date	09.17.19				
Stat Date	09.17.19				
ID	Indents	Nominal Dia [mm]	Orientat-ion [deg]	Distance [mm]	
Total	45	5.312	48.1	5.446	
Row 1	15		-44.2	5.490	
Row 2	15		59.8	5.424	
Row 3	15		40.3	5.424	



Indent Data								
ID	Indents	Volume [mm^3]	S.W. Area [mm^2]	Avg Depth [mm]	S.W. Angle [deg]	Avg Length [mm]	Width [mm]	Pitch [mm]
Total	45	0.545	0.951	0.103	23.95	3.311	1.882	6.345
Row 1	15	0.501	0.996	0.099	22.76	3.313	1.855	6.354
Row 2	15	0.452	0.777	0.088	21.65	3.351	1.813	6.343
Row 3	15	0.684	1.081	0.122	27.44	3.268	1.979	6.337

S.W. Area: The average sidewall area of the left and right side of the indents.

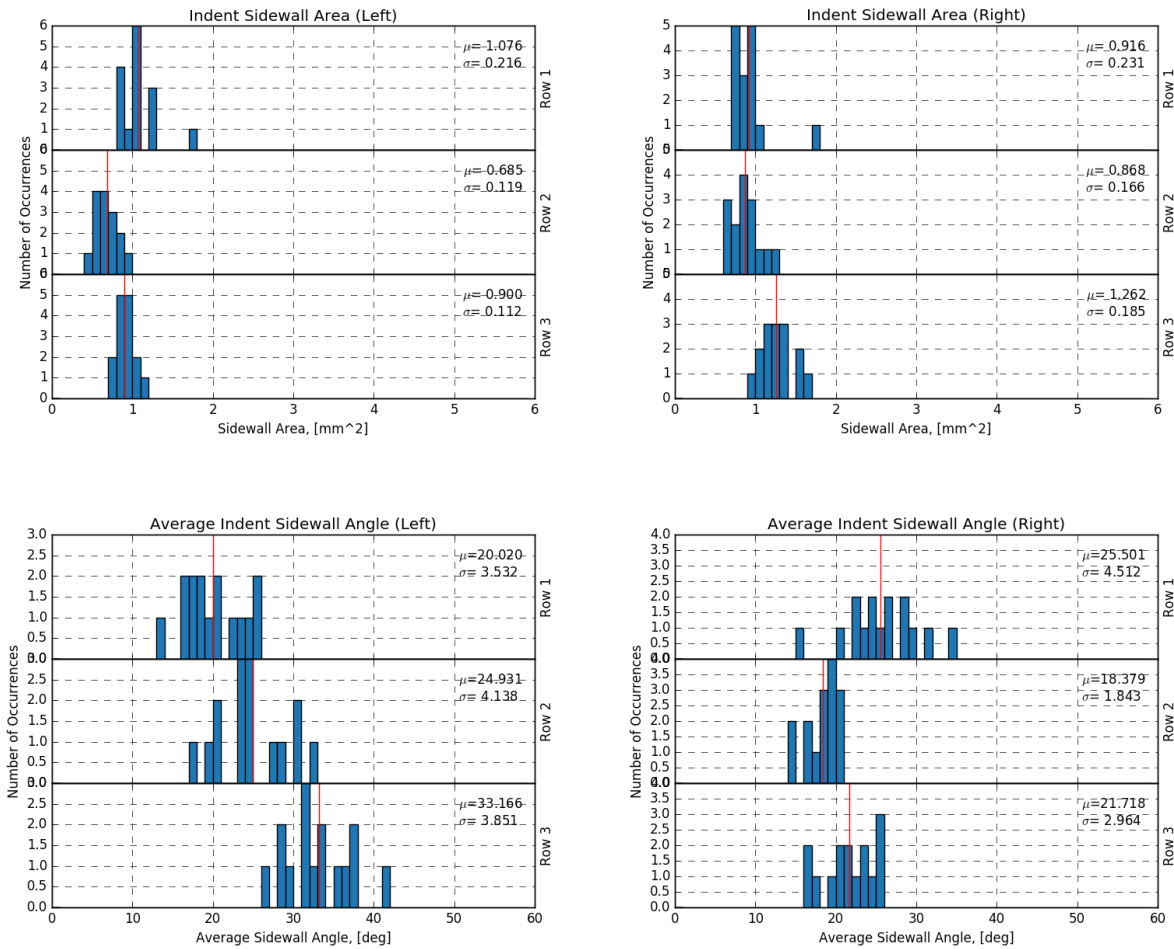
S.W. Angle: The average sidewall angle of the left and right side of the indents.



TEST REPORT: INDENT PROFILER

WIRE ID:45-S

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TEST REPORT: ASTM A881

WIRE ID:45-S

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SAMPLE ID		X5_105mm_Trued_11.16.18
SAMPLE LENGTH [MM]		105
NOMINAL DIAMETER [MM]		5.312
TEST ITEM	STANDARD VALUE	ACTUAL VALUE
INDENT DEPTH [MM]	0.115±0.035	0.103
SIDEWALL ANGLE [DEG]	In Contract	24.0
INDENT LENGTH [MM]	3.5±0.5	3.172
INDENT PITCH [MM]	5.46±0.29	6.35
ORIENTATION ANGLE [DEG]	≥45°	48.1
OUT OF ROUND [MM]	≤0.08	TBD

TEST REPORT: ISO 10138-2

WIRE ID:45-S

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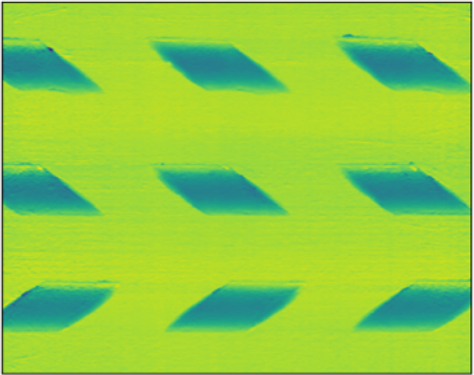
SAMPLE ID		X5_105mm_Trued_11.16.18
SAMPLE LENGTH		105
NOMINAL DIAMETER		5.312
TEST ITEM	STANDARD VALUE	ACTUAL VALUE
INDENT LENGTH [MM]	3.5±0.5	3.172
INDENT DEPTH [MM]	0.15±0.05	0.103
INDENT SPACING [MM]	5.50±0.50	6.35
INDENT DISTANCE [MM]	$\Sigma e \leq 3.343$	5.49, 5.42, 5.42
AVG DIAMETER [MM]	-	TBD
OVALITY	$\leq 0.01 \times D$	TBD

TEST REPORT: INDENT PROFILER

WIRE ID: 45-D

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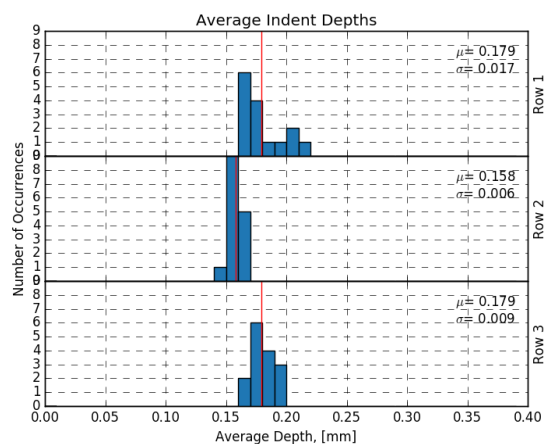
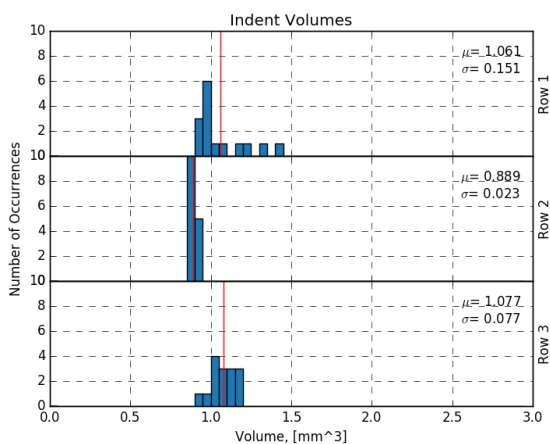
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Length [mm]	105				
Scan Date	11.15.18				
Proc Date	9.17.19				
Stat Date	9.17.19				
ID	Indents	Nominal Dia [mm]	Orientat-ion [deg]	Distance [mm]	
Total	45	5.255	47.0	5.192	
Row 1	15		46.6	5.240	
Row 2	15		-47.4	5.168	
Row 3	15		-47.1	5.168	



Indent Data								
ID	Indents	Volume [mm^3]	S.W. Area [mm^2]	Avg Depth [mm]	S.W. Angle [deg]	Avg Length [mm]	Width [mm]	Pitch [mm]
Total	45	1.009	1.066	0.172	30.19	3.255	2.070	6.354
Row 1	15	1.061	1.046	0.179	31.12	3.307	2.023	6.336
Row 2	15	0.889	0.993	0.158	28.67	3.222	2.035	6.362
Row 3	15	1.077	1.159	0.179	30.76	3.237	2.152	6.364

S.W. Area: The average sidewall area of the left and right side of the indents.

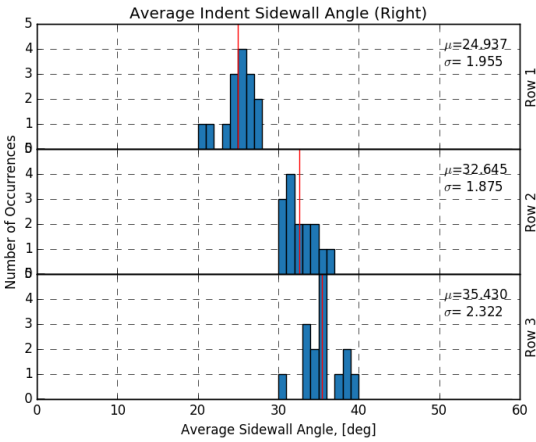
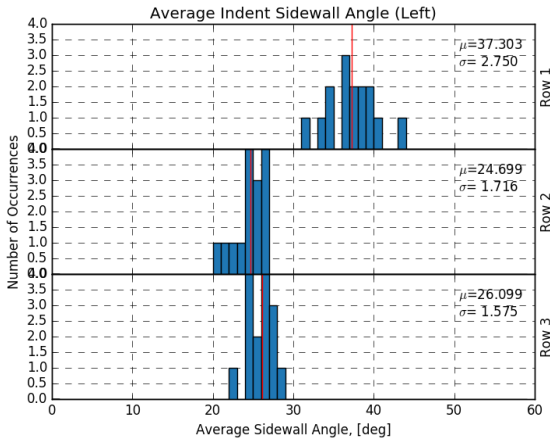
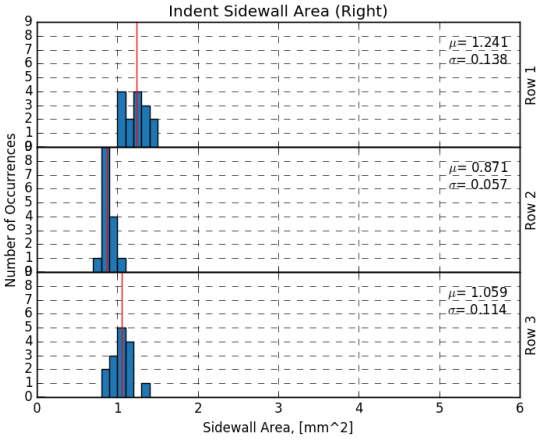
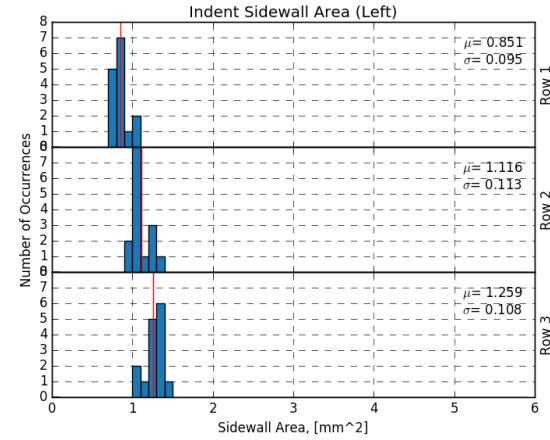
S.W. Angle: The average sidewall angle of the left and right side of the indents.



TEST REPORT: INDENT PROFILER

WIRE ID:45-D

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TEST REPORT: ASTM A881

WIRE ID:45-D

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SAMPLE ID		45-.16- T2_105mm_Trued_11.15.18
SAMPLE LENGTH [MM]		105
NOMINAL DIAMETER [MM]		5.255
TEST ITEM	STANDARD VALUE	ACTUAL VALUE
INDENT DEPTH [MM]	0.115±0.035	0.172
SIDEWALL ANGLE [DEG]	In Contract	30.2
INDENT LENGTH [MM]	3.5±0.5	3.370
INDENT PITCH [MM]	5.46±0.29	6.35
ORIENTATION ANGLE [DEG]	≥45°	47.0
OUT OF ROUND [MM]	≤0.08	TBD

TEST REPORT: ISO 10138-2

WIRE ID:45-D

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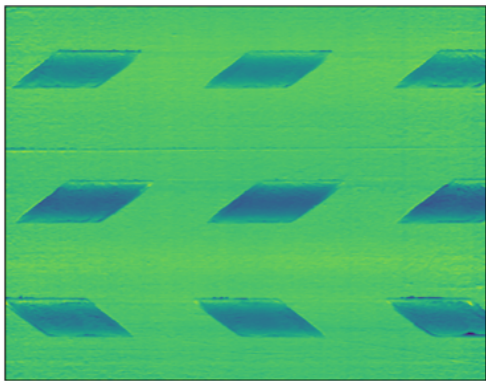
SAMPLE ID		45-.16- T2_105mm_TrueD_11.15.18
SAMPLE LENGTH		105
NOMINAL DIAMETER		5.255
TEST ITEM	STANDARD VALUE	ACTUAL VALUE
INDENT LENGTH [MM]	3.5±0.5	3.370
INDENT DEPTH [MM]	0.15±0.05	0.172
INDENT SPACING [MM]	5.50±0.50	6.35
INDENT DISTANCE [MM]	$\Sigma e \leq 3.343$	5.24, 5.17, 5.17
AVG DIAMETER [MM]	-	TBD
OVALITY	$\leq 0.01 \times D$	TBD

TEST REPORT: INDENT PROFILER

WIRE ID: 60-S

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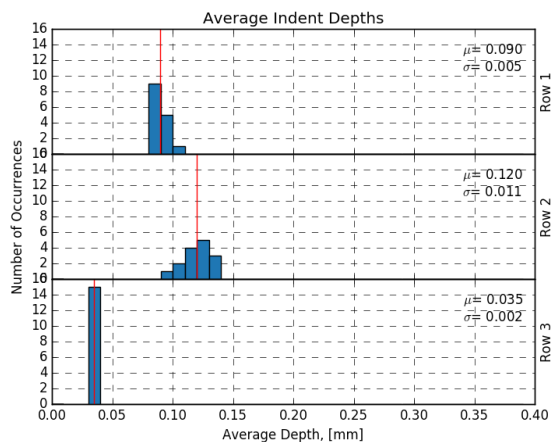
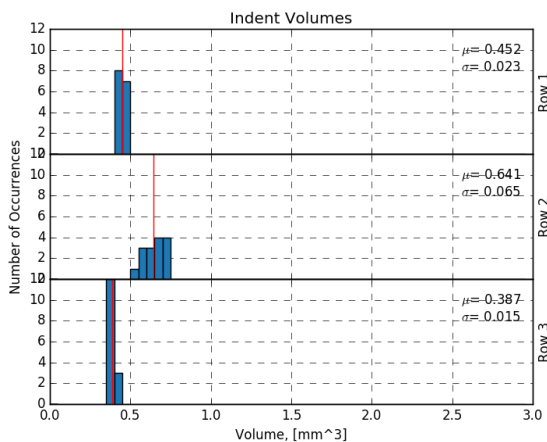
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Wire ID	X4_105mm_Trued_11.16.18				
Length [mm]	105				
Scan Date	11.16.18				
Proc Date	09.17.19				
Stat Date	09.17.19				
ID	Indents	Nominal Dia [mm]	Orientat-ion [deg]	Distance [mm]	
Total	45	5.300	48.3	4.839	
Row 1	15		-44.1	5.532	
Row 2	15		50.9	4.493	
Row 3	15		49.9	4.493	



Indent Data								
ID	Indents	Volume [mm^3]	S.W. Area [mm^2]	Avg Depth [mm]	S.W. Angle [deg]	Avg Length [mm]	Width [mm]	Pitch [mm]
Total	45	0.493	1.390	0.082	22.42	3.641	2.525	6.347
Row 1	15	0.452	0.859	0.090	24.16	3.326	1.808	6.369
Row 2	15	0.641	0.732	0.120	34.55	3.300	1.883	6.338
Row 3	15	0.387	2.579	0.035	8.54	4.296	3.885	6.334

S.W. Area: The average sidewall area of the left and right side of the indents.

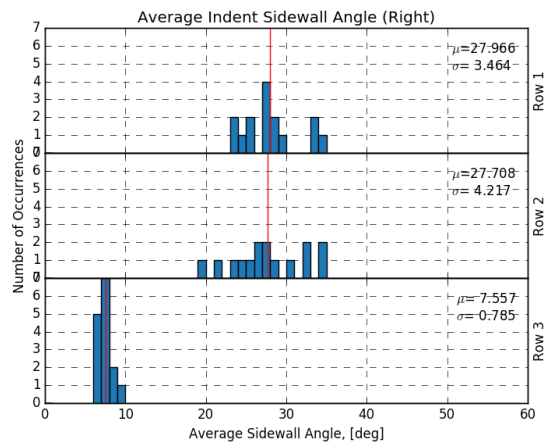
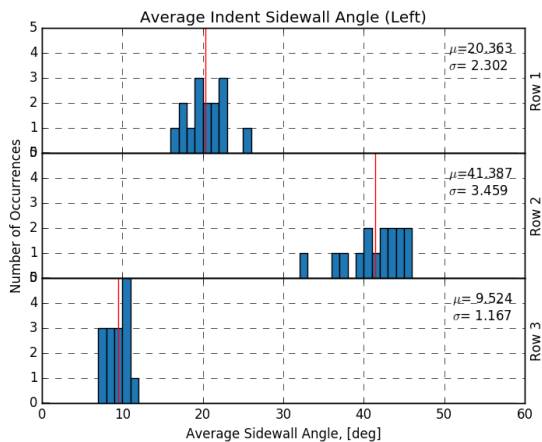
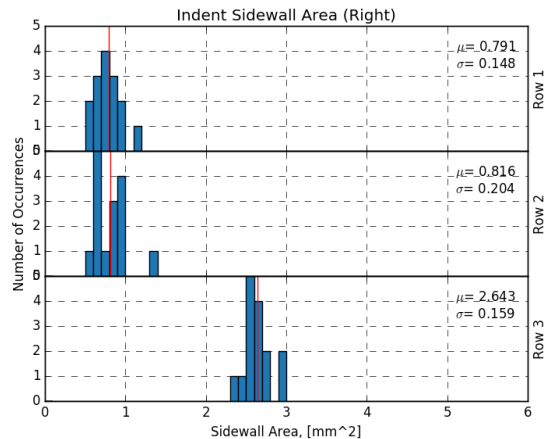
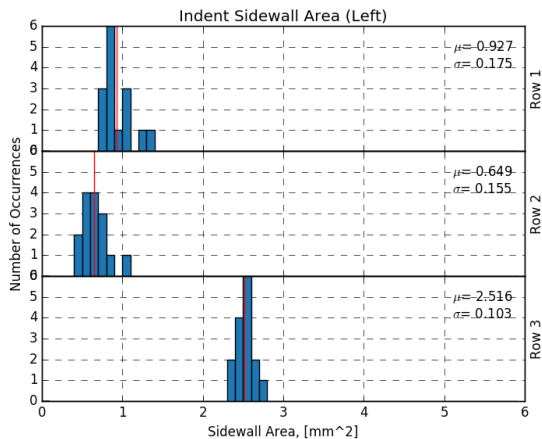
S.W. Angle: The average sidewall angle of the left and right side of the indents.



TEST REPORT: INDENT PROFILER

WIRE ID:60-S

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TEST REPORT: ASTM A881

WIRE ID:60-S

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SAMPLE ID		X4_105mm_Trued_11.16.18
SAMPLE LENGTH [MM]		105
NOMINAL DIAMETER [MM]		5.300
TEST ITEM	STANDARD VALUE	ACTUAL VALUE
INDENT DEPTH [MM]	0.115±0.035	0.082
SIDEWALL ANGLE [DEG]	In Contract	22.4
INDENT LENGTH [MM]	3.5±0.5	3.204
INDENT PITCH [MM]	5.46±0.29	6.35
ORIENTATION ANGLE [DEG]	≥45°	48.3
OUT OF ROUND [MM]	≤0.08	TBD

TEST REPORT: ISO 10138-2

WIRE ID:60-S

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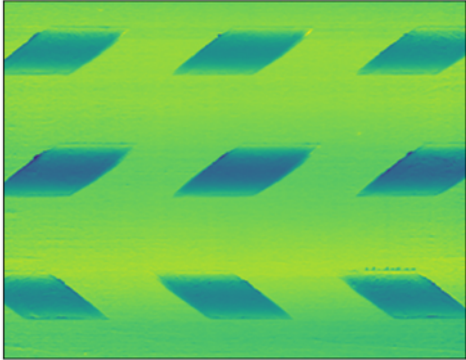
SAMPLE ID		X4_105mm_Trued_11.16.18
SAMPLE LENGTH		105
NOMINAL DIAMETER		5.300
TEST ITEM	STANDARD VALUE	ACTUAL VALUE
INDENT LENGTH [MM]	3.5±0.5	3.204
INDENT DEPTH [MM]	0.15±0.05	0.082
INDENT SPACING [MM]	5.50±0.50	6.35
INDENT DISTANCE [MM]	$\Sigma e \leq 3.343$	5.53, 4.49, 4.49
AVG DIAMETER [MM]	-	TBD
OVALITY	$\leq 0.01 \times D$	TBD

TEST REPORT: INDENT PROFILER

WIRE ID: 60-D

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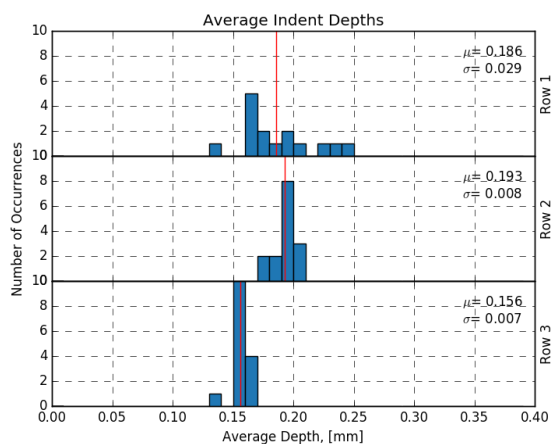
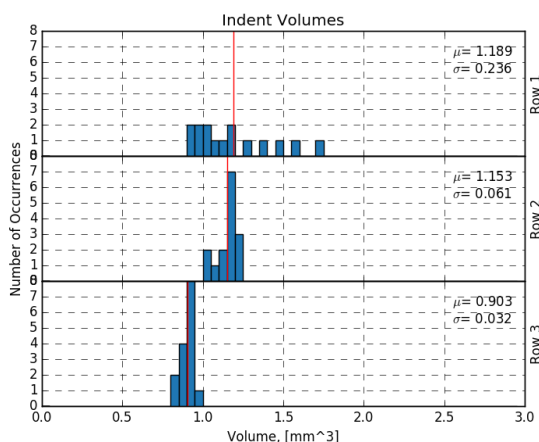
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Wire ID	60-16-T1_105mm_TrueD_11.15.18			
Length [mm]	105			
Scan Date	11.15.18			
Proc Date	09.17.19			
Stat Date	09.17.19			
ID	Indents	Nominal Dia [mm]	Orientat-ion [deg]	Distance [mm]
Total	45	5.236	47.9	5.182
Row 1	15		-50.1	5.103
Row 2	15		47.0	5.222
Row 3	15		46.5	5.222



Indent Data								
ID	Indents	Volume [mm^3]	S.W. Area [mm^2]	Avg Depth [mm]	S.W. Angle [deg]	Avg Length [mm]	Width [mm]	Pitch [mm]
Total	45	1.082	0.872	0.178	43.14	3.205	2.107	6.343
Row 1	15	1.189	0.956	0.186	42.15	3.216	2.239	6.365
Row 2	15	1.153	0.842	0.193	46.84	3.192	2.087	6.330
Row 3	15	0.903	0.818	0.156	40.41	3.208	1.995	6.334

S.W. Area: The average sidewall area of the left and right side of the indents.

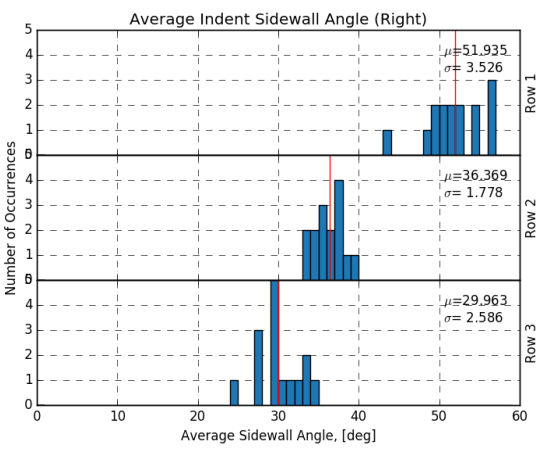
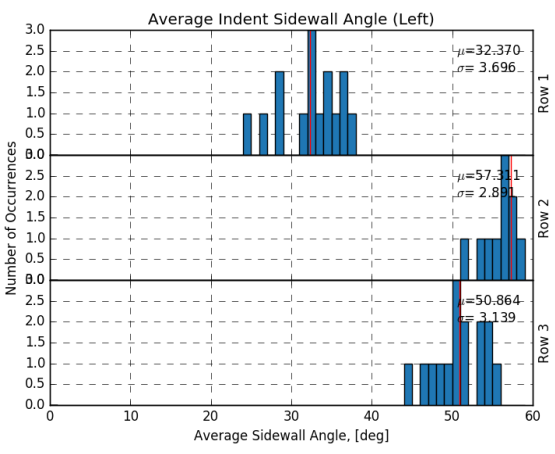
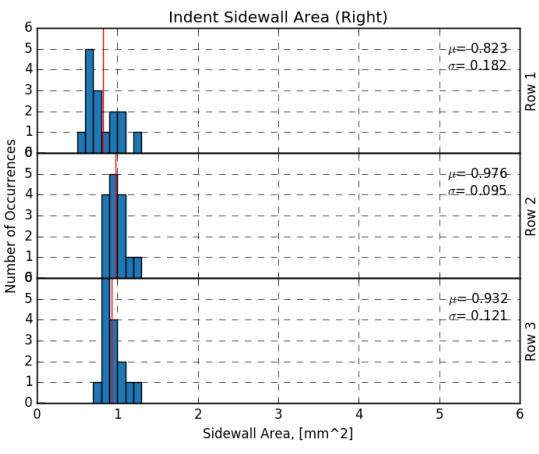
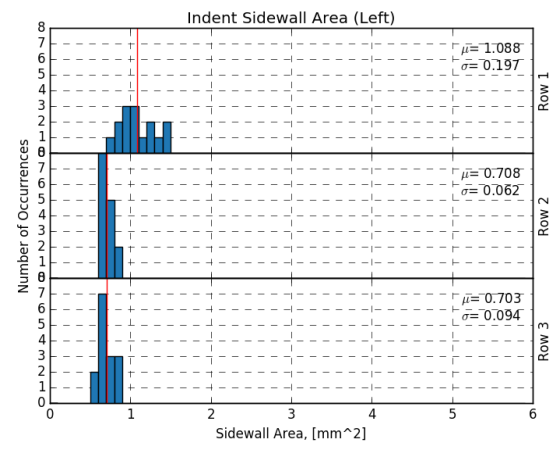
S.W. Angle: The average sidewall angle of the left and right side of the indents.



TEST REPORT: INDENT PROFILER

WIRE ID: 60-D

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TEST REPORT: ASTM A881

WIRE ID: 60-D

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SAMPLE ID		60-.16- T1_105mm_TrueD_11.15.18
SAMPLE LENGTH [MM]		105
NOMINAL DIAMETER [MM]		5.236
TEST ITEM	STANDARD VALUE	ACTUAL VALUE
INDENT DEPTH [MM]	0.115±0.035	0.178
SIDEWALL ANGLE [DEG]	In Contract	43.1
INDENT LENGTH [MM]	3.5±0.5	3.225
INDENT PITCH [MM]	5.46±0.29	6.34
ORIENTATION ANGLE [DEG]	≥45°	47.9
OUT OF ROUND [MM]	≤0.08	TBD

TEST REPORT: ISO 10138-2

WIRE ID: 60-D

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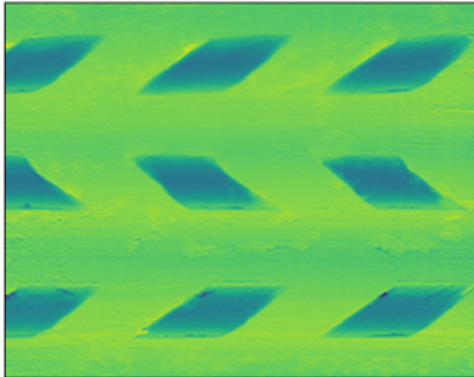
SAMPLE ID		60-.16- T1_105mm_TrueD_11.15.18
SAMPLE LENGTH		105
NOMINAL DIAMETER		5.236
TEST ITEM	STANDARD VALUE	ACTUAL VALUE
INDENT LENGTH [MM]	3.5±0.5	3.225
INDENT DEPTH [MM]	0.15±0.05	0.178
INDENT SPACING [MM]	5.50±0.50	6.34
INDENT DISTANCE [MM]	$\Sigma e \leq 3.343$	5.10, 5.22, 5.22
AVG DIAMETER [MM]	-	TBD
OVALITY	$\leq 0.01 \times D$	TBD

TEST REPORT: INDENT PROFILER

WIRE ID: 75-S

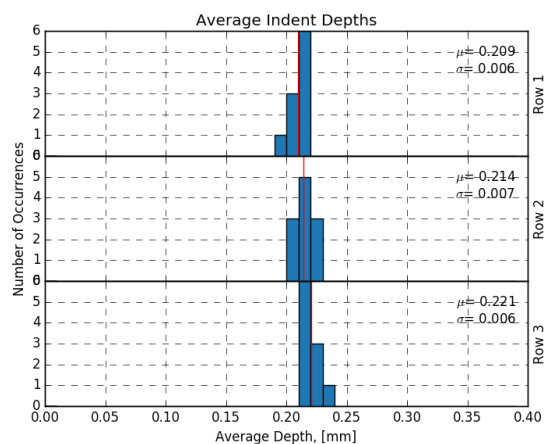
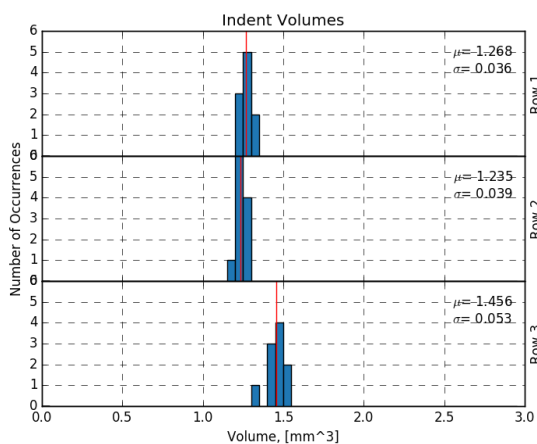
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Scan Information				
Wire ID	X2_105mm_Trued_11.16.18			
Length [mm]	105			
Scan Date	11.16.18			
Proc Date	09.17.19			
Stat Date	09.17.19			
ID	Indents	Nominal Dia [mm]	Orientat-ion [deg]	Distance [mm]
Total	31	5.263	44.5	4.978
Row 1	10		41.9	5.048
Row 2	11		-50.7	4.942
Row 3	10		40.8	4.942



Indent Data								
ID	Indents	Volume [mm^3]	S.W. Area [mm^2]	Avg Depth [mm]	S.W. Angle [deg]	Avg Length [mm]	Width [mm]	Pitch [mm]
Total	31	1.317	1.365	0.215	34.93	3.125	2.296	6.343
Row 1	10	1.268	1.330	0.209	36.35	3.164	2.220	6.331
Row 2	11	1.235	1.190	0.214	35.17	3.054	2.242	6.365
Row 3	10	1.456	1.593	0.221	33.23	3.164	2.430	6.330

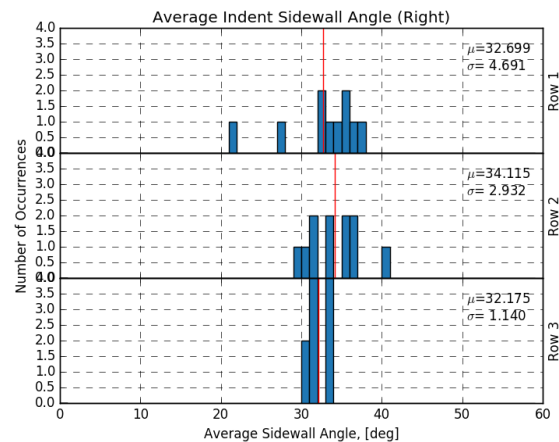
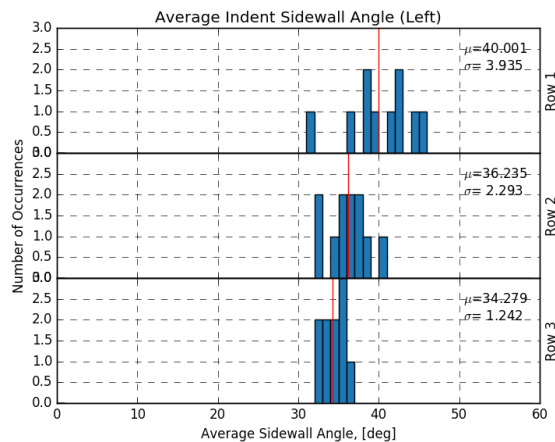
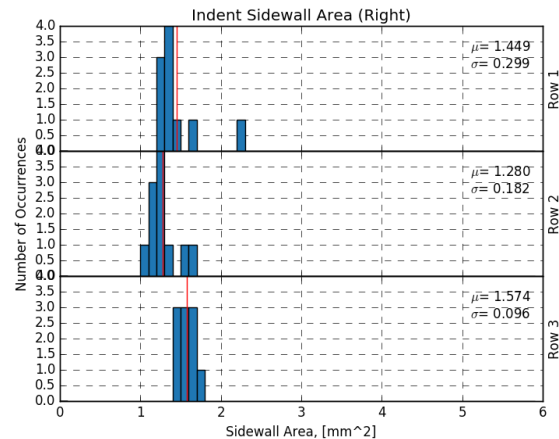
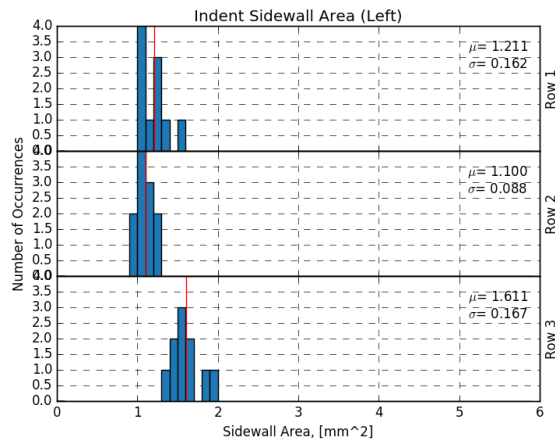
S.W. Area: The average sidewall area of the left and right side of the indents.
S.W. Angle: The average sidewall angle of the left and right side of the indents.



TEST REPORT: INDENT PROFILER

WIRE ID:75-S

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TEST REPORT: ASTM A881

WIRE ID:75-S

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SAMPLE ID		X2_105mm_Trued_11.16.18
SAMPLE LENGTH [MM]		105
NOMINAL DIAMETER [MM]		5.263
TEST ITEM	STANDARD VALUE	ACTUAL VALUE
INDENT DEPTH [MM]	0.115±0.035	0.215
SIDEWALL ANGLE [DEG]	In Contract	34.9
INDENT LENGTH [MM]	3.5±0.5	3.111
INDENT PITCH [MM]	5.46±0.29	6.34
ORIENTATION ANGLE [DEG]	≥45°	44.5
OUT OF ROUND [MM]	≤0.08	TBD

TEST REPORT: ISO 10138-2

WIRE ID:75-S

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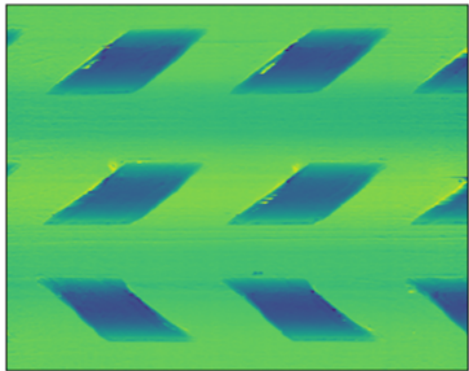
SAMPLE ID		X2_105mm_Trued_11.16.18
SAMPLE LENGTH		105
NOMINAL DIAMETER		5.263
TEST ITEM	STANDARD VALUE	ACTUAL VALUE
INDENT LENGTH [MM]	3.5±0.5	3.111
INDENT DEPTH [MM]	0.15±0.05	0.215
INDENT SPACING [MM]	5.50±0.50	6.34
INDENT DISTANCE [MM]	$\Sigma e \leq 3.343$	5.05, 4.94, 4.94
AVG DIAMETER [MM]	-	TBD
OVALITY	$\leq 0.01 \times D$	TBD

TEST REPORT: INDENT PROFILER

WIRE ID: 75-D

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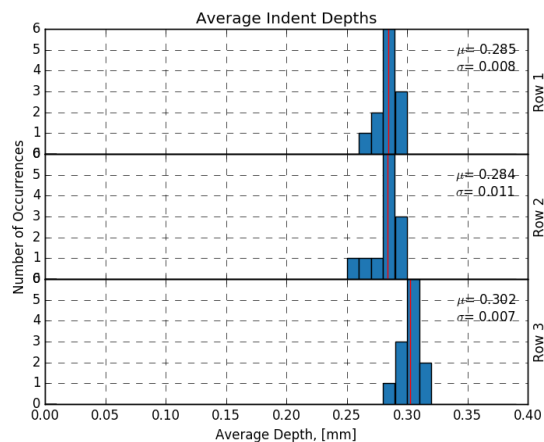
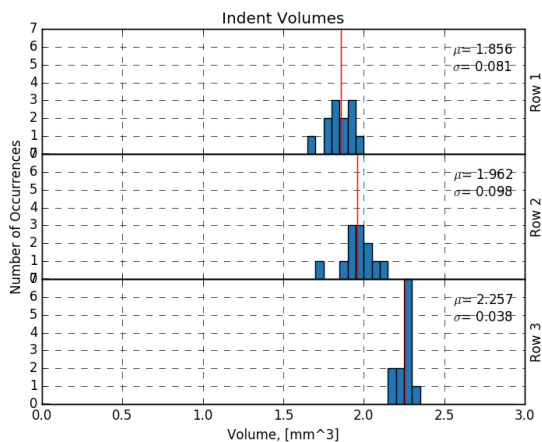
Scan Information					
Wire ID	75-16-T1_105mm_TrueD_11.15.18				
Length [mm]	105				
Scan Date	11.15.18				
Proc Date	09.17.19				
Stat Date	09.17.19				
ID	Indents	Nominal Dia [mm]	Orientation [deg]	Distance [mm]	
Total	36	5.182	46.9	4.673	
Row 1	12		-48.1	4.714	
Row 2	12		48.3	4.653	
Row 3	12		44.4	4.653	



Indent Data								
ID	Indents	Volume [mm^3]	S.W. Area [mm^2]	Avg Depth [mm]	S.W. Angle [deg]	Avg Length [mm]	Width [mm]	Pitch [mm]
Total	36	2.025	1.408	0.290	49.27	3.128	2.536	6.346
Row 1	12	1.856	1.331	0.285	49.50	3.029	2.492	6.370
Row 2	12	1.962	1.354	0.284	48.31	3.125	2.506	6.337
Row 3	12	2.257	1.540	0.302	50.02	3.232	2.611	6.333

S.W. Area: The average sidewall area of the left and right side of the indents.

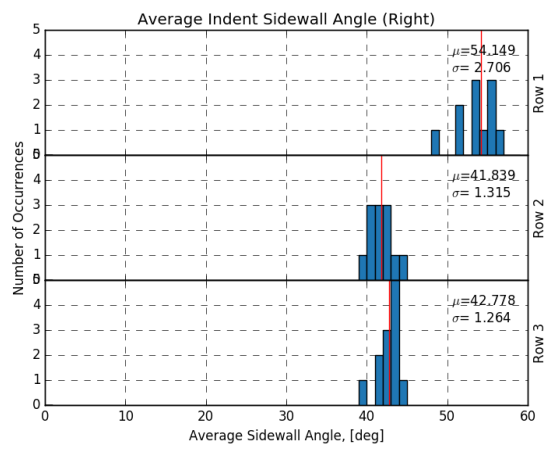
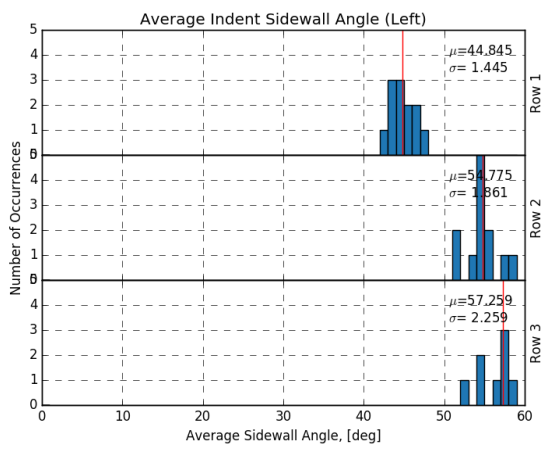
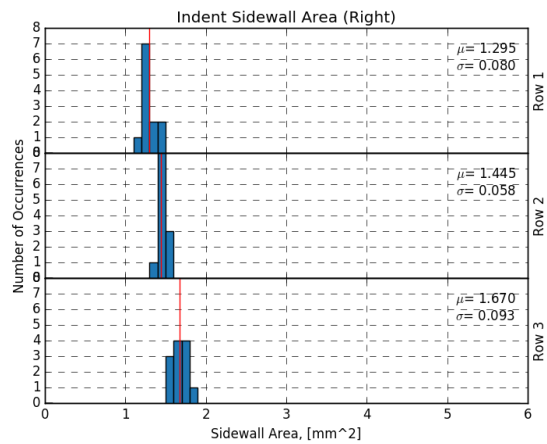
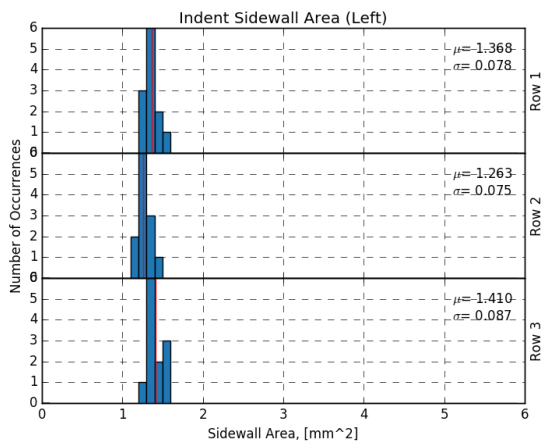
S.W. Angle: The average sidewall angle of the left and right side of the indents.



TEST REPORT: INDENT PROFILER

WIRE ID:75-D

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TEST REPORT: ASTM A881

WIRE ID:75-D

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SAMPLE ID		75-.16- T1_105mm_Trued_11.15.18
SAMPLE LENGTH [MM]		105
NOMINAL DIAMETER [MM]		5.182
TEST ITEM	STANDARD VALUE	ACTUAL VALUE
INDENT DEPTH [MM]	0.115±0.035	0.290
SIDEWALL ANGLE [DEG]	In Contract	49.3
INDENT LENGTH [MM]	3.5±0.5	3.134
INDENT PITCH [MM]	5.46±0.29	6.346
ORIENTATION ANGLE [DEG]	≥45°	46.9
OUT OF ROUND [MM]	≤0.08	TBD

TEST REPORT: ISO 10138-2

WIRE ID:75-D

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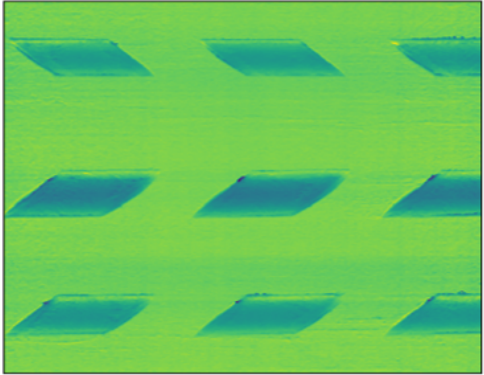
SAMPLE ID		75-.16- T1_105mm_Trued_11.15.18
SAMPLE LENGTH		105
NOMINAL DIAMETER		5.182
TEST ITEM	STANDARD VALUE	ACTUAL VALUE
INDENT LENGTH [MM]	3.5±0.5	3.134
INDENT DEPTH [MM]	0.15±0.05	0.290
INDENT SPACING [MM]	5.50±0.50	6.35
INDENT DISTANCE [MM]	$\Sigma e \leq 3.343$	4.71, 4.65, 4.65
AVG DIAMETER [MM]	-	TBD
OVALITY	$\leq 0.01 \times D$	TBD

TEST REPORT: INDENT PROFILER

WIRE ID: 90-S

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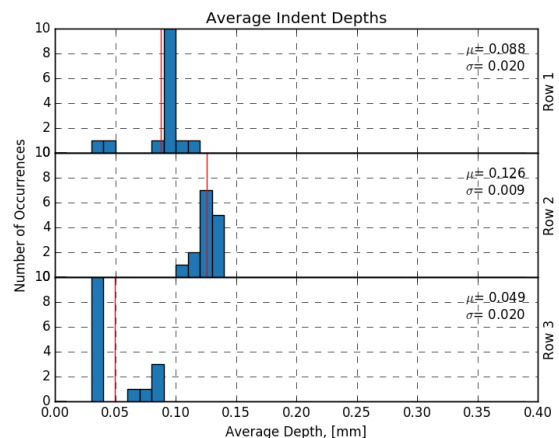
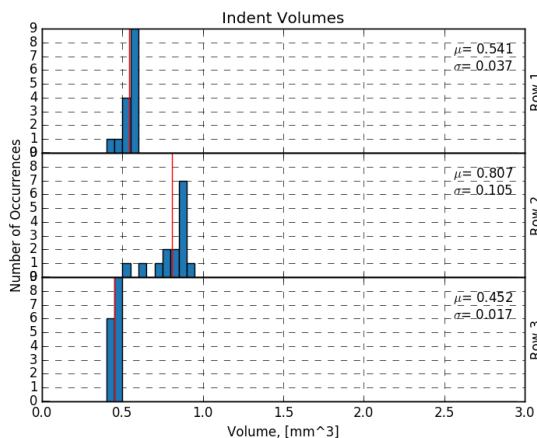
Scan Information				
Wire ID	X1_105mm_Trued_11.16.18			
Length [mm]	105			
Scan Date	11.16.18			
Proc Date	09.17.19			
Stat Date	09.17.19			
ID	Indents	Nominal Dia [mm]	Orientation [deg]	Distance [mm]
Total	45	5.296	44.9	4.890
Row 1	15		50.9	5.292
Row 2	15		43.3	4.689
Row 3	15		-40.6	4.689



Indent Data								
ID	Indents	Volume [mm ³]	S.W. Area [mm ²]	Avg Depth [mm]	S.W. Angle [deg]	Avg Length [mm]	Width [mm]	Pitch [mm]
Total	45	0.600	1.437	0.088	22.96	3.968	2.402	6.342
Row 1	15	0.541	1.052	0.088	24.05	3.863	2.087	6.326
Row 2	15	0.807	0.920	0.126	31.50	3.744	1.934	6.333
Row 3	15	0.452	2.340	0.049	13.35	4.298	3.184	6.366

S.W. Area: The average sidewall area of the left and right side of the indents.

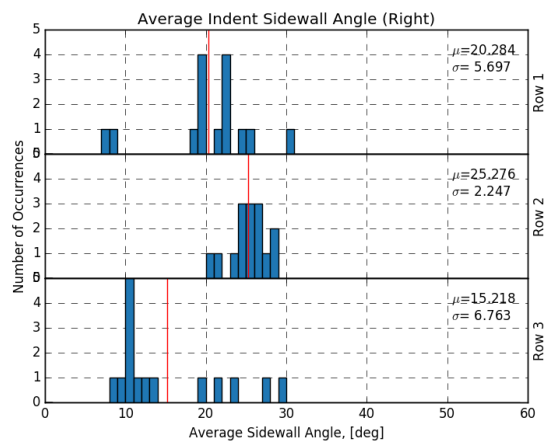
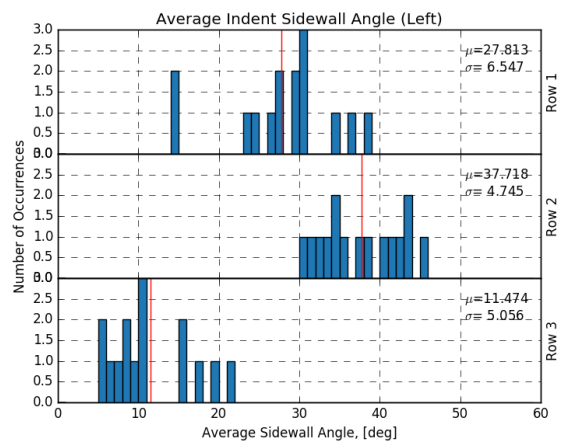
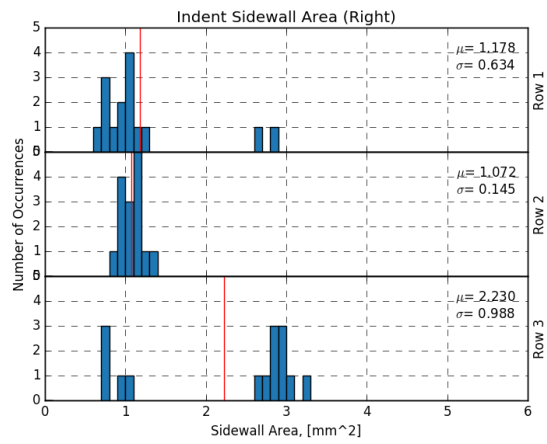
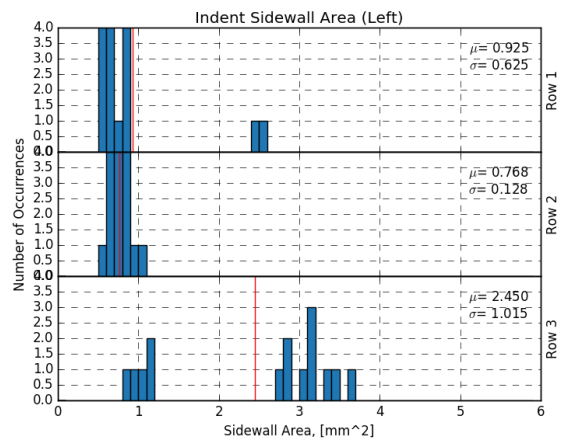
S.W. Angle: The average sidewall angle of the left and right side of the indents.



TEST REPORT: INDENT PROFILER

WIRE ID:90-S

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TEST REPORT: ASTM A881

WIRE ID:90-S

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SAMPLE ID		X1_105mm_Trued_11.16.18
SAMPLE LENGTH [MM]		105
NOMINAL DIAMETER [MM]		5.296
TEST ITEM	STANDARD VALUE	ACTUAL VALUE
INDENT DEPTH [MM]	0.115±0.035	0.088
SIDEWALL ANGLE [DEG]	In Contract	23.0
INDENT LENGTH [MM]	3.5±0.5	3.731
INDENT PITCH [MM]	5.46±0.29	6.34
ORIENTATION ANGLE [DEG]	≥45°	44.9
OUT OF ROUND [MM]	≤0.08	TBD

TEST REPORT: ISO 10138-2

WIRE ID:90-S

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SAMPLE ID		X1_105mm_Trued_11.16.18
SAMPLE LENGTH		105
NOMINAL DIAMETER		5.296
TEST ITEM	STANDARD VALUE	ACTUAL VALUE
INDENT LENGTH [MM]	3.5±0.5	3.731
INDENT DEPTH [MM]	0.15±0.05	0.088
INDENT SPACING [MM]	5.50±0.50	6.34
INDENT DISTANCE [MM]	$\Sigma e \leq 3.343$	5.29, 4.69, 4.69
AVG DIAMETER [MM]	-	TBD
OVALITY	$\leq 0.01 \times D$	TBD

TEST REPORT: INDENT PROFILER

WIRE ID: 90-D

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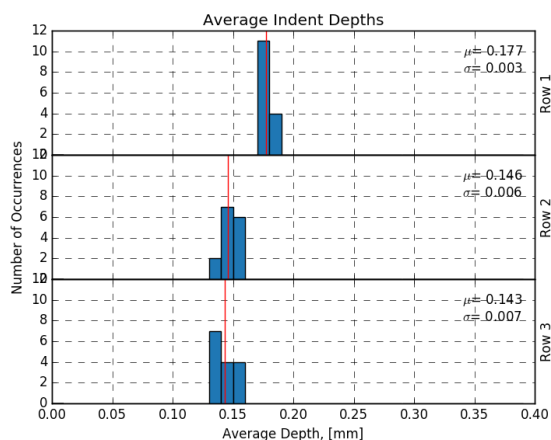
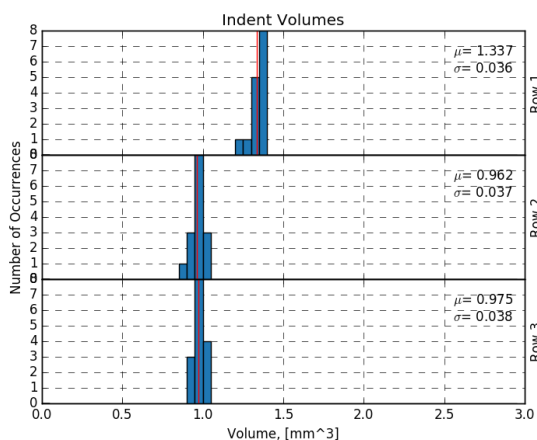
Scan Information				
Wire ID	90-16-T3_105mm_Trued_11.15.18			
Length [mm]	105			
Scan Date	11.15.18			
Proc Date	09.17.19			
Stat Date	09.17.19			
ID	Indents	Nominal Dia [mm]	Orientat-ion [deg]	Distance [mm]
Total	45	5.264	47.9	5.250
Row 1	15		46.0	5.215
Row 2	15		-52.6	5.268
Row 3	15		45.1	5.268

Not Available

Indent Data								
ID	Indents	Volume [mm^3]	S.W. Area [mm^2]	Avg Depth [mm]	S.W. Angle [deg]	Avg Length [mm]	Width [mm]	Pitch [mm]
Total	45	1.091	1.030	0.156	32.43	3.817	2.069	6.343
Row 1	15	1.337	1.167	0.177	32.70	3.862	2.189	6.333
Row 2	15	0.962	0.886	0.146	32.63	3.823	1.945	6.365
Row 3	15	0.975	1.037	0.143	31.97	3.767	2.072	6.331

S.W. Area: The average sidewall area of the left and right side of the indents.

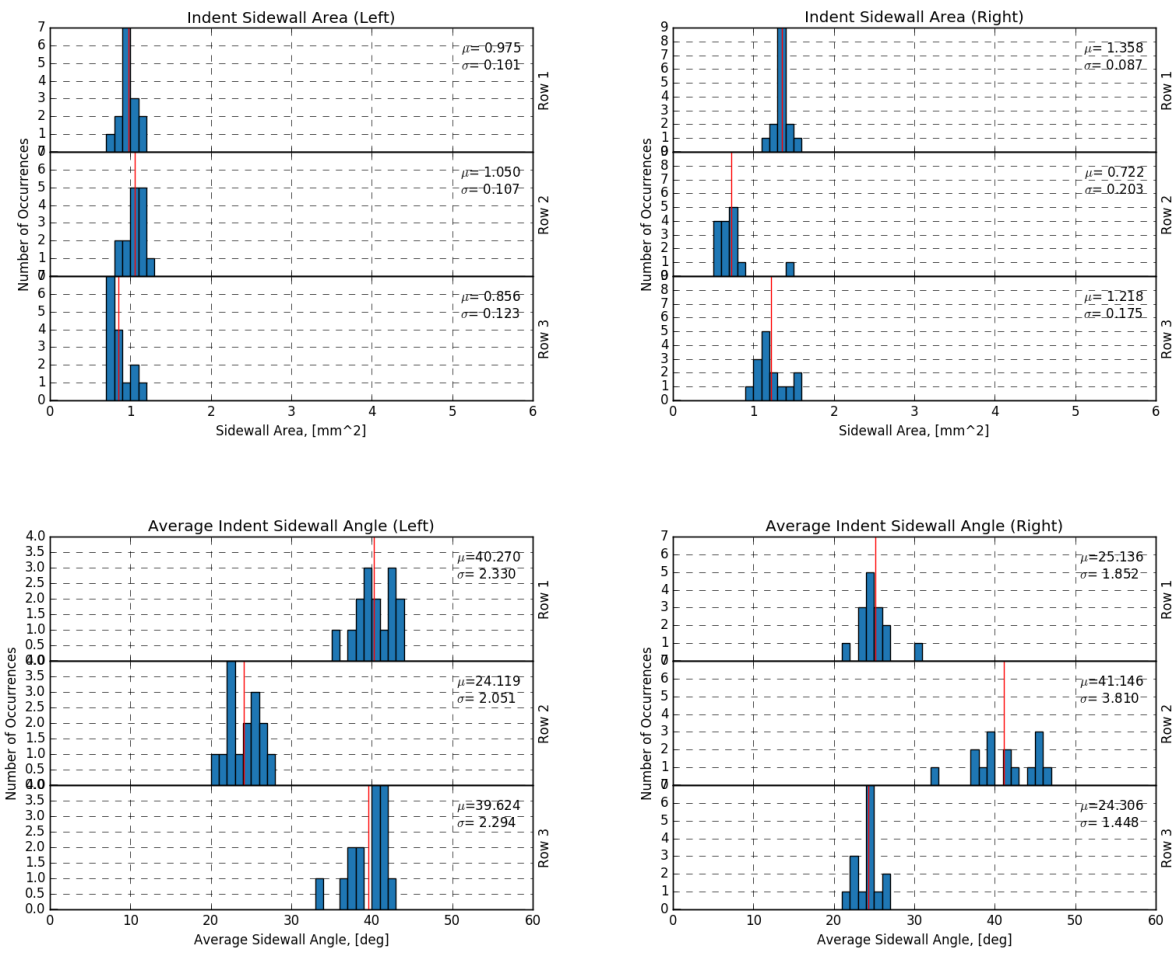
S.W. Angle: The average sidewall angle of the left and right side of the indents.



TEST REPORT: INDENT PROFILER

WIRE ID: 90-D

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TEST REPORT: ASTM A881

WIRE ID: 90-D

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SAMPLE ID		90-.16- T3_105mm_Trued_11.15.18
SAMPLE LENGTH [MM]		105
NOMINAL DIAMETER [MM]		5.264
TEST ITEM	STANDARD VALUE	ACTUAL VALUE
INDENT DEPTH [MM]	0.115±0.035	0.156
SIDEWALL ANGLE [DEG]	In Contract	32.4
INDENT LENGTH [MM]	3.5±0.5	3.921
INDENT PITCH [MM]	5.46±0.29	6.34
ORIENTATION ANGLE [DEG]	≥45°	47.9
OUT OF ROUND [MM]	≤0.08	TBD

TEST REPORT: ISO 10138-2

WIRE ID:90-D

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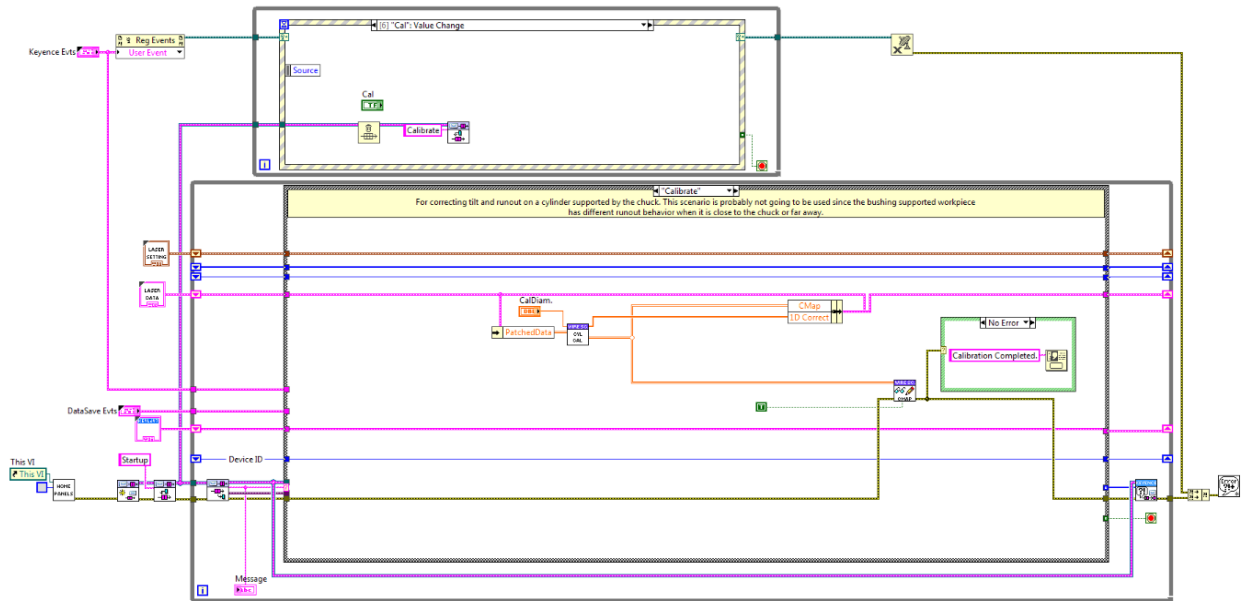
SAMPLE ID		90-.16- T3_105mm_Trued_11.15.18
SAMPLE LENGTH		105
NOMINAL DIAMETER		5.264
TEST ITEM	STANDARD VALUE	ACTUAL VALUE
INDENT LENGTH [MM]	3.5±0.5	3.921
INDENT DEPTH [MM]	0.15±0.05	0.156
INDENT SPACING [MM]	5.50±0.50	3.34
INDENT DISTANCE [MM]	$\Sigma e \leq 3.343$	5.22, 5.27, 5.27
AVG DIAMETER [MM]	-	TBD
OVALITY	$\leq 0.01 \times D$	TBD

End of Appendix C

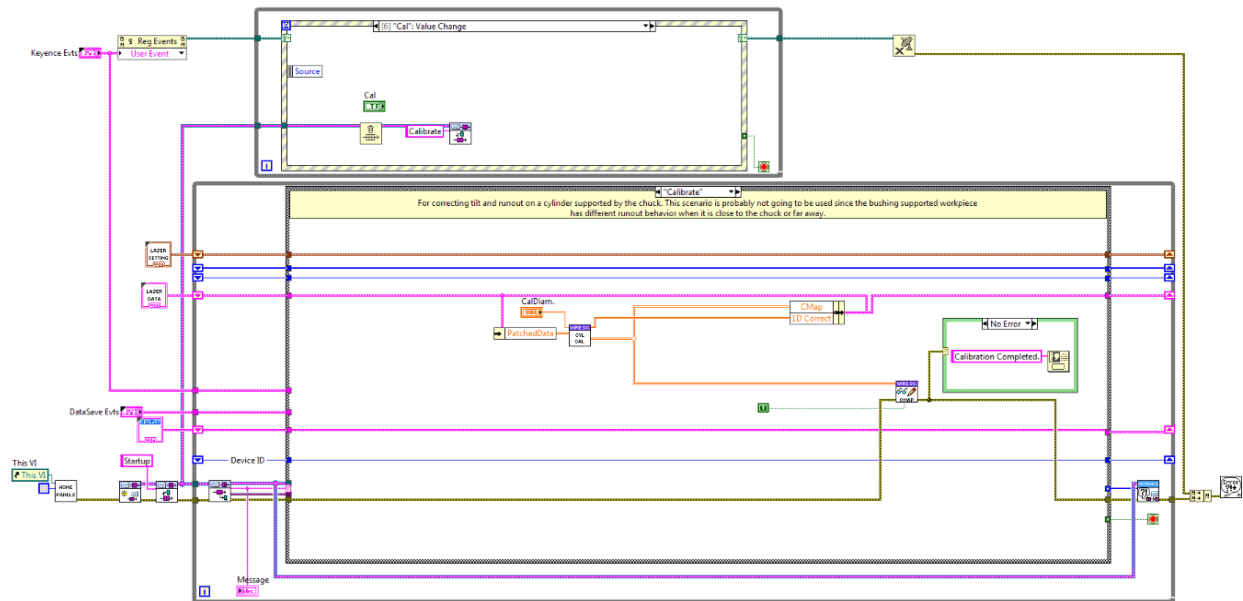
Appendix D - LabVIEW VI Layout

This Appendix contains the base LabVIEW VI layouts used in the data acquisition and data processing stages of the Indent Profiling System. The LabVIEW program makes extensive use of subVIs that complicate program visualization, as such, the main components of the program are listed below for the sake of posterity and completeness.

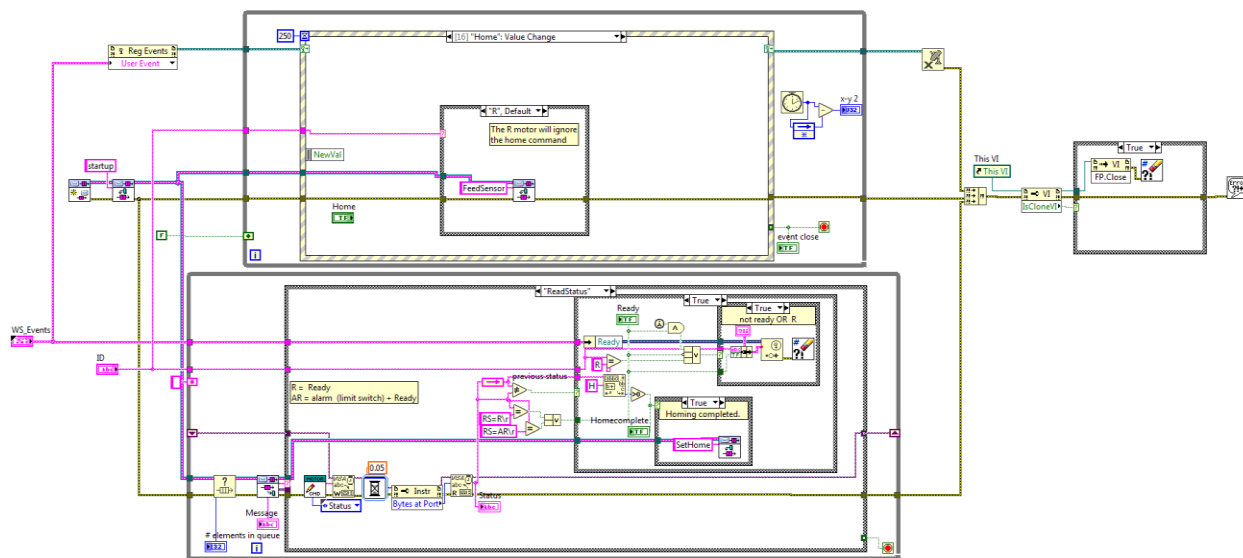
WS_Main: The VI that is launched when the laser scanner is operating.



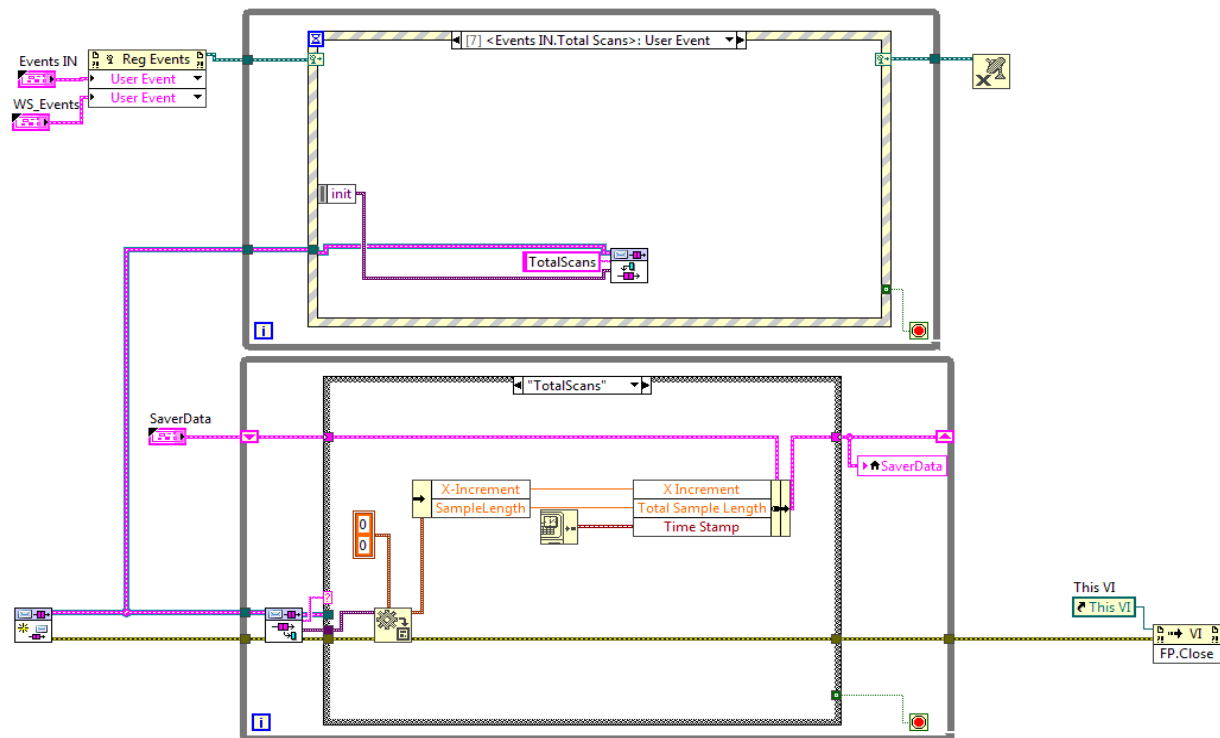
Keyence_Interface: Utilized by WS_Main and handles the communication with the Keyence laser line scanner.



Motor_Control: Launched by WS_Main and handles the stepper motor control for rotation and axial movement.



Save_Data: Used by WS_Main to handle the saving of the scan files to permanent storage.



WS_Viewer: The application that opens the scan files and processes them.

