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EFFECT OF COOLANT AND LUBRICANT ON TOOL-LIFE

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by

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REVIEW OF TOOL-LIFE TESTING AND TOOL LIFE EQUATIONS

The first comprehensive report dealing with the tool-life testing and tool-life equations was presented by F. W. Taylor in 1906[(1)*]. In 1930, T. G. Digges[(2)] published a general tool-life equation, using cemented carbide as the tool material. His paper gives complete information on ninety-seven tests.

The contemporary authorities in tool-life testing are O. W. Boston[(3)] and W. W. Gilbert[(4)], both of whom followed the general pattern of Taylor's approach. B. N. Colding's[(5)] paper presented a different approach to find a new tool-life equation. He has introduced the concept of "chip equivalent" as one of the new variables involved in machining. The idea of a "response surface" has been used most recently by Professor S. M. Wu[(12)] of The University of Wisconsin in tool-life testing and in finding a tool-life equation. The work of these authors will be reviewed briefly. Other contributors to this field of tool-life testing and tool-life equation studies include Dronenberg, Semko, Siekman, French, Bayonne, Digge, and Woxen. Contributions have also been made from other countries like Russia, but their approach has followed Taylor's principle and hence, will not be discussed here.

*Numbers in parenthesis refer to the references in bibliography.

F. W. Taylor

The paper presented at the New York meeting (December, 1906) of ASME, on "The Art of Cutting Metals," by F. W. Taylor was one of the first comprehensive reports dealing with the subject of metal cutting. Taylor's results were based on experimental data collected over a period of twenty-six years (1880-1906). From 30,000 to 50,000 recorded experiments were made, and 800,000 pounds of steel and iron were cut. The basic principle of tool-life testing and the fundamental tool-life equations used today were suggested by F. W. Taylor. The efforts he made were unprecedented and his influence is still felt in many phases of metal cutting.

In dealing with tool-life testing, Taylor listed twelve variables.

1. Quality of the metal to be cut.
2. Diameter of the work.
3. Depth of cut.
4. Feed.
5. Elasticity of work and tool.
6. Shape or contour of the cutting edge together with its clearance and lip angles.
7. Chemical composition and heat treatment of the tool.
8. Cooling medium.
9. Tool-life.
10. Cutting force.
11. Possible speeds and feeds in the lathe.
12. Power of the lathe.

In 1895, Taylor's famous tool-life equation $VT^n = C$, was determined (V designated cutting speed, T designated tool-life, and n and c were constants).

Taylor found n by finding tool-life at twenty minutes. The general tool-life equation, $VT^n f^m d^p = K$*, was also proposed. Taylor argued that the smaller the nose radius, the thicker is the chip and the smaller is the cutting speed. Trying to include nose radius, r, in the equation, he found a very complex equation.

$$V = \frac{\text{Constant } \left(1 - \frac{8}{7(32r)}\right)}{f^{\frac{2}{s}} + \frac{2.12}{5 + 32\ r} \quad \left(\frac{48}{32\ r}\ d\right) \quad \frac{2}{15} + 0.06 \sqrt{32r} + \frac{0.8(32r)}{6(32r)+48d}}$$

The equation was so complicated that it was rarely mentioned in other papers. Hence, never used.

The important fact was the attempt that Taylor made to summarize his results into a mathematical equation, but quoting his own words, "By far the most difficult and illusive portion of this work has been the mathematical side."

One of the great contributions by Taylor was his method of research. He emphasized the "One-Variable-at-a-Time" method to determine the effect of the individual variables. For the last sixty years this has been the most dominating research method in the field of metal cutting.

F. W. Taylor was the first investigator to study the effect of cooling the tool with a heavy stream of water. He gave the concept of a closed cyclic system for the flow of water supersaturated with soda to prevent the machines from rusting. By using about three gallons of water per minute for a large roughing tool (say two inches by two and one-half inches) he found a gain in cutting speed of 40% for H.S.S. tools.

Taylor's recommendation regarding the point of application of the jet of water is worth observing. To quote his own words,

*Refer to Nomenclature.

"We, therefore, arranged for a strong water jet to be thrown, between the clearance flank of the tool and the flank of the forging, and made a series of experiments to determine the cooling effect of water with various feeds and depths of cut. So confident were we of the truth of this theory that we did not deem it worth while to experiment with throwing streams of water in any other way until months afterward, when upon throwing a stream of water upon the chip directly at the point where it is being removed from the forging by the tool, we found a material increase in the cutting speed, and thus our first experiments rendered valueless."*

At the present time, experiments have shown that Taylor's former approach was correct. W. E. Lauterback[11] has shown a 107 percent increase in tool-life when the cutting oil is directed up in the clearance crevice instead of directing down on tool chip.

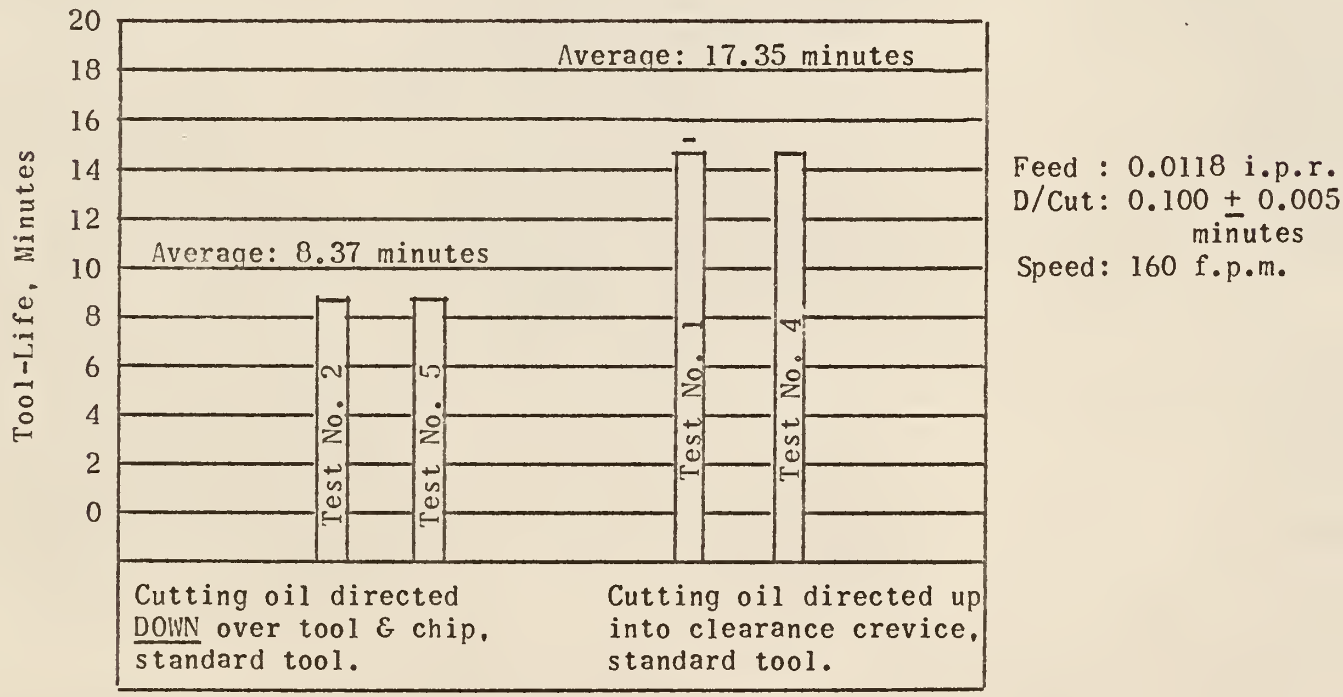

FIGURE 1
INFLUENCE OF POINT OF APPLICATION OF
CUTTING OIL ON TOOL-LIFE

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*Paragraph 608, "The Art of Cutting Metals," by F. W. Taylor.

Works of Poliakoff, Smith, and Jinaya, Ripper and Burley, Herber, Smith and Leight; and Smith and Hey in 1910's after Taylor in the field of metal cutting and the application of cutting fluid in tool-life testing can be seen from Table I. The method of tests were either direct measurements or indirect methods of measurement of tool wear.

In 1930, French, Bayonne and Digge[10] in combination, studied the effect of lard oil and water on the cutting speed of H.S.S. tools.

Mathematically, their results are given as:

For dry tests: $VT^{0.100} = 485$

For tests with lard oil: $VT^{0.115} = 567$

For tests with water: $VT^{0.131} = 585$

The form of the equations suggest that they have adopted Taylor's basic equation $VT^n = C$. Author feels that such a type of equation does not have much practical value.

T. G. Digges

T. G. Digges was, perhaps, the first one to study the general tool-life equation using carbide tools. Following F. W. Taylor's general approach, Digges found for a tool-life of 90 minutes, after ninety-seven tests, that,

$$V\ f^{0.58}\ d^{0.2} = K = 12 \tag{2.1}$$

By keeping the feed and depth of cut constant, he first established a relationship between V and T by plotting the data which was shown in Table 2.1 on a log-log coordinates. He found $n = \frac{1}{5}$ and $C = 255$ in $VT^n=C$.

He then ran a series of tests with constant depth of cut (d = 0.1875") while varying feeds from 0.031 to 0.098 inches per revolution. The results, based on a tool-life of 90 minutes, are given in Table 2-1. From there, he found,

$$V\ f^{0.58} = 16.6$$

TABLE I

Investigator	Criterion of Tool Failure	Tool Steel	Metal Cut	Approx. feeds ipr	Range of depths in.	Coolant	Effect of Cutting Speed on Tool
Poliakoff	0.0015 in wear	C and H.S.S.	0.35 C. Steel	0.014	0.0056	Soap	Life Irregular with respect to cutting speed.
Smith and Tinoya	0.001 in wear	C and H.S.S.	Medium Stell	0.05	0.003	Soda and Water	Life increases with speed.
Ripper and Burley	0.005 in wear	C and H.S.S.	Mild to very hard steel	0.00275	0.020/0-12	Dry	For C tool steel: $V \; C/A$ For H.S.S. $V \; \frac{K_1}{r^{2/3}} - (K_2 - K_3 f)$*d
Herbert	0.001 in wear	C and H.S.S.		0.0021	0.0625	Water in Tube	Life irregular with respect to cutting speed.

*Refer Nomenclature.

Forging No.*	Cutting Conditions			Number of Tests	Average Tool Life, min.	Calculated Cutting Speed + ft.per.min.	Average Power required in cutting k.w.
	Speed, per.min.	Feed, per.rev.	Depth, inches				
44 & 45 ...	90	0.031	0.1875	5	155.9	93	4.1
44 & 45 ...	110	0.031	0.1875	6	74.9	108	5.4
44 & 45 ...	120	0.031	0.1875	6	45.9	119	5.5
44 & 45 ...	130	0.031	0.1875	3	26.7	132	6.2
44 & 45 ...	140	0.031	0.1875	6	21.2	139	6.4
44 & 45 ...	160	0.031	0.1875	5	9.0	164	6.8

TABLE 2-1

*All tests were run dry.

+ Computed by means of equation $VT^n = C$ with $n = \frac{1}{5}$ and $C = 255$.

Forging No.	CUTTING CONDITIONS			TOOL-Life Min.							Average Tool-Life Min.	Cutting Speed- 90 Min. Ft./Min.	Average Power Required in Cutting k.w.
	Speed Ft./Min.	Feed In./Rev.	Depth In.	Test 1	Test 2	Test 3	Test 4	Test 5	Test 6	Test 7			
52	160	0.031	0.1875	30.6	11.5	21.2	20.8	20.8	27.3	25.0	22.5	121	5.5
52	120	0.054	0.1875	26.9	31.0	27.3	40.5	12.2	26.4	6	27.4	94	7.1
52	105	0.078	0.1875	23.3	8.0	12.1	16.0	6*	12.7	12.6	14.1	72	8.5
52	90	0.096	0.1875	16.7	14.8	19.3	6	9.1	16.7	6	15.3	63	9.3

TABLE 2-2

*b. Tool Broke.

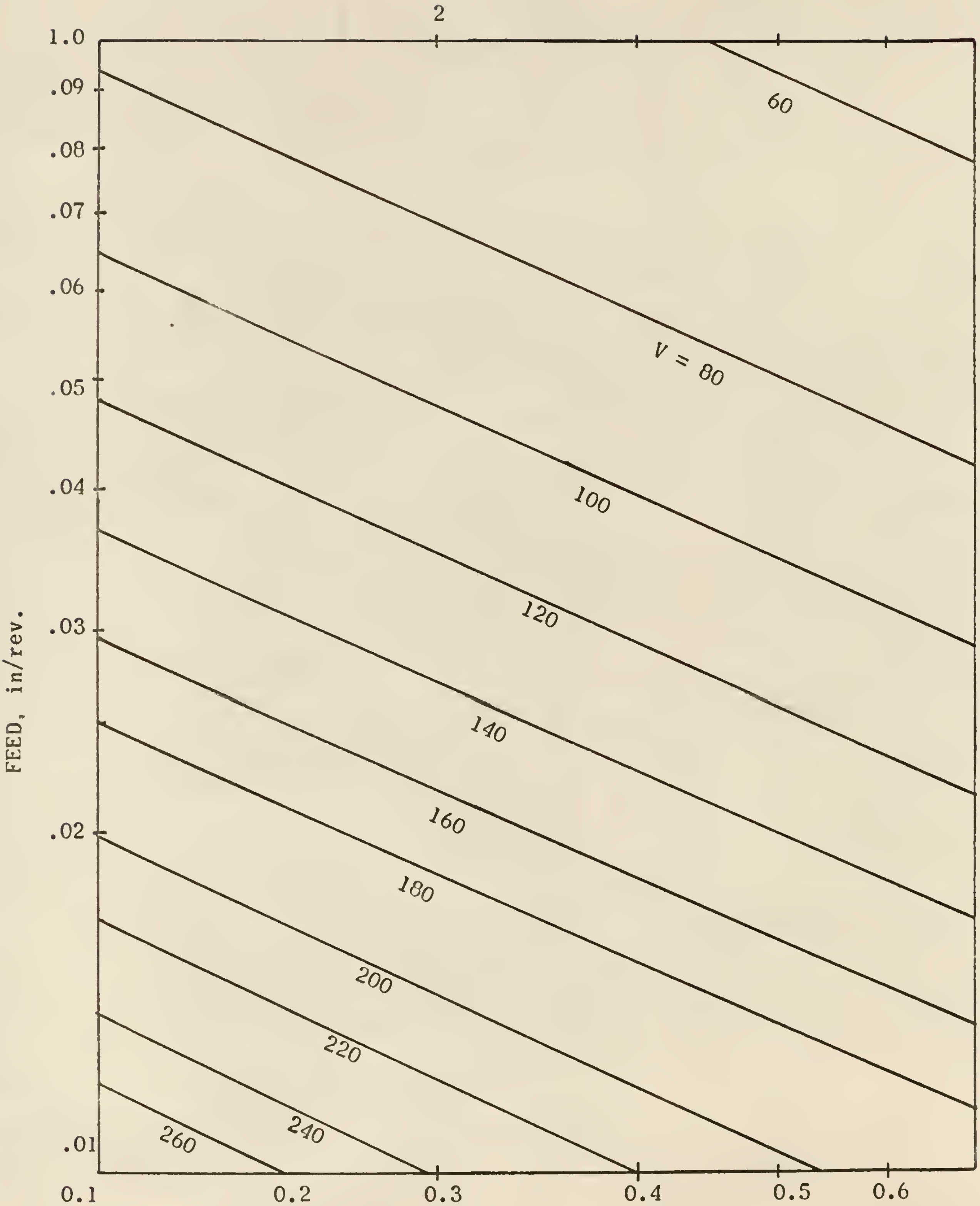

FIGURE 2-1

CUTTING SPEED - FEED - DEPTH CHART FOR SELECTED SIZE AND FORM OF TOOLS AND CUTTING MATERIAL

During the second series of tests, he kept the feed constant at 0.031 inches per revolution, but varied depths of cut from 0.125 to 0.5625 inches, The results, based again on a tool-life of 90 minutes, showed that

$$Vd^{0.2} = 90.$$

By combining the relationship of V, f and d and setting T = 90 minutes, Digges proposed the general tool-life equation (2-1). Using this equation, Digges made the cutting - speed - feed - depth chart (Figure 2-1), for a 90 minute tool-life. It should be noted, however, that the relationship of Vf and Vd is based on the assumption that $n = \frac{1}{5}$.

To use the chart (Figure 2-1), one would find the intersection of the desired feed and depth coordinates. This point of intersection will give the approximate cutting speed V for a tool-life of 90 minutes. The cutting speed for a tool-life within the range of 1 to 200 minutes may be obtained by recalculating the relationship of V, f, and d.

A brief comment on Digges' paper is as follows:

a. It is well known that the composition of the material cut is an important variable in any tool-life test. This fact has been completely ignored by Digges. Not only the six figures used by Digges had different chemical composition but they also had different heat treatments and different mechanical properties. This can be seen from his report[2] published in 1930.

b. From Table 2-1, the actual speed, V and the calculated speed, $\bar{V}$, were compared.

V	$\bar{V}$	$V-\bar{V}$
90	93	-3
110	108	+2
120	119	+1
130	132	-2
140	139	+1
160	164	-4

Hence, $\sum (V - \bar{V}) = -5$. If the estimate of 'n' is the best estimation, $\sum (V - \bar{V})$ should be zero.

c. Estimation of the exponential constants m and p was entirely based upon the value of n. If n were not accurate, then m and p would not be accurate.

O. W. BOSTON AND W. W. GILBERT

Boston's approach in studying tool-life testing and the tool-life equation was basically similar to that of Taylor's. However, Boston made one change. Taylor gave a rating to the tool according to the value of cutting speed required to cause complete tool failure in twenty minutes. Boston pointed out that almost any change in tool, material, cutting fluid and machining variables (n..e feed and depth of cut), might cause a change in the value of 'n,' the exponential constant in the tool-life equation $VT^n = C$. Therefore, the rating based on the cutting speed for a twenty-minute tool-life would not correspond with the similar rating based on some other cutting speed, such as a sixty-minute tool-life. Taylor assumed that the slope n, of all the tool-life lines for H.S.S. tools turning steels was equal to $\frac{1}{8}$. Boston from his twenty-five years of research, concluded that n might cover a range from $\frac{1}{3}$ to $\frac{1}{25}$. Thus, a large number of lines of different slopes may pass through the point of cutting speed for a twnety-minute tool-life and have different values for speed for another tool-life. Boston recommended that a number of tests should be run at different speeds to give corresponding values of tool-life. This is the common practice in tool-life testing now-a-days.

As for the criterion of tool-life, Boston used complete tool failure as the basis for indicating tool-life of H.S.S. tools. According to him, flank wear was the best way for evaluating cemented carbide tool failures. This eventually led to the generally accepted criterion of 0.030" flank wear for carbide tool-life testing. He also proposed a general tool-life equation for H.S.S. tools.

$$V_{90}\ f^{0.77}\ d^{\ 0.37} = k$$

where

K = 1.2 for dry cutting.

W. W. Gilbert, a close associate of Boston at the University of Michigan, now working with General Electric Company, also proposed a general tool-life equation, using Boston's data. The equation is:

$$VT^{0.125}\ f^{0.61}\ d^{0.36} = K_{tm}\ K_{mc}{}^{*}$$

Using this equation, Gilbert devised tool-life monographs. These monographs formed the basis for the design of the machinability computer which was used to provide operating information about metal cutting for the solution of production problems.

B. N. COLDING

In studying machine economics, B. N. Colding started doubting that the Taylor's equation $VT^n = C$ was really the fundamental one in the field of metal cutting. Colding proposed a three-dimensional tool-life equation by deriving an approximate relationship between tool-life, cutting speed,

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*explained in the nomenclature.

feed, depth of cut, nose radius and side cutting edge angle, taking into account the variation of the exponent, 'n'.

a. "Chip Equivalent."

The three-dimensional tool-life equation was derived by using a new variable called "Chip Equivalent," q. This term was suggested by R. Woxen in 1931, and defined by,

$$q = \frac{L}{A_0} \text{ *}$$

The chip equivalent, q, is a physical quantity which, together with cutting speed, V, and material properties, determines the temperature in the cutting edge.

From Figure 3, it can be seen that,

$$L = \frac{d - r\,(1 - \sin \alpha)}{\cos \alpha} + \frac{(90 - \alpha)}{180}\ \pi\ V + \frac{f}{2}$$

and $A_0 = d.f.$

Woxen showed by the use of the tool-work thermocouple method and tool-life data:

1. That the same temperature was obtained, if feed, depth of cut, nose radius, and side cutting edge angle were combined so that the values of the chip equivalent were equal, the cutting speed being constant.
2. For a constant value of chip equivalent the temperature rises with increased cutting speed.
3. For the same cutting speed the temperature rises with a diminished chip equivalent.
4. A generalized tool-life equivalent may be written,

$$V = \left(\frac{T^*}{T}\right).\ C_e.\ \frac{q + q_0}{1 + C_w q}$$

T = An arbitrary tool-life.

T*= A certain tool-life; e.g., 60 minute.

But, this was never derived and it drew much criticism against its validity from R. C. Brewer*.

b. "Dimensional Analysis."

Colding proposed a new general tool-life equation through the dimensional analysis technique by using the chip equivalent, q, and the cutting speed, V, as two independent variables. The physical quantities regarded as essential for the analysis are contained in Table 3.

TABLE 3

Physical Quantity	Symbol	Dimension
Tool-life ...	T	(T)
Cutting speed	V	(LT^{-1})
Chip equivalent	q	(L^{-1})
Thermal conductivity	k	$(MLT^{-3}\theta^{-1})$
Volume specific heat	P_c	$(M\ L^{-1}\ T^{-2}\ \theta^{-1})$
Thermal diffusivity	$K\ \frac{k}{P_c}$	$(L^2\ T^{-1})$

An application of the principles of dimensional analysis to the quantities T, V, q, and K yielded the equation,

$$KT\ q^2 = \varphi\ (V\ T\ q) \qquad (2\text{-}2)$$

By plotting the actual data on log-log graph paper (e.g., $KT\ q^2$ versus $(VT\ q)\frac{1}{2}$ holding T and K constant), a straight line relationship was found. Hence, function (2-2) could be written as,

$$(KT\ q^2) = U\ (VT\ q2^{\frac{B}{}} \qquad (2\text{-}3)$$

Where U is a dimensionless constant and B is the slope corresponding to a

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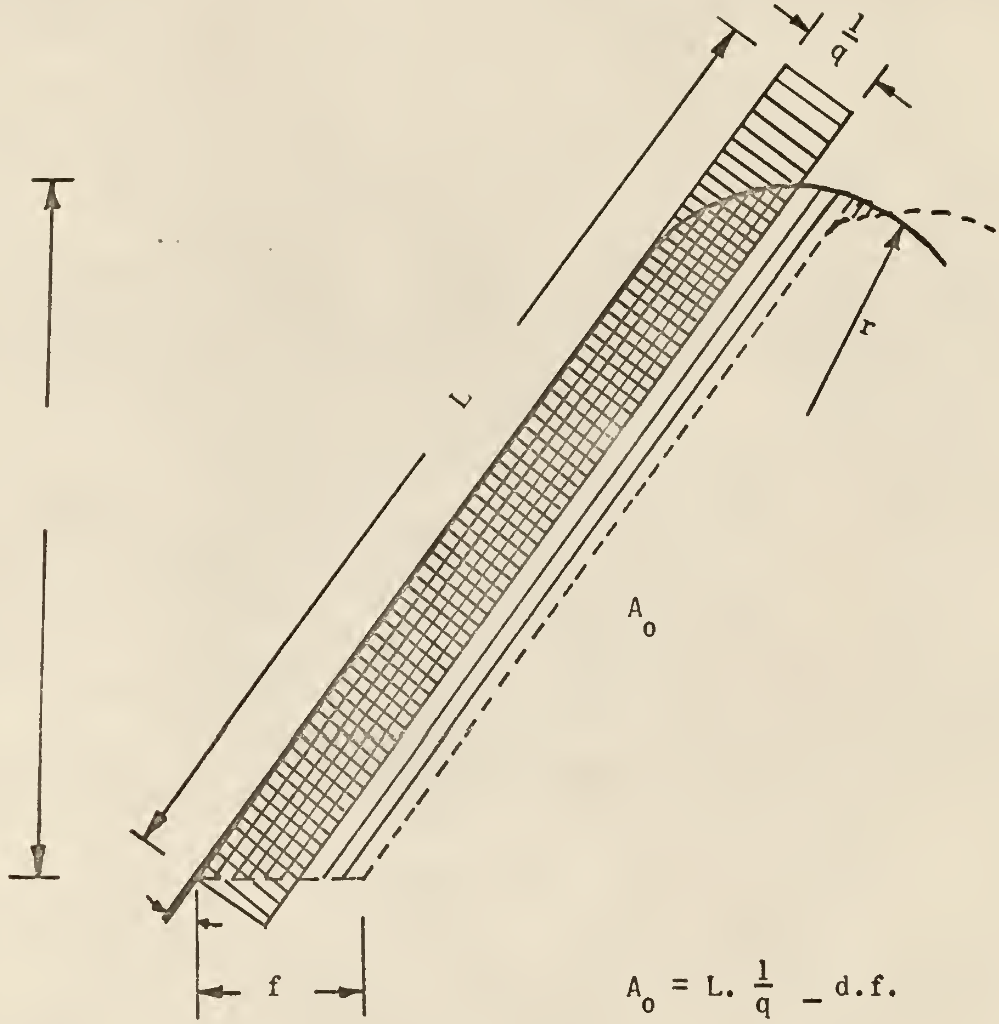


$A_o = L.\ \frac{1}{q}\ \_\ d.f.$

$q\ -\ \frac{L}{d.f.}$

FIGURE 3-1
DEFINITION OF CHIP EQUIVALENT

certain tool-life T. From (2-3) the corresponding cutting speed V_T could be written as,

$$V_T = (\Omega_T)^{\beta T}\ T^{\beta T-1}\ q^{2\beta T-1} \qquad (2\text{-}4)$$

where

$$\Omega_T = \frac{K_T}{U_T}\ ,\ \beta_T = \frac{2}{B}$$

If T = 1, then

$$V_1 = (\Omega_1)^{\beta 1}\ q^{2\beta 1^{-1}} = C \qquad (2\text{-}5)$$

Note that V_1 was the constant C in Taylor's equation $VT^n = C$. Therefore,

$$VT^n = (\Omega_1)^{\beta 1}\ q^{2\beta 1^{-1}} \qquad (2\text{-}6)$$

or $\quad VT^n + A\ q^m$

where $A = (\Omega_1)^{\beta 1}$ and $m = 2\beta_1 - 1$ are constants valid for the particular combination of tool-work, and tool angles considered.

Variation of the exponent n was obtained by introducing equation (2-4) into (2-6)

$$T^n = A\ \Omega_T{}^{-\beta T}\ T^{1-\beta T}\ q^{m-2\beta T+1} \qquad (2\text{-}7)$$

Choosing a particular value of T, e.g., T = 60 minutes,

$$e^{a_o \cdot n} = B\ q^{(m-1)} \qquad (2\text{-}8)$$

where $A_o = \log 60,\ 1 = 2\beta_{60} - 1$

$$B\ \frac{A}{(\Omega_{60})^{\beta 60}}\ 60^{1-\beta}60$$

Rewritting (2-8), we get:

$$n\ \frac{1}{A_o}\left[\log B\ q^{(m-1)}\right] \qquad (2\text{-}9)$$

Determination of constants S, B, m, and 1 was done from the graphs on the basis of two accurately determined tool-life relations, e.g., q = 1, q = 3, or q = 10 and q = 15.

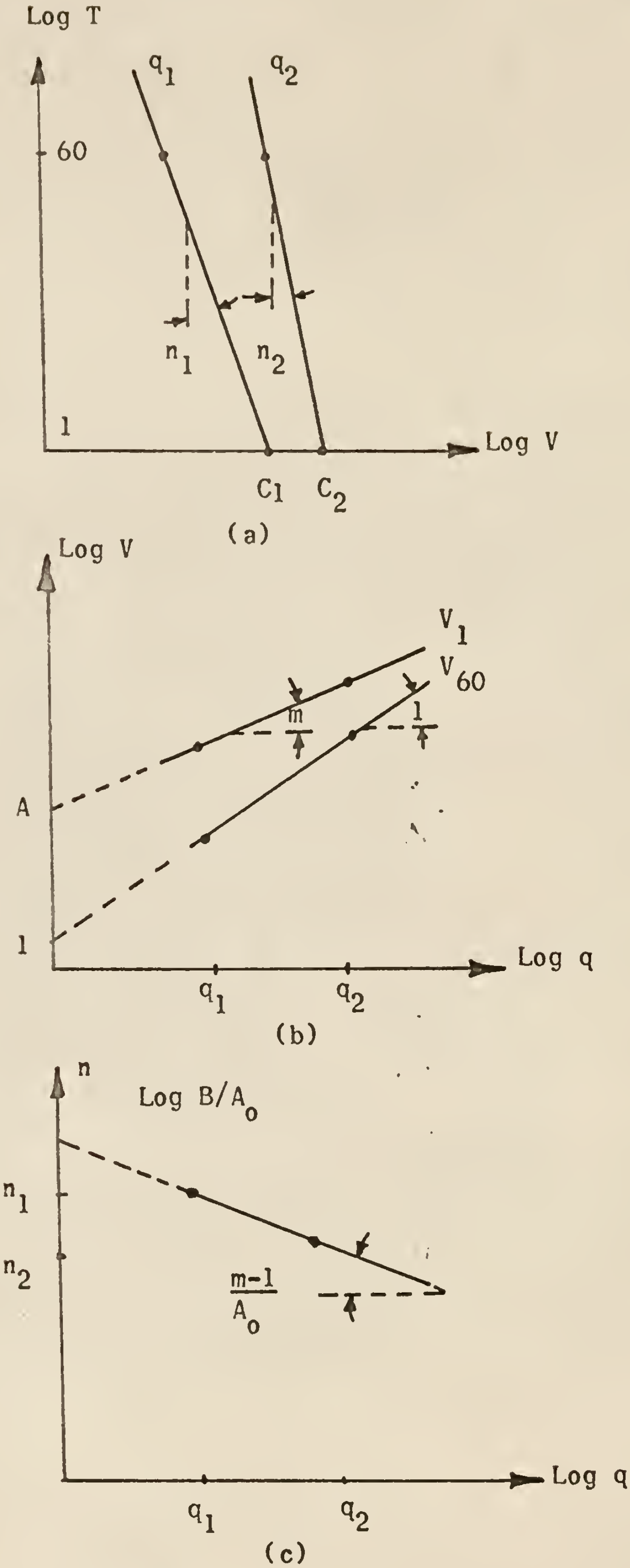


FIGURE 3-2

PRINCIPLES TO DETERMINE A LIMITED TOOL-LIFE EQUATION FOR ARBITRARY q ON BASIS OF TWO EXPERIMENTAL CURVES

In Figure 3-2 (a), a schematic representation of two tool-life circuits for $q = q$, and $q = q_2$ gave the slopes n_1, and n_2, and the constants C_1 and C_2. In Figure 3-2 (b), V_1 and V_{60} were plotted against q, yielding the values of m, l, and A. Therefore, Equation (2-6) was determined, except for the variation of n with q. By plotting the values of n_1 and n_2 from Figure 3-2 (a) versus q_1 and q_2, as was done in Figure 3-2 (c), equations (2-8) and (2-9) were established.

Equation (2-6), (2-8), and (2-9) constituted a general, approximate tool-life equation for V, T, and q. Colding suggested that these general equations had advantages over other equations, much as $VT^n F^m d^b = K$, because the latter equation takes into consideration the variation of the exponent n, while the general equations be proposed depended solely on the chip equivalent.

The contribution Colding made in deriving his general tool-life equation deserves close attention because (1) he put five variables in one equation which was a new attempt to form a tool-life equation, and (ii) his equation was independent of the exponent n.

S. M. Wu

S. M. Wu, was perhaps, the first to adopt the concept of a response or dependent variables as a surface to the theory of metal (12) cutting. This paper, presented at the Production Engineering Conference, Cincinnati, Ohio, May 7-9, 1963, of the American Society of Mechanical Engineers, was a portion of his Ph.D. Thesis. At the time of writting this thesis, the author did not see any published paper which has given an equation for tool-life like the one given by S. M. Wu. Ahtour believes, that by using the equation proposed by S. M. Wu, the tool-life can be most conveniently and accurately calculated for any combination of the machining variables (speed, feed, depth of cut).

Dr. S. M. Wu assumed the functional relationship $VT^n f^m d^b = K$ and proposed a tool-life equation which has been verified by twelve tests. The tool-life predicting equation is:

$$\bar{Y} = 4.231 - 0.846\ x_1 = 0.164\ x_2 = 0.089\ x_3$$

where

$$x_1 = \frac{2(\ln V - \ln 700)}{(\ln 700 - \ln 330)} + 1$$

$$x_2 = \frac{2(\ln f - \ln 0.022)}{(\ln 0.022 - \ln 0.010)} + 1$$

$$x_3 = \frac{2(\ln d - \ln 0.100)}{(\ln 0.100 - \ln 0.049)} + 1$$

Since the predicting equation is a first-order linear equation, the response surfaces are constant tool-life planes (Figure 4).

The experiment was a 2^3 factorial design with an added center point repeated four times. To give a brief comment on S. M. Wu's paper:

1. The tool-life criteria was assumed to be 0.030 inches of flank wear without any proof. This criteria is a matter of slight controversy today. He found flank wear to increase linearly with respect to time which disproves the idea forwarded by Bickel (29).
2. It has been concluded that the effects of depth of cut on tool-life is almost negligible and the effect of feed is also relatively small as compared with the effect of the cutting speed.
3. The tool-life testing was done under the dry condition.

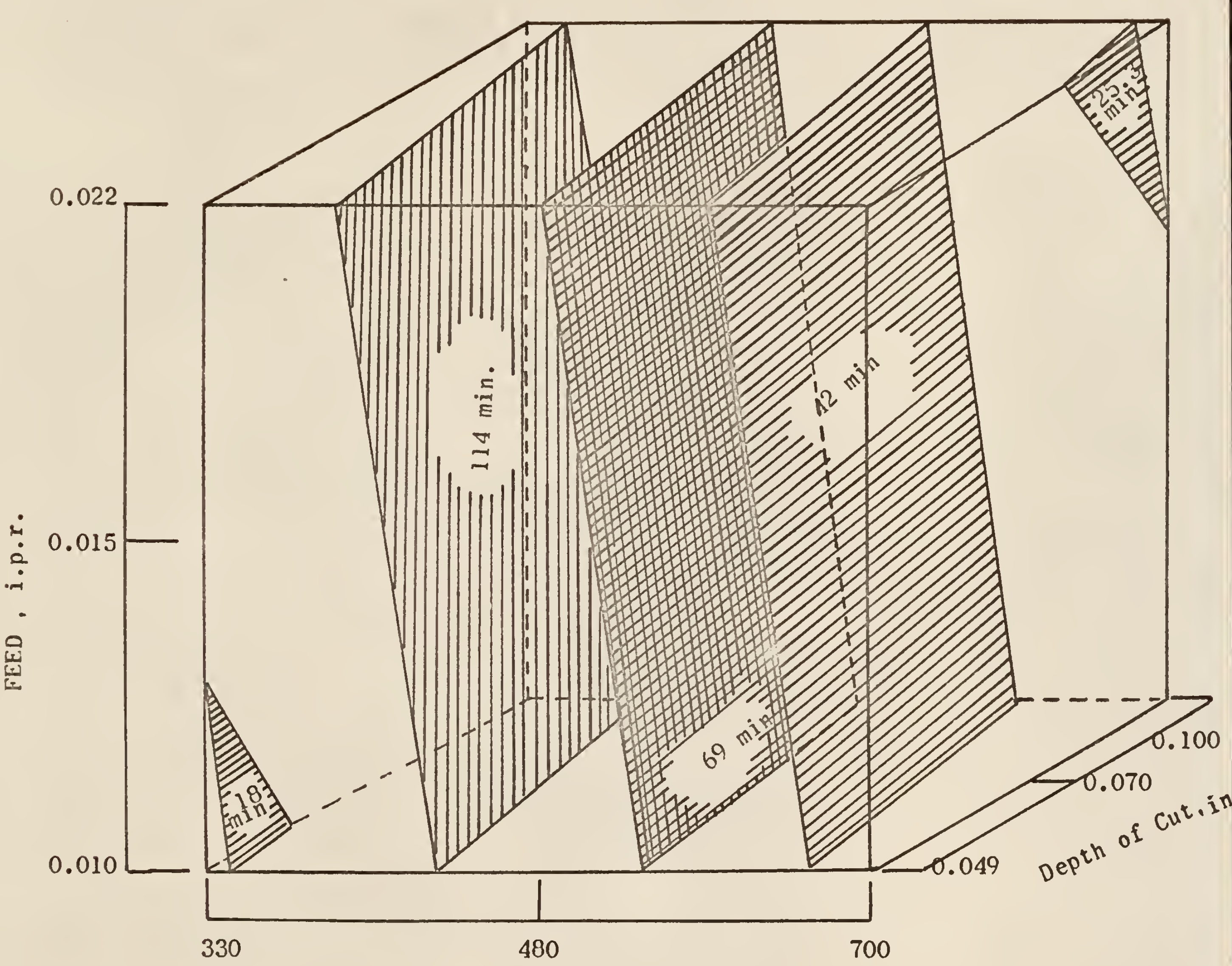


FIGURE 4

TOOL-LIFE RESPONSE SURFACE

UNIT: min

$\bar{y} = 4.231 - 0.846\ X_1 - 0.164\ X_2 - 0.089\ X_3$

PRESENT KNOWLEDGE OF CUTTING FLUIDS

The improvement in tool-life by the application of cutting fluid to a machining operation was shown by F. W. Taylor in his paper[1] presented at the 1906 Conference of ASME. His cutting fluid was a stream of water supersaturated with soda to prevent the machine from rusting. He found a gain in cutting speed of 40% for H.S.S. tools.

In 1930's, French, Bayone and Digges[10] in combination, studied the effect of lard oil and water on the cutting speed of H.S.S. tools. Mathematically, their results are:

For dry tests: $VT^{0.100} = 485$

For tests with lard oil: $VT^{0.115} = 547$

For tests with water : $VT^{0.131} = 585$

Currently, Author feels, that the research on cutting fluids has been mainly directed towards the evaluation of the effects of the different chemical compounds present in them. Author, at the time of writting this thesis, did not find any published literature, which has given a quantitative approach to study the effect of the application of cutting fluid on tool-life.

Works of investigators like L. H. Sudholz[13], K. E. Bisshopp, E. F. Lype, and S. Raynor[14]; M. E. Merchant [15]; W. E. Lauterback and E. A. Ratzel[16]; S. J. Beaubien[17]; F. J. Daasch, S. L. Eisler, W. D. McHenry, and R. K. Paton[18]; D. Kcecioglu and A. Sorensen, Jr.[19] are worth mentioning.

L. H. Sudholz, after performing Almen and Falex tests could not conclude anything definitely and recommended that tests should be performed by employing actual metal cutting observations. However, from the results of threading tests on a laboratory test lathe, he found that the maximum tool-life is effected when the total sulphur content is approximately 1.7% and maximum tool-life is obtained when the active sulphur content is approximately 0.9%. He also performed tapping and drilling tests. But finally he concluded that accurate evaluations of cutting fluids can be conducted only in metal cutting equipment. In another of his works, he recommends a radioactive tracer method to study the performance of cutting fluids[21].

Bishop, Lype, and Raynor, in their paper[14] have attempted to prove that a hydrodynamic film cannot exist at the point of cutting tool. Though the conclusion is obviously valid, still M.C. Shaw does not believe in the argument cited.

Past research[20] in the field of metal cutting has revealed certain basic facts that have a direct bearing on the action of a cutting fluid. In the process of chip formation, heat is developed from two sources:

1. The energy used up in deforming the metal.

2. The energy used up in overcoming friction between the chip and tool.

The basic process of chip formation is shown in Figure 5.

According to Merchant[15], the two basic functions which any cutting fluid must perform well are:

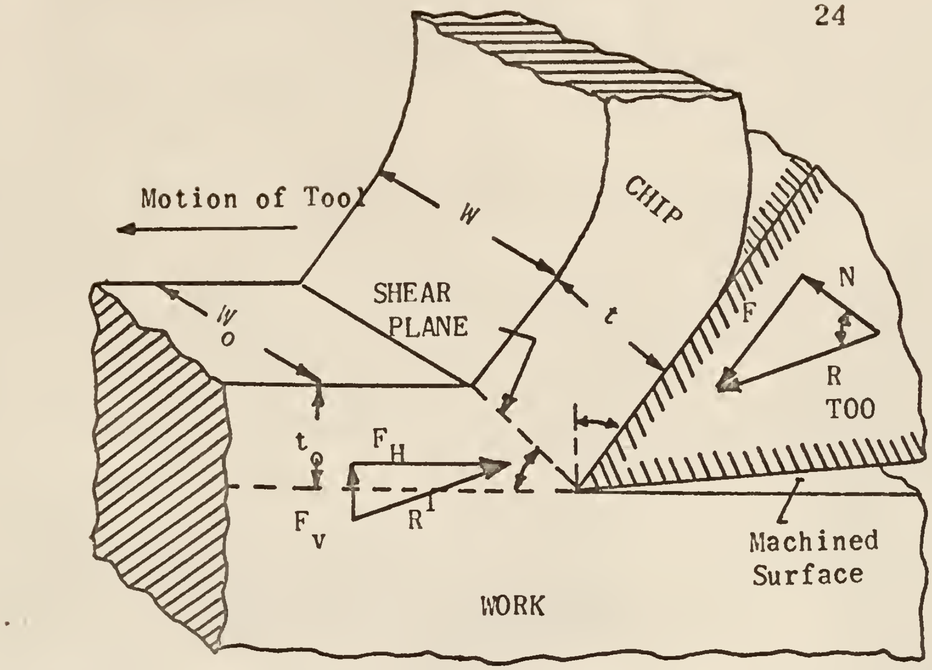
1. To remove heat from the cutting tool, workpiece and chips (i.e., to cool).

2. To reduce the friction between the flowing chip and the cutting tool, thus reducing the heat generated in cutting and in addition providing other benefits.

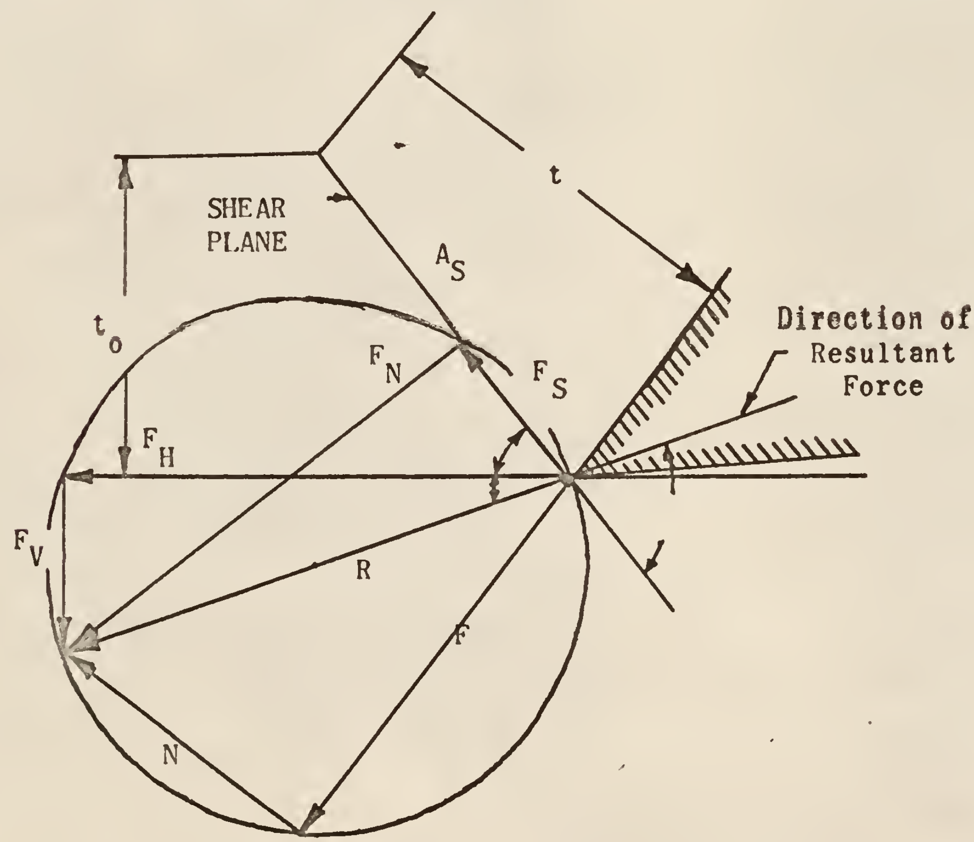
In his paper[15] he has evaluated the reduction in friction due to the application of cutting fluids and compared it with the reduction in shear strength. Lauterback and E. A. Ratzel[16] concluded that the cutting oil penetrates between the tool and workpiece and between the tool and chip through the clearnace crevice and not from the rake crevice, for very low cutting speeds. Cutting fluid does not provide hydrodynamic lubrication at higher cutting speeds. Beaubien, in his experiment[17], has tried to study the effect of fluid properties on surface finish and tool forces. He concluded that for single contact cutting, cooling due to the application of fluid seems to have a slight negative effect on surface finish. Also, no significant effect of cooling on the magnitude of the resultant tool force has been found.

Daasch, Eisler, McHenry and Paton[18] used mathematical statistics to evaluate the relative performance of the emulsifiable iols and three compounded mineral oils by the use of radioactive tools. By using the technique of analysis of variance, a significant difference was found in the rate of tool wear between the mineral oils and the emulsifiable oils; however, there was no significant difference noted between the oils within either group. A parallel study of tangential and feed forces proved insensitive for the conditions of their tests. They also found a significant difference between the tools. This difference could not be explained as all tools were originally from the same piece and were prepared to the same specification.

In contrast with Daasch[18] is criterion on q tool wear for evaluating cutting luids, H. W. Husa and W. L. Bulkley[22] of Standard Oil Company, suggested strongly that the most reliable technique requires the evaluation of wear rate, cutting temperature and surface finish. If this is not possible, at least wear rate and surface finish or wear rate and temperature should be used.



MODEL FOR ORTHOGONAL METAL CUTTING



FORCE SYSTEM IN ORTHOGONAL METAL CUTTING

Dimitri Kececioglu and Arthur Sorensen(19) found from their experimental analysis that flood cooling is sent best to mist cooling in improving tool-life at speeds below 590 fpm. At certain combinations of feeds and speeds, dry cutting gave better machinability factors than either mist a flood cooling.

TOOL-LIFE AND IT'S IMPORTANCE

The importance of tool-life is obvious from the amount of past research. Only a few have attempted to put a quantitative approach in their research to analyze the tool-life. Work of Dr. S. M. Wu in arriving at a tool-life predicting equation through response surface metodology is a significant step in the science of metal cutting. However,he did not take cutting fluids into consideration. The importance of the direct cooling action of a cutting fluid in increasing tool-life and so saving money for the users cannot be over emphasized. The present workis carried out to predict the tool-life under the application of different cutting fluids. Although, this sounds very simple, no one has found such predicting equations. The past research on tool-life has mainly been concentrated in studying the effect of the different chemical composition of the fluids on tool-life.

Before attempting to study the tool-life, an attempt was made to see the behavior of cutting and feeding forces developed in turning mild steel under the application of cutting fluids. After several runs under different cutting conditions, no significant difference was observed in the magnitude of these forces for different fluids. The forces are recorded with the help of a lathe dynamometer and a two-channel Sanborn recorder. The results can be seen from Figure 7. This result is in agreement with the work of F. J. Daasch[18].

For a number of years, it has been common practice to select the proper cutting fluid for a particular operation on the basis of experience with the same or similar materials. Since there are many types and brands available, and in some cases no past experience to draw upon the user generally has been unable to make the best selection. This has been further complicated by the lack of a standard method to evaluate cutting fluids. The writer feels that some form of a functional approach to determine the tool-life

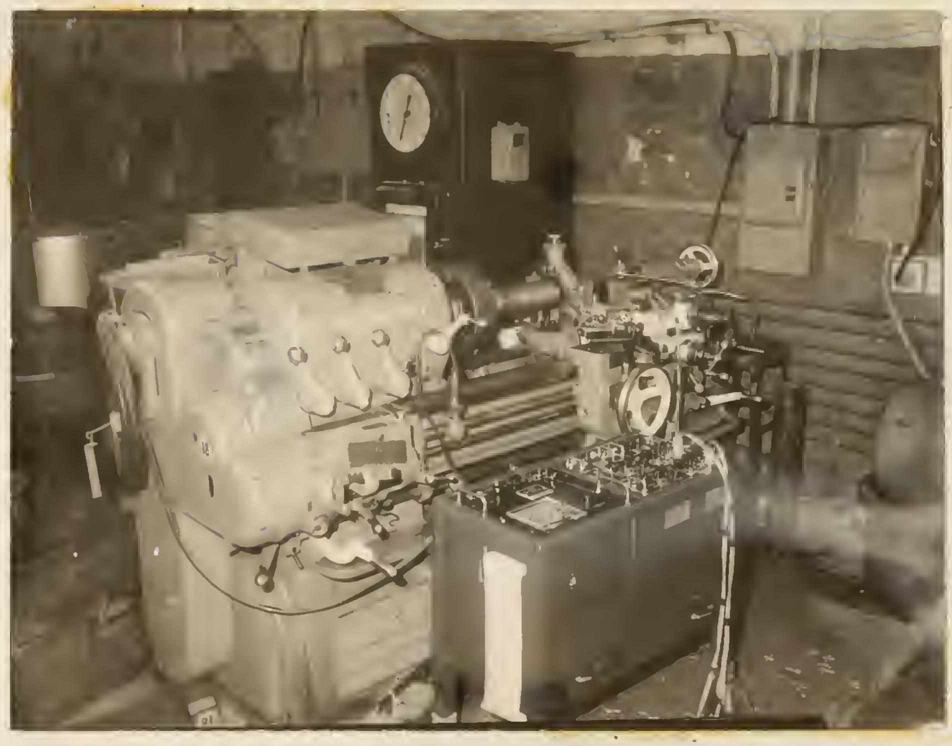


FIGURE 6

MACHINE SET-UP FOR RECORDING TOOL FORCES WITH A TWO-CHANNEL SANBORN RECORDER AND A LATHE DYNAMOMETER

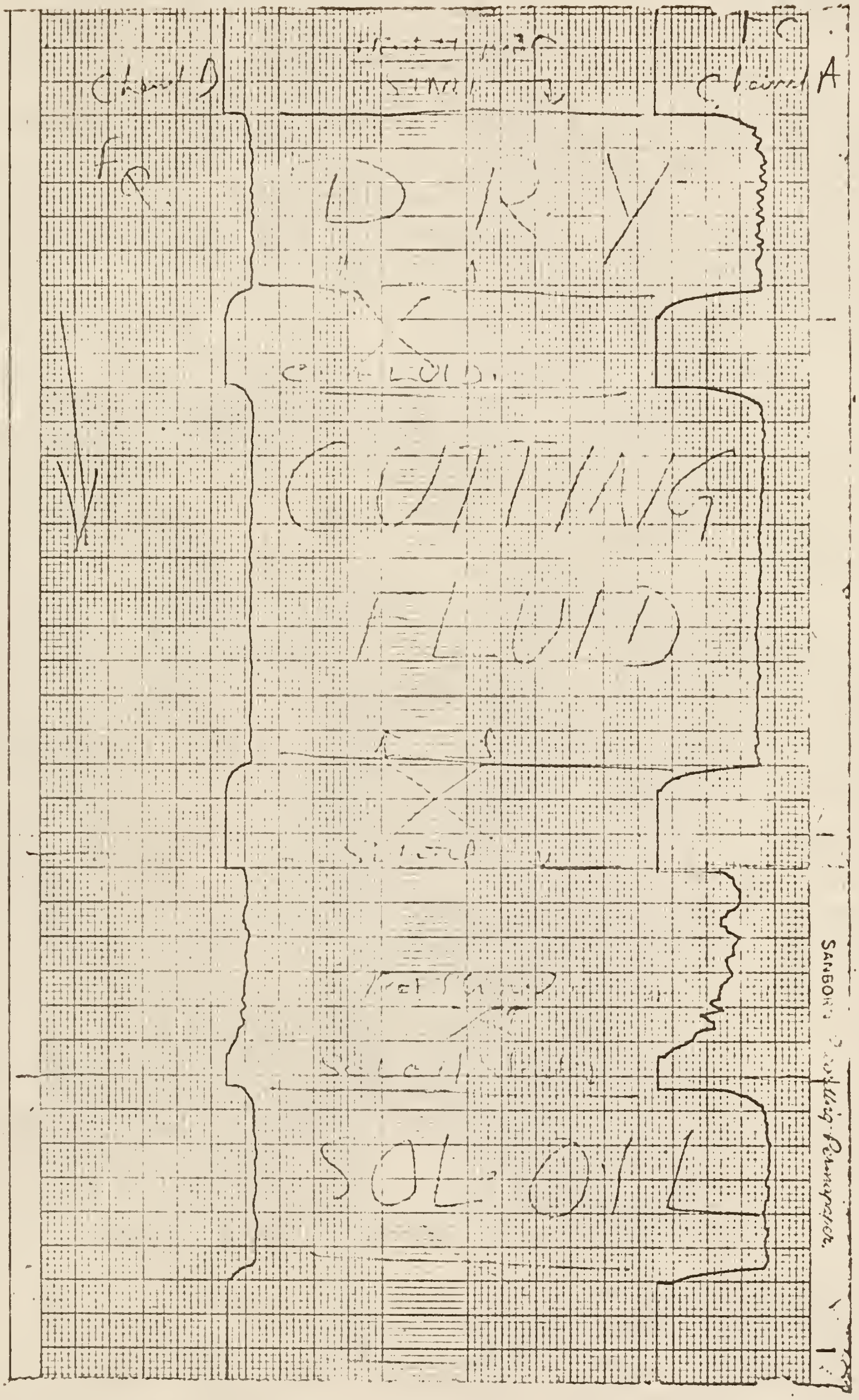


Figure 7
VARIATION IN CUTTING FORCE AND FEED FORCE UNDER DIFFERENT CUTTING COMPOUND

different machining conditions should be supplied with a cutting fluid for the common materials that are used day-to-day. Keeping this in mind, the present work is carried out to study the effects of different machining variables on tool-life under the application of cutting fluids and no fluid and to determine the tool-life predicting equations.

DESIGN OF THE EXPERIMENT

The statistical technique of analysis of variance was choosen as the statistical method of the features of the analysis of variance is that the variability of the components in an experiment is measured in terms of sums of squares of deviation about the general mean or average. These components of total variability may be calssified under two main catagories:

1. Those ascribable to cause variations. These include the effects of different factors or combinations of factors.
2. That due to random variations, or variations between observations due to non-assignable or uncontrollable factors. This residual variance may then be used to test the significance of the effects of several factors on the experimental data.

Thus, analysis of variance is a powerful technique to use when variations in data may come from several variables. The results of the analysis with inform the investigator which variables have pronounced effects on the data. The greater the residual variance the greater the other variances must prove to be significant.

Snedecor's Variance Ratio or F-test, will reveal if non-equal variances are significantly different or are different only because of random or uncontrollable variations in the data, and that due to sampling error.

To test for a significant difference in variances, the hypothesis is made that there is no significant differences in the variances. This rull hypothesis is tested by means of tables of percentage points of the F distribution. These tables show (for a given ratio of variances and given degrees of freedom) the probability of error if the hypothesis is rejected.

Selection of Factors

Though the factors that affect the machining conditions are numerous it was considered appropriate to limit the controlling factors to cutting speed, rate of feed, and the different varieties of cutting fluids. It should be emphasized that apart from these three factors, there are many others which have a direct bearing on the values of the tool-life. To name a few, depth of cut, change of tool angles, machining at different temperatures, etc., could all be expected to create dissimilar machining conditions and thereby, after the magnitude of the tool-life. However, building a statistical model to accomodate all these different factors would complicate the experimental design. Further, controlling all these factors at different levels according to the design requirements is often impracticable in many instances. Therefore, it was decided to consider for this experiment, only three of the more important factors, which have decisive influence on the tool-life. The three factors considered are:

1. The cutting speed in feet per minute.
2. The rate of feed in inches per revolution.
3. Different cutting fluids.

The experimental data measured was the tool-life in minutes. Here again it may be suggested that many other forms of experimental data could be gathered to supplement the tool-life, as the test criteria. For example, the surface finish, tool temperature, the chip thickness and type and others may be investigated as dependent variables. In this project, however, the variable of interest was the tool-life and hence effort was made to measure and analyze only this factor.

Selection of the Levels of Factors

Rate of Feed

The magnitude and span of the levels of feed were influenced by running trial tests on the test material prior to the actual experiment. Before choosing the rates of feed, it was decided to observe a particular value for the depth of cut. It was observed in these trial tests that a depth of cut of 0.3125 ($\frac{5}{16}$ of an inch) could produce a significant tool wear above which it was difficult to measure the data. It was, therefore, proposed to fix the depth of cut at $\frac{5}{16}$ inch and to maintain this constant throughout the experiment, along with other constant factors.

The necessity of accepting a depth of cut of $\frac{5}{16}$ inch, it became apparent that a feed rate of over 0.020 ipr resulted in excessive tool wear and found to be extremely rapid and gave rise to land and crater wear and welding action of the chip to the tool. The tool wear observed at high feed rates was so high that total destriction of the tool became a problem. Hence, it was concluded that the maximum level of feed should be 0.020 ipr. According to the availability of the feeds on the lathe it was decided to fix the levels ipr respectively, and these are designated as F_1, F_2, F_3, and F_4 respectively.

Cutting Speed

Persisting with the trial tests, it became clear that at speeds exceeding 100 rpm (115 sfpm), excessive heat generation, welding of the chip on to the tool and the machine load bearing capacity became a cause of concern. Hence, the upper limit of cutting speed was fixed at 100 rpm or 116 sfpm and then the four levels of speed selected as follows:'

S_1 = 36 rpm (38 sfpm)
S_2 = 58 rpm (61 sfpm)
S_3 = 91 rpm (95 sfpm)
S_4 = 110 rpm (115 sfpm)

Cutting Fluid

The main objective of this project is to study the behavior of tool-life while machining with and without cutting fluids. In practice, machining is done usually with some type of cutting fluids. For a manufacturer, cost is the main criteria for using a cutting fluid. There should be some way that the user of a cutting fluid can know the benefits he can derive from it in advance. Bearing this in mind, two tool-life predicting equations have been suggested for two different cutting fluids. The selection of cutting fluids was done on the basis of their practical use. Two fluids were choosen for this project which were most widely used in industry. The cutting media are designated as follows:

C_1: Cutting oil, sulphurized, fatty, mineral. Type A, Grade B.
Supplied by J. W. Kelley Company, Cleveland.

C_2: Soluble oil, Supprala
Supplied by Standard Oil Company, Concentration. 1:10

C_3: Dry

Advantages Pertaining to Factorial Models

For the study of the variations brought about by deliberate changes in the experimental conditions, a generally useful technique is provided by the factorial experiment. The general intention of an experiment similar to the one used is to appraise the effects of one or more factors on the experimental outcome of the proposed study. A considerable advantage is gained if the experiment is so designed that the effect of changing any one variable can be assessed independently of the others. One way of achieveing this objective is to decide over a set of values or levels, for each of the factors to be studied, and to carry out one or more trials of the process with each of the possible combinations of the levels of the factors. A further interesting property of a factorial design is that it is possible to study the interacting nature of the variables. By interaction is meant the failure of the levels of one factor to retain the same order and magnitude of performance (within random sampling errors) throughout all levels of another factor. Thus, if the effect of one factor is dependent on the level of another factor, then the two factors are said to interact. It is imperative to note that in experiments where numerous factors appear, a study of interaction between factors aids in illuminating the combinational effects of the factors on the experimental data. Furthermore, when factors are not independent the simple effects of a factor vary according to the particular comtaintion of the other factors with which they are produced.

The main advantages of a factorial arrangement may be summarized as follows:

1. Greater efficiency in the use of available experimental resources is achieved.
2. Information is obtained about various interactions.
3. The experimental results are applicable over a wide range of conditions, that is, due to the combining of the various factors in one experiment, the results are of more comprehensive nature.

The experimental design adopted for this project is of a "Factorial Classification in a Completely Randomized Design," type. This completely randomized design has several conveniences.

1. Complete flexibility is allowed. Any number of treatments and of replicates may be used. All the available experimental material can be utilized -- an advantage in small preliminary experiments where the supply of material is scarce.

2. The statistical analysis is easy even if the number of replicates are not the same for all treatments or if the experimental errors differ from treatment to treatment.
3. The method of analysis remains simple when the results from some units or from whole treatments are missing or are rejected. Moreover, the relative loss of information due to missing data is smaller than with any other design.

No replication was done due to the non-availability of material. The loss of accuracy due to this can be compensated to some entent by the fact that the material was quite homogeneous in nature. The structure of the material has been tested (Figure 12).

Randomization

Randomization avoids biasness. With a repetitious operation, like this, the order of the events may be important, either because of learning process is involved which tends to make later operations better than the earlier ones, or because fatigue tends in the opposite direction. Systematic biases is guarded against by randomizing the order in which the operation is performed on the different treatments.

Having decided upon four levels of feed, four levels of speed, and three different forms of cutting media, there arise in all 4 x 4 x 3 = 48 different cutting fluid - feed - speed combinations, or 48 different treatments possibilities within the scope of this experiment. The 48 possible combinations are shown on the next page.

TABLE 4

Serial No.	Speed	Feed	Cutting Media	Serial No.	Speed	Feed	Cutting Media	Serial No.	Speed	Feed	Cutting Media
1	S_1*	F_1*	C_1*	17	S_2	F_1	C_2	33	S_3	F_1	C_3
2	S_1	F_2	C_1	18	S_2	F_2	C_2	34	S_3	F_2	C_3
3	S_1	F_3	C_1	19	S_2	F_3	C_2	35	S_3	F_3	C_3
4	S_1	F_4	C_1	20	S_2	F_4	C_2	36	S_3	F_4	C_3
5	S_1	F_1	C_2	21	S_2	F_1	C_3	37	S_4	F_1	C_1
6	S_1	F_2	C_2	22	S_2	F_2	C_3	38	S_4	F_2	C_1
7	S_1	F_3	C_2	23	S_2	F_3	C_3	39	S_4	F_3	C_1
8	S_1	F_4	C_2	24	S_2	F_4	C_3	40	S_4	F_4	C_1
9	S_1	F_2	C_3	25	S_3	F_1	C_1	41	S_4	F_1	C_2
10	S_1	F_2	C_3	26	S_3	F_2	C_1	42	S_4	F_2	C_2
11	S_1	F_3	C_3	27	S_3	F_3	C_1	43	S_4	F_3	C_2
12	S_1	F_4	C_3	28	S_3	F_4	C_1	44	S_4	F_4	C_2
13	S_2	F_1	C_1	29	S_3	F_1	C_2	45	S_4	F_1	C_3
14	S_2	F_2	C_1	30	S_3	F_2	C_2	46	S_4	F_2	C_3
15	S_2	F_3	C_1	31	S_3	F_3	C_2	47	S_4	F_3	C_3
16	S_2	F_4	C_1	32	S_3	F_4	C_2	48	S_4	F_4	C_3

*S_1 = 38 sfpm (36 rpm) F_1 = 0.006 ipr C_1 = Cutting oil
S_2 = 61 sfpm (58 rpm) F_2 = 0.010 ipr C_2 = Soluble Oil
S_3 = 95 sfpm (91 rpm) F_3 = 0.015 ipr C_3 = Dry
S_4 = 115 sfpm (110 rpm) F_4 = 0.020 ipr

In randomizing the sequence of operations, help of a random number table has been taken. The random numbers picked up from the table refer to the serial number of Table 4. The first number picked up from the random number table, which corresponds to a certain serial number of Table 4, is given first priority for the sequences of operation. The second number picked up is given second priority and so on until all 48 combinations are exhausted. Random numbers which are greater than 48 neglected. Two R. N. Digits were picked up.

Table 5 shows the designated machining combinations and the results of picking up a two-digit number from a random number table to give the sequence of treatment combinations. Machining was then performed keeping strictly to the randomized pattern.

TABLE 5
SEQUENCE OF OPERATION UNDER THE 48 DIFFERENT TREATMENTS

Random Number	Experiment Number	TREATMENTS Speed sfpm	Feed ipr	Cutting Media	Random Number	Experiment Number	TREATMENTS Speed sfpm	Feed ipr	Cutting Media
10	1	38	0.010	Dry	40	25	115	0.020	C.oil
22	2	61	0.010	Dry	12	26	38	0.020	Dry
24	3	61	0.020	Dry	21	27	61	0.006	Dry
42	4	115	0.010	S.oil	27	28	95	0.015	C.oil
37	5	115	0.006	C.oil	33	29	95	0.006	Dry
28	6	95	0.020	C.oil	20	30	61	0.020	S.oil
09	7	38	0.006	Dry	04	31	38	0.020	C.oil
07	8	38	0.015	S.oil	26	32	95	0.010	C.oil
02	9	38	0.010	C.oil	18	33	61	0.010	S.oil
01	10	38	0.006	C.oil	11	34	38	0.015	Dry
48	11	115	0.020	Dry	35	35	95	0.015	Dry
32	12	95	0.020	S.oil	31	36	95	0.015	S.oil
29	13	95	0.006	S.oil	16	37	61	0.020	C.oil
05	14	38	0.006	S.oil	03	38	38	0.015	C.oil
25	15	95	0.006	C.oil	30	39	95	0.010	S.oil
17	16	61	0.006	S.oil	38	40	115	0.010	C.oil
46	17	115	0.010	Dry	23	41	61	0.015	Dry
14	18	61	0.010	C.oil	47	42	115	0.015	Dry
34	19	95	0.010	Dry	13	43	61	0.006	C.oil
08	20	38	0.020	S.oil	19	44	61	0.015	S.oil
15	21	61	0.015	C.oil	44	45	115	0.020	S.oil
39	22	115	0.015	C.oil	45	46	115	0.006	Dry
06	23	38	0.010	S.oil	41	47	115	0.006	S.oil
36	24	95	0.020	Dry	43	48	115	0.015	S.oil

TOOL-LIFE MEASUREMENT

Tool-life tests which are conducted primarily to indicate proper techniques need not be very precise due to the relatively large normal variations which occur in practice. However, in order to study tool-life from a scientific point of view, tests of high precision are required. Precision and repeatability are difficult to obtain because most tool-life tests are inherently long time tests requiring large amounts of tool and work materials. Even with extreme care, there will be some variation of the physical and metaurgical properties of two pieces of material. Indeed, even in one large billet it is difficult to obtain homogeneous structure.

One of the variations most difficult to exclude from tool-life tests is that due to grinding and setting the tool. Apparently insignificant differences such as a slight change in wheel dressing technique can alter the surface properties of the tool and hence alter tool-life.

In the past, wear land values have been measured directly using a Brinell microscope. The resulting data have dhown considerable scatter indicating a large amount of uncertainty in the measurements. This scatter may be attributed to two main causes.

1. Due to the variations of the wear land across the tool. This leads to difficulties in determining the exact extent of the wear land (see Figure 8).
2. Due to a more subtle cause that is inherent in the wear land technique. When an amount of metal ABC is worn from the clearance face of a tool, the extent of the wear land is BC (Figure 8) For a zero make angle tool,

   $BC = AB \cot \theta$

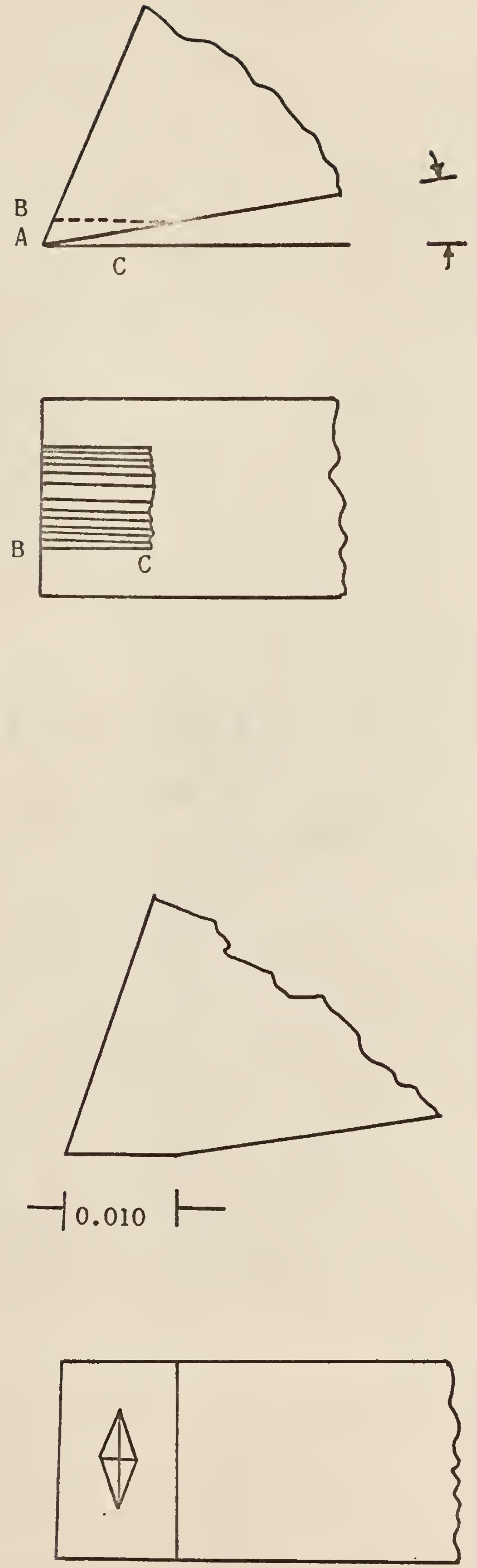


FIGURE 8

VARIATION IN WEAR LAND AND THE POSITION OF THE INDENTATION where θ is the clearance angle. The amount removed is,

$$ABC = \frac{1}{2} \cdot BC \cdot \frac{BC}{\cot\theta} = \frac{(BC)^2}{2\cot\theta}$$

for a given amount of wear (i.e., ABC = const),

$$BC \sim \sqrt{\cot\theta}$$

and the change of BC (ΔBC) corresponding to a small change in θ , ($\Delta\theta$) is

$$\frac{\Delta BC}{BC} = -\frac{1}{2}\ \frac{\Delta\theta}{\theta}$$

Thus, for $\theta = 5^0$ and $\Delta\theta = 2^0$ (11^0) BC will have a total variation of 20 percent, and it is seen that slight errors in grinding and setting will lead to large errors in the data.

The method adopted here was initially proposed by M. C. Shaw[23], and has been characterized as the "diamond indentor technique." This technique rests heavily on the assumption that the wear shows a linear trend with time. This is very true as seen from past research.

Diamond Indentor Technique

The foregoing difficulties can be overcome by the use of impressions made in the clearance face of a tool with an oversize Knoop hardness indentor. By making an impression on the wear land of a tool, subsequent wear can be conveniently and precisely determined. The pyramidal diamond used in the following test had a length to depth ratio of 30·53. Thus, the actual wear which is measured by the change in depth of the impression, is multiplied by 30·53 when readings are made of the change in length of the longest diagonal. The multiplying factor thus obtained is much greater than when directly measuring the length of the wear land, and is not influenced by errors in clearance angle. Also, the measurement reference points are very sharp as compared to the ragged end of a wear land.

Hence, reproducibility of tool-life data should be greatly improved by use of the diamond indentor method. Furthermore, the amount of metal that must be cut in order to obtain wear data can be reduced by taking advantage of the fact that tool wear on the clearance face is linear with time. The following procedure was adopted to make full use of the above possibilities for obtaining precise, reproducible wear data.

1. The freshly sharpened test tool was held in a universal vise and an artificially wear land very close to 0.010 inch was carefully ground on the clearance face by means of a surface grinder.
2. The tool was placed in a Vickers hardness testing machine in which a Knoop indentor was used to put an impression on the wear land as shown in Figure 9.
3. A small amount was cut to condition the wear land and cause it to wear in.
4. Successive readings of the major diagonal of the impression are then made with a microscope attached to the lathe and the wear rate is thus established.

Since most wear data are expressed in terms of a standard wear land, it is convenient to convert the impression readings to equivalent wear land values.

For a clearance angle of θ degree,

$$\Delta BC \quad \frac{\cot\theta}{30.53} \, \Delta C$$

where ΔBC is the increase of wear land corresponding to a decrease of impression diagonal ΔC.

The inverse slope of the curve plotted with wear as ordinate and time as abscisa will give the rate of wear. It is evident that the wear rate is essentially constant for a given speed and the data may be entrapolated

FIGURE 9

THE KNOOP'S INDENTATION ON THE CLEARANCE FACE OF THE TOOL
THE TOP EDGE IN THE PHOTOGRAPH REFERS TO THE CUTTING EDGE

to produce a standard wear land of length BC. Thus,

$$T = 30{\cdot}53 \cdot \frac{BC}{\cot\theta} \cdot \frac{dT}{dC} \qquad (3)$$

where $\frac{dT}{dC}$ is the inverse slope of the wear time curves.

The tool life expressed in cubic inches of material cut to give a wear land BC is,

$$L = vfdT = 30{\cdot}53\ Vtb\ \frac{BC}{\cot\theta}\ \frac{dT}{dC}$$

where f = feed, ipr

d = depth of cut, inches

V = cutting speed, inches per minute

T = tool-life in minutes.

EXPERIMENTAL EQUIPMENT

The following equipment was used in this research:

1. Experimental lathe.
2. Leitz Metallurgical microscope.
3. Rex-95 tool.
4. Cutting fluids.
5. Workpiece.
6. Fixture.

Lathe

The experiments were conducted on a Reed-Prentice engine lathe, 5 H.P. capacity, 30 inches between centers.

Microscope

The microscope used for measuring the tool wear was one of the metallurgical microscopes used for observing the metal structure. The knob in the micrometer eyepiece had 100 equally spaced divisors. The microscope, with the particular objective (Number 2) and eyepiece was calibrated before the experiment. A scale having hundred divisors for an inch was used for calibration. Thirty observations were taken of the eyepiece knob reading correspondence, to 0.01 of the scale at different sections. At each section several readings are taken to avoid any personal error. Reading at different sections was taken to eliminate the manufacturing error, if any, in each divisor of the scale. Average of the 30 readings was taken as the scale of conversion for conversing the eyepiece reading of the major diagonal of the impression to equivalent inches. The results of calibration follows:

TABLE 6

Section Number Along the Scale	Number of Observations N	EYEPIECE KNOB READING Initial	No. of Complete Rotation	Final	Total Number of Divisions Passed D_i
1	1	66	1	30	164
	2	70	1	31	161
	3	70	1	32	162
2	4	33	1	97	162
	5	31	1	96	165
	6	31	1	96	165
3	7	46.5	1	7	160.5
	8	47	1	9	162
	9	45	1	8.5	163.5
4	10	77	1	39	162
	11	75	1	37	162
	12	75	1	36.5	161.5
5	13	98	1	59	161
	14	97	1	59	162
	15	97	1	59	162
6	16	84	1	46	162
	17	84.5	1	47	162.5
	18	84	1	47	163
7	19	32.5	1	97	164.5
	20	33	1	97	164
	21	33	1	97	164
8	22	45	1	6	161
	23	46	1	6	160
	24	44	1	6	162
9	25	7.5	1	70.5	163
	26	7	1	71	164
	27	7	1	71	164
10	28	45	1	8	163
	29	46	1	10	164
	30	46	1	10	164

$$\sum_{i=1}^{30} = 4882.5$$

$$\frac{\sum_{i=1}^{30} D_i}{N} = \frac{4882.5}{30} = 162.75$$

Hence, the scale of conversion is:

0.01 inch = 162.75 divisions.

Cutting Tool

The cutting tool used was Rex-95 High Speed Steel type. The composition is shown below.

C :	0.80%	Si:	0.30%
V :	2.00%	Mo:	0.75%
Mn:	0.30%	Ci:	4.00%
W :	14.00%	Co:	5.25%

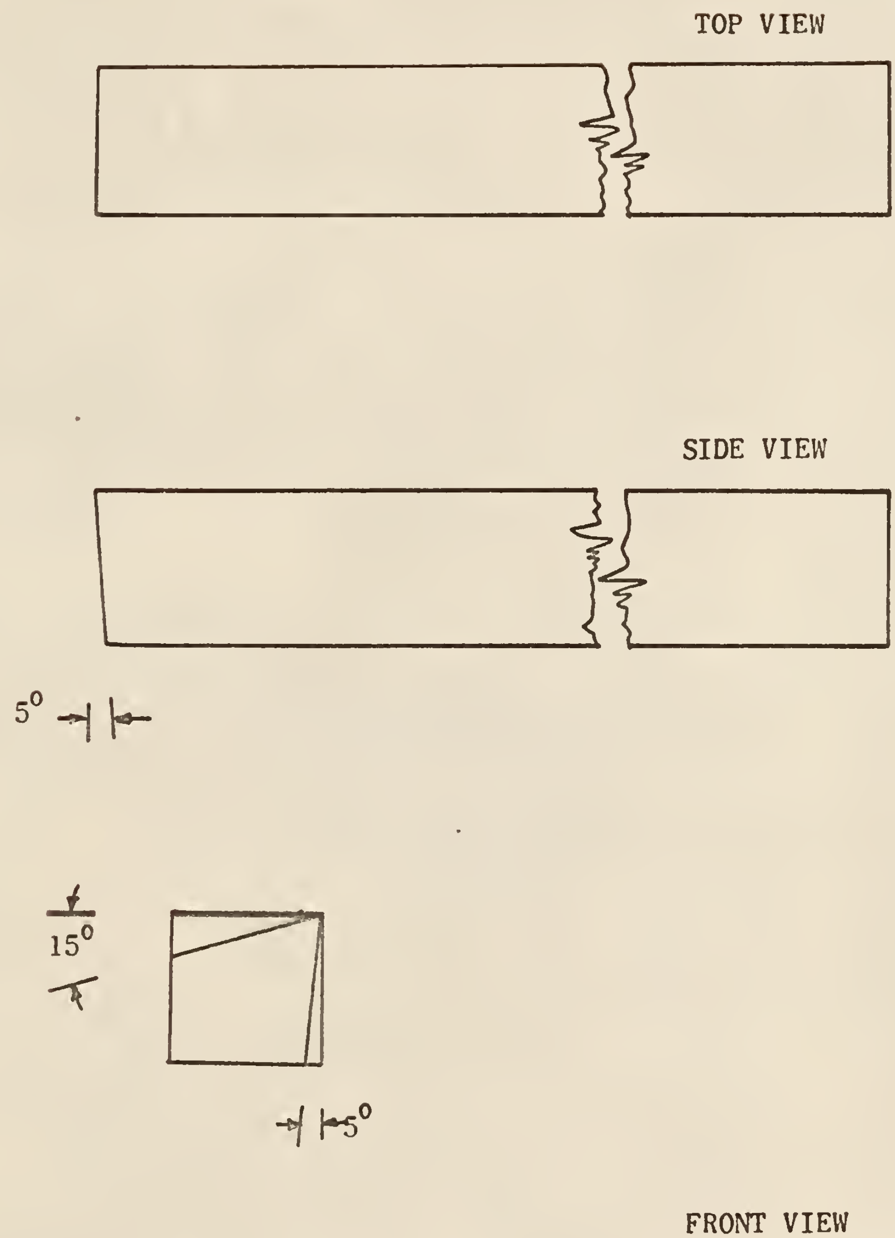
Rex-95 tungsten-vanadium-cobalt high speed steel which was developed to meet the requirements of a steel combining high red hardness, superior abrasion resistance, and good toughness.

The tool geometry was designed to meet the orthogonal cutting condition. The cutting edge was straight and parallel to work thickness. The tool angle geometry is shown in Figure 10.

Cutting Fluids

The test was run with three different cutting media. Two different cutting fluids were tested against the effect of running dry. The selection of the cutting fluids was mainly based on their commercial use value. The two oils are:

REX - 95 TOOL



Back rake angle
Side rake angle
End relief angle
Side relief angle
End cutting edge angle
Side cutting edge angle
Nose radius (in)

FIGURE 10

TOOL GEOMETRY

FIGURE 11

CUTTING TOOL, CUTTING FLUID PIPE & THE STEADY REST IN WORKING POSITION
THE TRAY IS USED TO RECIRCULATE THE CUTTING FLUID

1. "Superla"

   Soluble Oil

   Concentration, 1:10

   Supplied by, Standard Oil Company.

2. Sulphurized, Fatty, Mineral cutting oil.

   Type A, Grade B.

   Supplied by, J. W. Kelley Company, Cleveland.

Workpiece and Fixture

A 4-inch dia, t foot long steel tube was obtained from a local dealer. The composition was not known, except for the fact that it was a "dreel steel" tubing. The tube was cut into three equal pices, of 24 inches long. A small piece was cut from each of the three and specimens were made after some heat treatment (varied to 1600^{o}F - kept in that temperature for 45 minutes and then fast air cooling was done) were studied under microscope to estimate the carbon content. A sample structure can be seen from Figure 12. Several observations were taken over the entire surface of the specimens to reach an average carbon content. The average carbon content was found to be:

C = 0.557

Mn= 0.025 (estimated from the spheriodized structure).

The only fixture used was a "steady rest." This was used to prevent the vibration and eccentricity of rotation of workpiece. The steady rest was used only after turning the outside surface of the workpiece to give it a true and even surface.

Average thickness of the tube was observed to be $\frac{5}{16}$ inches.

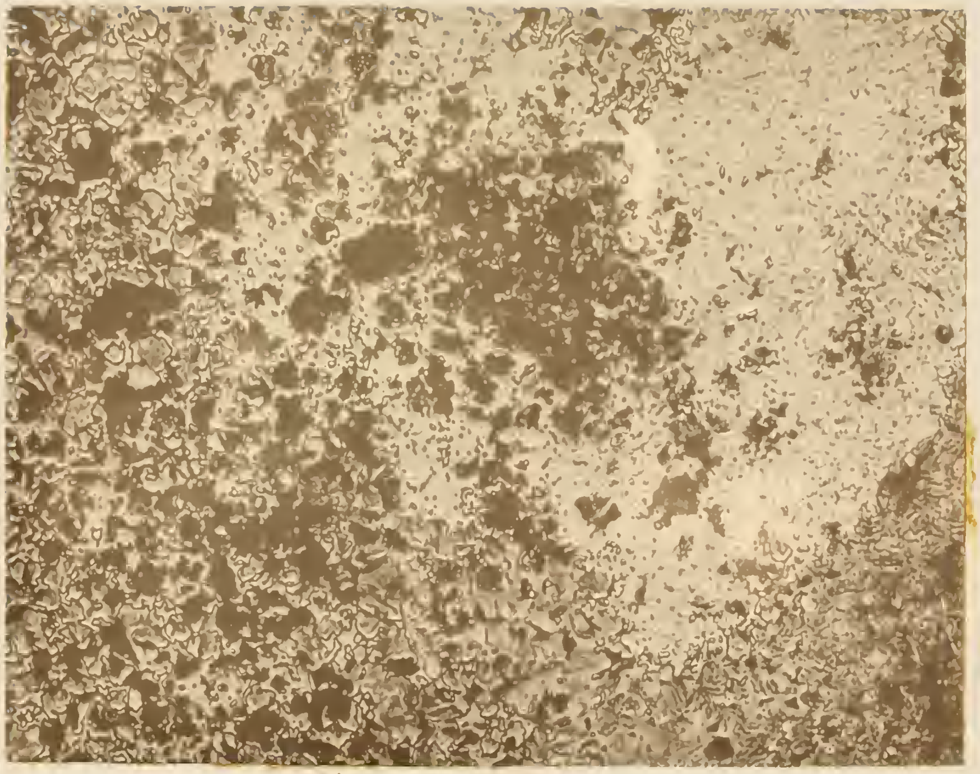


FIGURE 12

STRUCTURE OF WORK MATERIAL

EXPERIMENTAL PROCEDURE

The experimental set-up can be seen from Figure 13. A fluid flow system was designed which can be seen from Figure 14. A sheet metal pan was made and kept below the tool to restore the used oil and to help recirculation. Tool was applied at the end of the tube and the whole tube thickness was used as depth of cut. The tube thickness was made to the previously fixed level of depth of cut by a few preliminary passes. Black grease was used to lubricate the contact surface of the steady rest and the workpieces.

Due to randomization, different oils were used at different times as the treatment warranted. To eliminate the effect of mixture of two oils, time was allowed for the oil to pass to a waste tank, immediately after a change. The machining was restored only when the pure oil started to flow.

The time interval for measurement of tool wear was not fixed but varied depending on the machining conditions.

To avoid the effect of tool material, only one tool was used. This was reground when the indentation was worn down or when the tool wear warranted a resharpening of the tool.

No replication of the tool-life data could be done due to insufficient work material. However, author is quite satisfied with the results obtained and believes the results to be quite satisfactory for finding the range of operation. As suggested later, more detailed and replicated tests should be carried out within this prescribed scope, to study the behavior of tool-life.

The results are tabulated as follows in Table 7.

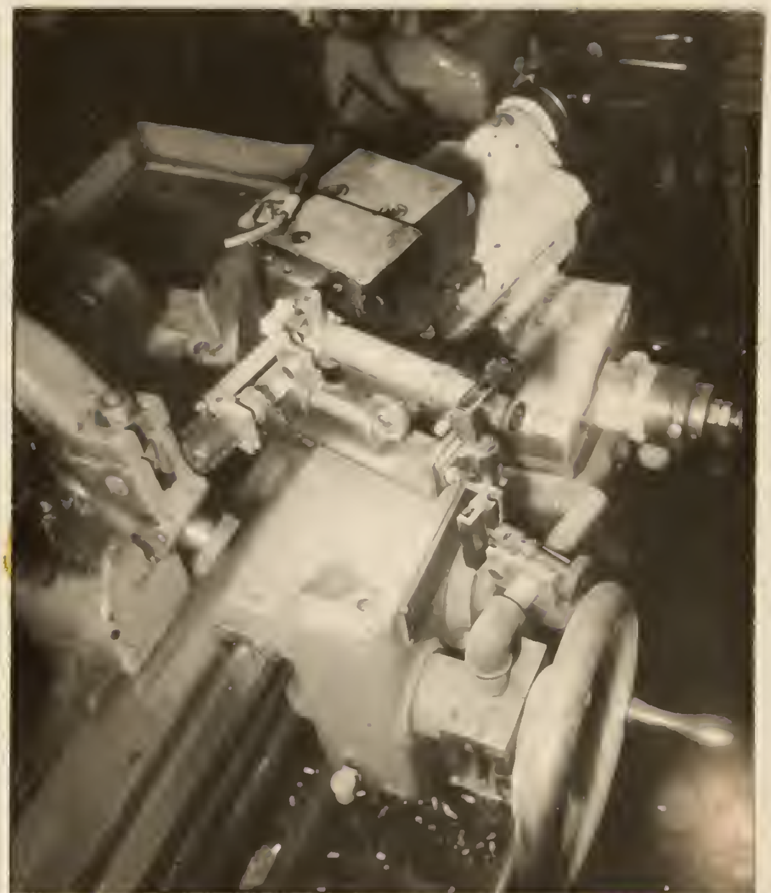


FIGURE 13

THE TOOL POST IS TURNED TOWARDS THE OPERATOR TO ENABLE HIM TO VIEW THE INDENTATION UNDER MICROSCOPE AND THEREBY MEASURE THE MAJOR DIAGONAL OF THE IMPRESSION

THE EYEPIECE KNOB WITH IT'S GRADUATIONS CAN BE SEEN AT RIGHT

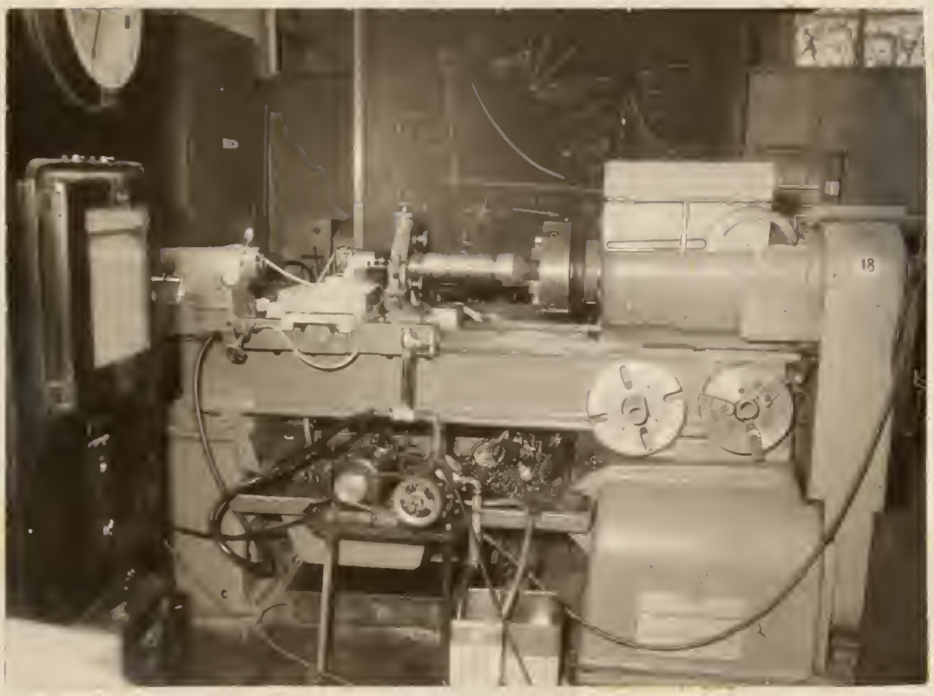


FIGURE 14

THE CUTTING FLUID FLOW SYSTEM

			EYEPIECE READING AFTER A TIME (MINUTE ELAPSE OF																		
Cutting Speed ft/min	Feed ipr	Cutting Medium	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	1.0	1.1	1.2	1.5	1.6	1.7	2.0	2.5	3	4	6	Initial Reading
38	0.010	Dry									817					894		837				931
61	0.010	Dry									783			553			244					933
61	0.020	Dry	888		761		551															931
115	0.010	S.oil		902		827		711														938
115	0.006	C.oil			864		730			518												944
95	0.020	C.oil		694		571		379														753
38	0.006	Dry									300						285		247			308
38	0.015	S.oil									660						605		531			685
38	0.010	C.oil									682			674			660					682
38	0.006	C.oil															660			645	620	660

TABLE 7

Cont........

Table 7 Cont.......

			EYEPIECE READING AFTER A TIME (MINUTE) ELAPSE OF																		
Cutting Speed ft/min	Feed ipe	Cutting Medium	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	1.0	1.1	1.2	1.5	1.6	1.7	2.0	2.5	3	4	6	Initial Reading
115	0.020	Dry	780	463	451*																	930
95	0.020	S.Oil			487		506		303													766
95	0.006	S.oil			430				465								190					551
38	0.006	S.oil									889						872		846			897
95	0.006	C.oil		884				800		688												910
61	0.006	S.oil											475				425		360			501
115	0.010	Dry	842	652	356																	931
61	0.010	C.oil				843		891						687								957
95	0.010	Dry		716	566		313															817
38	0.020	S.oil					832				750				625							880

*A new indentation was given and the initial reading prior to starting was 933.

Table 7 Cont.......

Cutting Speed ft/min	Feed ipr	Cutting Medium	EYEPIECE READING AFTER A TIME (MINUTES) ELAPSE OF																			Initial Reading
			0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	10.	1.1	1.2	1.5	1.6	1.7	2.0	2.5	3	4	6	
61	0.015	C.oil						261			517			336								574
115	0.015	C.oil	471	533	679																	914
38	0.010	S.oil									670					725		685				750
95	0.020	Dry	810	618	308																	910
115	0.020	C.oil		59	617	247																939
38	0.020	Dry					503				495				330							551
61	0.006	Dry	432	394		343																447
95	0.015	C.oil				833		685			446											933
95	0.006	Dry		855		689		447														933
61	0.020	S.oil					590				501						313					605

Table 7 Cont......

			EYEPIECE READING AFTER A TIME (MINUTES) ELAPSE OF																		
Cutting Speed	Feed ipr	Cutting Medium	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	1.0	1.1	1.2	1.5	1.6	1.7	2.0	2.5	3	4	6	Initial Reading
38	0.020	C.oil								844				768				643				867
95	0.010	C.oil		899		830		724														933
61	0.010	S.oil										521		452			359					529
38	0.015	Dry									867						737		540			932
95	0.015	Dry		811		561		191														931
95	0.015	S.oil			756		668			528												808
61	0.020	C.oil		859		783		682														955
38	0.015	C.oil									617			733				650				768
95	0.010	S.oil					856				708			480								933
115	0.010	C.oil	886				717		476													920

Table 7 Cont......

Cutting Speed ft/min	Feed ipr	Cutting Medium	EYEPIECE READING AFTER A TIME (MINUTES) ELAPSE OF																	Initial Reading
			0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	1.0	1.1	12.	1.5	1.6	1.7	2.0	2.5	3 4	
61	0.015	Dry	514		457	374														540
115	0.015	Dry		779	535		130													933
61	0.006	C.oil												122			485		248	622
61	0.015	S.oil					878				817					713				908
155	0.020	S.oil			413		338	62												552
115	0.006	Dry		252	402	633														933
115	0.006	S.oil				850				728					482					910
115	0.015	S.oil		869	770		609													93[illegible]

TOOL-LIFE CALCULATION

The cell values of Table 7, represents the length of the major diagonal of the given indentation (Figure 9) after the corresponding time. For evaluating the tool-life the following steps have been taken.

1. Initial reading of table represents the length of the major diagonal of the indentation at the beginning of the run.
2. Wear of the diagonal during any particular time 't' for a particular run is calculated by subtracting the cell value corresponding to time 't' for that run from it's preceeding higher cell value. This gave tool land wear figures for three different time intervals for each of the 48 runs or treatments.
3. The units of these cell values and tool wear values are in "number of divisions of the eyepiece knob."
4. Knowing that 162.75 divisions - 0.01 inches (from the calibration of Table 6), we are now in a position to convert these wear values from number of divisions to corresponding inches of land wear.
5. The land wear, as ordinate, is plotted against the corresponding time on abscissa, to give the near rate. This is done for all the 48 different treatments (Appendix A, page 93)
6. The tool-life criterion is fixed at 0.010 inches of land wear. This is based on the past research[14].
7. Knowing the wear rate and the tool geometry, the equation 3 is used to determine the tool-life, T in minutes.
8. The calculations are shown in Appendix B.
9. Appendix B also shows the calculations for tool-life in terms of cubic inch of material cut.
10. The tool-life in minutes is shown in Table 8, and Table 9 gives the tool-life in cubic inches of material removed.

F E E D S

SPEEDS ft/min	0.006			0.010			0.015			0.020		
	Dry	C.oil	S.oil	Dry	C.oil	S.oil	Dry	C.oil	S.oil	Dry	C.oil	S.oil
38	217	654	303	115.7	400	165.5	39.6	78.5	98.5	25.202	51.7	33
61.	29.2	32	123	16.82	24.6	64	13.97	21.6	43.1	7.16	16.1	30.1
95	6.524	18.5	21.8	5.09	14.57	17.2	4.2	10.44	14.72	2.61	8.40	8.7
115	3.468	9.66	17.20	2.704	7.57	13.7	2.7	3.39	8.08	1.624	2.76	5.67

TABLE 8

RESULTS FOR THE 4 x 4 x 3 FACTORIAL EXPERIMENT

Tool: Rex-95

Cell Values indicate tool-life in minutes.

FEEDS

CUTTING SPEED fpm	0.006			0.010			0.015			0.020		
	Dry	C.oil	S.oil	Dry	C.oil	S.oil	Dry	C.oil	S.oil	Dry	C.oil	S.oil
38	184.363	555.638	257.429	163.692	565.920	234.149	83.968	166.451	208.859	71.272	146.104	93.258
61	39.969	45.171	168.362	38.340	56.073	145.882	47.724	73.790	147.238	32.600	73.303	137.045
95	14.011	39.731	48.818	18.203	52.107	61.512	22.512	55.957	78.898	18.645	60.005	62.149
115	9.000	25.077	44.651	11.689	32.725	59.225	17.493	21.964	52.350	14.023	23.833	43.780

TABLE 9

CELL VALUES INDICATE TOOL-LIFE IN TERMS OF CUBIN INCHES OF METAL CUT

ANALYSIS OF VARIANCE

The analysis of variance is defined as the analysis breakdown of total variability into component parts. Thus,it is possibel to determine which variable under study caused the significant difference in the results.

Postulation of the Mathematical Model

The contribution of statistical techniques is to increase the rate of convergence in the solution of a problem. This is accomplished by an iterative procedure as illustrated in Figure 15.

The research worker should have an idea or conjective which leads to the design of an experiment. The experiment is then performed and the results are analyzed. This leads to new ideas and the entire process is repeated.

The conjecture stage in the present project is relatively simple because tool-life has been studied intensively for the past three to four decades. The independent variables investigated were speed V, feed f, and cutting medium C. The response, or dependent variable, was tool-life T. The functional relationship which has been proposed by previous investigators is,

$$V\ T^n\ f^m\ d^b = K$$

For the present project, depth of cut being constant, the above equation can be written as,

$$V\ T^n\ f^m = K^1.$$

For the purpose of this investigation, this equation can be written as a more convenient form by taking logarithors of both sides.

$$\eta = \beta_0 + \beta_1\ x_1 + \beta_2\ x_2$$

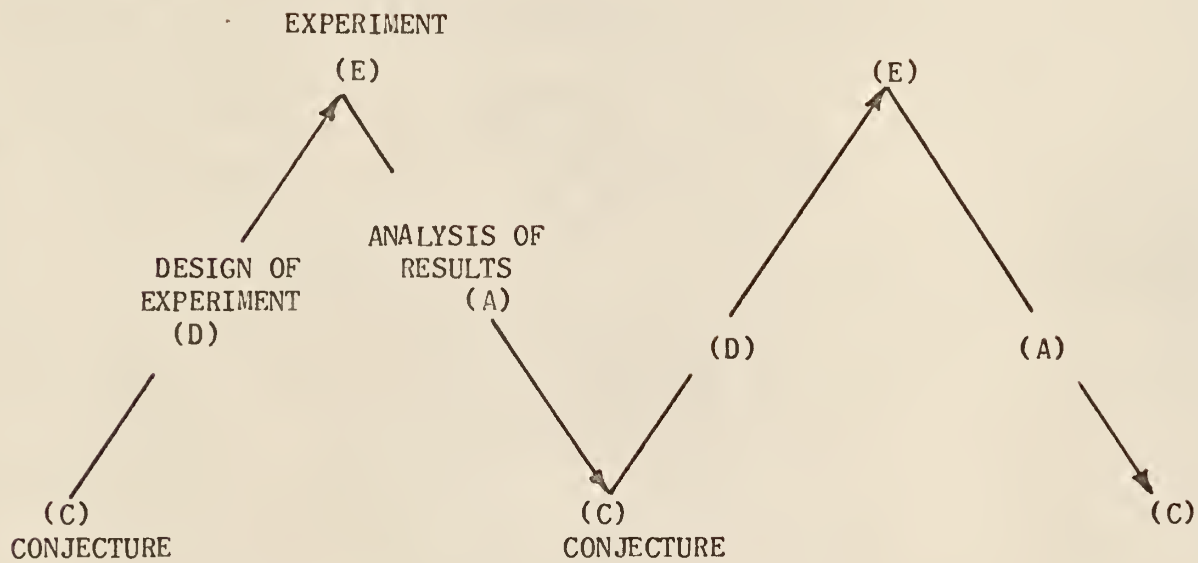


FIGURE 15

ITERATION CYCLES OF EXPERIMENTATION

where η is the true response of tool-life on a logarithmic scale, $x_{.}$ and x_2 are the logarithmic transformations of V and f respectively, and β_0, β_1, and β_2 are the parameters. This can also be written,

$$y = b_0 + b_1 x_1 + b_2 x_2 + \varepsilon \tag{4}$$

where y is the observed tool-life on a logarithmic scale, b_0, b_1, and b_2 are estimates of the parameters β_0, β_1, β_2 respectively, and ε is the experimental error.

Equation 4 is a polynomial of first degree. The coefficients of this linear equation have been estimated by the computerized program for Stepwise Multiple Regression(31), written in S.P.S. for IBM 1620.

The coefficients have been established separately for each of the three different cutting medium.

Assumptions made in the model.

1. The treatment effects are additive.
2. The experimental errors are independent from observations to observation and are distributed with zero mean and the same variance ^{2}.
3. For tests of significance, the experimental errors are assumed to follow the normal or G aussian frequency distribution.

Computation

The detailed computations for the analysis of variance is shown in Appendix C. The Anova presented here is a two-way analysis with the main effect and the interactions considered. It is known from the past research that in a project like this dealing with tool-life, interactions of various factors play an important role. The ANOVA is presented in Table .

Conclusions from ANOVA

Referring to Table 10 and statistical tables we find that:

1. The interactions of speed and feed are significant at one percent level.
2. The interactions of speed and cutting compound is significant at five percent level.
3. The interactions of feed and cutting compound is not significant.
4. Speed has the greatest effect on tool-life, feed the second and cutting compounds have the least effect on tool-life.

Reference may be made to Appendix C for a detailed explanation of these conclusions.

TABLE 10

ANOVA

Source of Variation	Degrees of Freedom	Sums of Squres.	Mean Sum of Squres.	Ratio F	Significance
Speed (S)	3	248494.146	82831.382	26.186	***
Feed (F)	3	79281.995	26427.332	8.355	**
Cutting Compound	2	23255.375	11627.688	3.676	*
S x F	9	161178.427	17908.714	5.662	**
S x C	6	66654.445	11109.074	3.512	*
F x C	6	16706.860	2784.477	0.880	Insignificant
S x F x C	18	56937.976	3163.221		
TOTAL	47	652509.224			

*** Highly significant.

** Significant at one percent level.

* Significant at five percent level.

TESTING EFFECTS SUGGESTED BY THE DATA

The F-test performed on all the treatment means indicated that the speed, feed, and speed cutting compound interactions are significant. Due to these highly significant interactions, we need not analyze the factors for their main effect. The ordinary t-test for the difference between two means is applied to every pair of means. Any two means whose difference exceeds the "least significant difference" (LSD), are declared significantly different. The LSD is given by (25),

$$LSD = t_{\alpha,v}\sqrt{\frac{2\cdot S}{r}}$$

where, α = Level of significance = 0.05.

v = Degree of freedom.

S = Estimated Standard error.

r = Number of replications.

The cell values in Tables 11 and 12 represents the average tool-life (near), the average being taken over the three cutting compounds, namely dry, cutting oil, and soluble oil. Reference may be made to Table 8 for these three different values for each combination of feed and speed levels.

From Table 10, for ANOVA, we find that:

$v = 18$

$S = 3163.221$

r = Number of observations = 3.

Hence,

$$LSD_1 = t_{.05,18}\sqrt{2(3163.221)/3}$$

$$= 1.734 \times 32.471 \times 1.414$$

$$LSD_1 = 79.6149$$

where LSD_1, refers to Table 11 for speed and feed interaction.

Table 12 is drawn for testing the speed and cutting compound interactions. The cell values represent the average tool-life, the average now being taken over the four feed levels for each possible combination of speed and cutting compounds. At this stage reference may be made to Table 8 for computations.

Again,

$$LSD_2 = t_{0.05,\ 18} \sqrt{\frac{2(3163.221)}{4}}$$

$$= 1.734 \sqrt{1581.620}$$

$$= 1.734 \times 39.769$$

$$= 68.959$$

TABLE 11

Feeds Speeds ipr fpm	0.006	0.010	0.015	0.020
38	391.333	227.067	72.200	36.634
61	61.733	35.140	26.023	17.787
95	15.608	12.287	9.787	6.570
115	10.109	7.991	4.723	3.351

The significant difference region.

TABLE 12

Cutting Compound Speed fpm	Cutting Oil	Soluble Oil	Dry
38	296.050	150.000	99.376
61	23.825	65.050	16.788
95	12.978	15.605	4.606
115	5.845	11.163	2.624

The significant difference region.

-*- Mean significant.

CONCLUSION

The following conclusions may now be drawn for the observed data in the table.

1. There is significant difference in the tool-life for a feed range from f = 0.006 to 0.015 at the low speed of 38 feet per minute.
2. At the low speed of 38 sfpm, the tool-life is not affected appreciably by the inverse of feed f = 0.015 to f = 0.020.
3. In the range of speed = 61 to 115 feet per minute the tool-life is not changed significantly with the change in feed.
4. A sharp reduction in tool-life occurs when the speed increases from 38 fpm to 61 fpm at low feed rate of f = 0.006 and 0.010.
5. The effect of speed and feed on tool-life is prominent in the following range.

   Speed : 38 to 61 feet per minute.

   Feed : 0.006 to 0.010 ipr.

The following conclusions are drawn from the table .

1. There is no significant difference in the tool-life at speeds 95 and 115 feet per minute under the application of different oils and no oil.
2. The tool-life is significantly higher when run dry at low speed than at high speeds.
3. The tool-life decreases sharply when run at high speed (greater than 95 sfpm) than 38 sfpm. This is true for both the oils.
4. At low speed, cutting oil is the best to apply and there is appreciable difference in the tool-lives obtained from cutting oil, soluble oil and dry; cutting oil being the best and dry cutting is the worst. The good effect of cutting oil cannot be neglected.

5. At higher speeds ($58 \leq V \leq 110$ fpm), cutting oil and soluble oil have equivalent performances. Also, cutting oil and dry have equivalent performance. However, soluble oil was significantly higher than the tool-life under dry machining.

PREDICTING TOOL-LIFE EQUATION

A polynomial of first degree was choosen to be the postulated model. This has been mentioned earlier while we were dealing with postulated models. Reference may be made to page . The model is given by:

$$y = b_o + b_1 x_1 + b_2 x_2'$$

where,

y is the estimated tool-life in minutes, in a logarithmic scale.

x_1 & x_2 is the value of feed in ipr and speed in fpm in logarithmic scales.

b_o is a constant evaluated separately for the different cutting media.

b_1 & b_2 are the parameters determined individually for the different cutting media.

The following predicting equations are arrived at by a stepwise multiple regression program[31] written in S.P.S. for IBM 1620.

1. Dry:

$$Y = 10.43482 - 1.04368\ X_1 = 2.99097\ X_2$$

R^2 = Proportion of tool variance in log tool-life accounted for by log feed and log speed

= 0.96296

$Y = \ln.T.$

$X_1 = \ln.$ Feed (ipr)

$X_2 = \ln.$ Speed (fpm)

Standard error of Y = 0.29651.

2. Soluble Oil:

$$Y = 9.69769 - 0.64538\ X_1 - 2.18241\ X_2$$

where $R^2 = 0.78596$

Standard error of Y = 0.56602.

3. Cutting Oil:

$$Y = 10.7589 - 1.15429\ X_1 - 2.99963\ X_2$$

where

$$R^2 = 0.90690$$

Standard error of Y = 0.49217.

FUTURE WORK

It is suggested that more effort be placed in the area of application of statistics to the field of metal cutting. In the project discussed in this report only two variables were selected to study the effect of cooland and lubricant where as there are many others that could be analyzed. Some of the areas for further work are:

1. A fractional factorial design should be adopted to enable the experimentor to analyze the greater number of variables involved in such as analysis.
2. A detailed analysis between the speed range of 38 to 61 sfpm and feed range of 0.006 to 0.010 pir will explain the sharp decrease in tool-life and will give a better knowledge of the role played by cutting compounds.
3. Since the amount of heat generated at the cutting edge would appear to be important, further work should consider materials not only of different hardness, but also those whose properties of thermal conductivity, coefficient of thermal expansion cover a suitable range.
4. Study of the effect of changing tool geometry would go a long way in analyzing the effect of cutting compounds on tool-life.
5. In addition to all this, author feels a separate investigation of the effect of Built Up Edge on surface finish and tool force would be very helpful.

EFFECT OF COOLAND AND LUBRICANT ON TOOL LIFE

by

PRABHAT KUMAR MISRA

B. S. (ME), Utkal University, India, 1963

AN ABSTRACT OF A MASTER'S THESIS

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requirements for the degree

MASTER OF SCIENCE

Department of Industrial Engineering

KANSAS STATE UNIVERSITY
Manhattan, Kansas

1965

Major Professor

A study has been undertaken to study the effect of running dry, with soluble oil and a cutting oil, on tool-life. The diamond indentor techniques as suggested by M. C. Shaw is adopted to measure the tool-life. The independent variables combined are feed, speed, and cutting medium.

It is observed that cutting oil is the best at low speeds. At higher speeds, cutting oil and soluble oil have equivalent performances. Also, cutting oil and dry have equivalent performance. However, soluble oil (1:10) yielded a significantly higher tool-life than the tool-life under dry machining.

The observed tool-life data for the three different medium were used separately to yield the following fool-life predicting equations.

$$Y = 10.43482 - 1.04368\,X_1 - 2.99097\,X_2 \quad \ldots\ldots \quad \text{Dry}$$

$$Y = 9.69769 - 0.64538\,X_1 - 2.18241\,X_2 \quad \ldots\ldots \quad \text{Soluble Oil}$$

$$Y = 10.75890 - 1.15429\,X_1 - 2.99963\,X_2 \quad \ldots\ldots \quad \text{Cutting Oil}$$

With the help of this project, an effective range is established which needs a detailed analysis to give some insight into the effect of cutting fluids. The sharp reduction in tool-life in this range is worth further investigations.

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Kansas State University, Manhattan, Kansas

NOMENCLATURE

V	Cutting speed, s.f.p.m.
S	Cutting Speed, r.p.m.
n, m, p	Exponential constants.
r	nose radius of cutting tool, in.
f	feed, i.p.r.
d	depth of cut, in.
C, K	constants
$\bar{V}$	calculated speeds, s.f.p.m.
q	equals L/A_o, chip equivalent
L	contact length of part of tool edge engaged in cutting
A_o	cross sectional area of "chip" before removal from workpiece
K_{tm}	constant depending on tool material
K_{mc}	constant depending on work material
α_s	side-cutting-edge angle
C_w, q_o	constants
k	thermal conductivity of work material
P_c	volume specific heat of work material
K	equals k/P_c, thermal diffusivity of work material or Y lnT
X_1	equals ln.f
X_2	equals lnV
λ	angle between the shear plane and the resultant tool force
α	rake angle, deg
β	equals $\tan^{-1}\left\{\frac{F_v + F_H \tan\alpha}{F_H \alpha F_v \tan\alpha}\right\}$, friction angle, deg.
Φ	equals $\tan^{-1}\left\{\frac{v \cos\alpha}{1-r \sin\alpha}\right\}$, shear angle, deg.

λ	equals $\Phi + \beta - a$, deg.
t_o	thickness of layer of metal removed inches
t	chip thickness, inches
w_o	wall thickness of workpiece, inches
w	width of chip, inches
F_H	force component in direction of motion, pound
F_V	force component normal to the direction of motion, pound
R	equals $(F_H^2 + F_V^2)^{1/2}$, resultant force, pound
F	equals $R \sin \beta = F_H \sin \alpha + F_V \cos \alpha$, force component parallel to tool face, pound
N	equals $R \cos \beta = F_H \cos \alpha - F_V \sin \alpha$, force component normal to tool face, pound
T_i	tool-life corresponding to treatment "i"
d.f	degree of freedom
S.S	sums of squares
$X_{S.S}$	sum of square corresponding to the factor X
XY_{SS}	sum of square corresponding to the interaction of factors X and Y
Y_{ijk}	observed tool-life for speed level 'i', feed level 'j' and cutting medium 'k'
$Y_{.jk}$	summation of observed tool-lives, summation being taken over speed.

APPENDIX A

This includes graphs I and X which are used to determine the rate of wear. "Wear" is plotted as ordinate with "time" as abscissa. Each curve represents one and only one of the 48 different treatments and each graph is numbered according to the serial order in which the treatments were performed.

Graphy Y and Z explain the average main effect of the three different factors. Reference, at this stage, may be made to page .
These two graphs are used to explain Tables 11 and 12.

Graphs A to H show the behavior of the observed tool-life over the many levels of the assumed factors. These are drawn with a view to give true idea of the effective range (as suggested in "future work" to the observer.

Graphs K to T are similar to above, except for the fact that the tool-life is now expressed in cubic-inch of material removed.

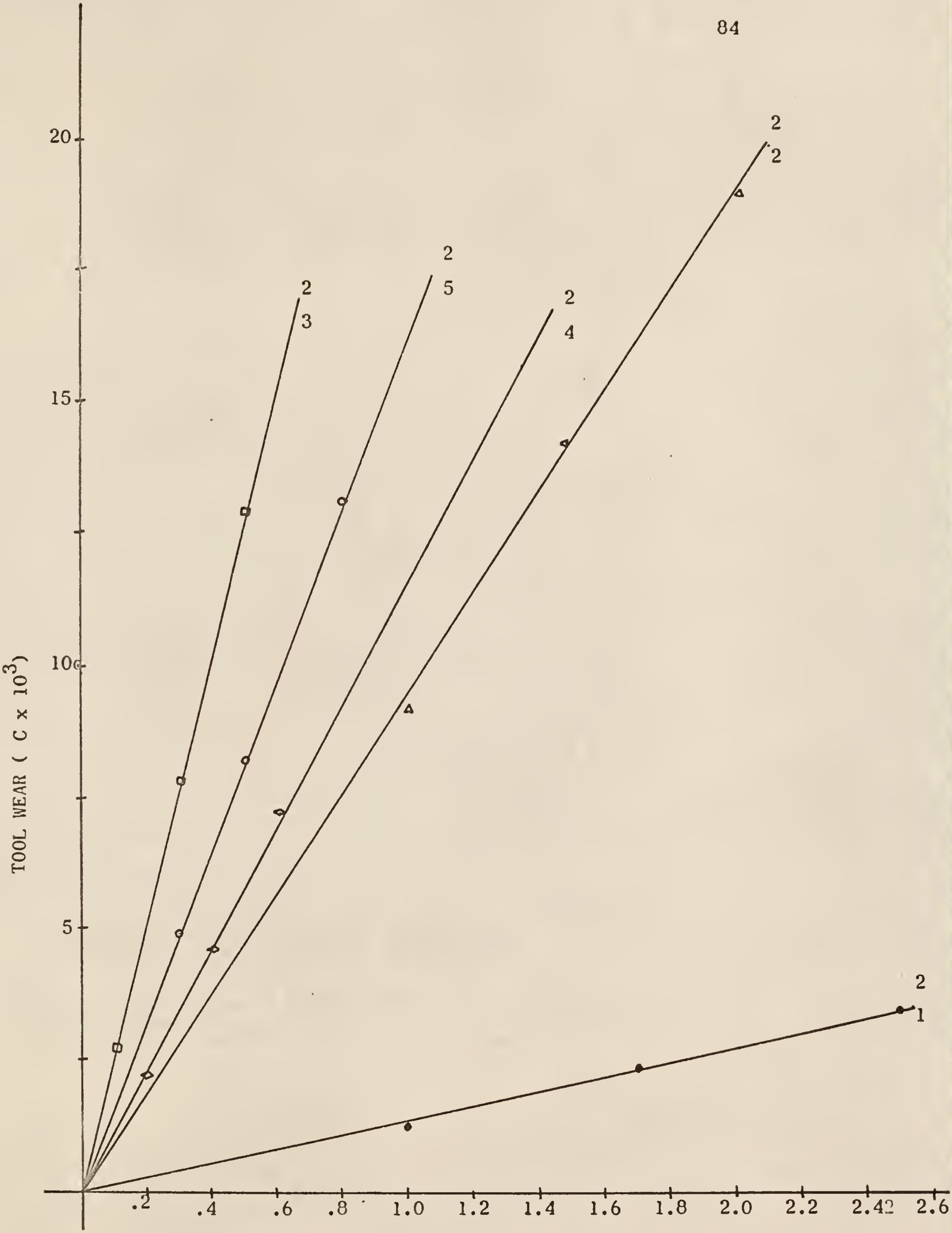


FIGURE I

TIME IN MINUTES

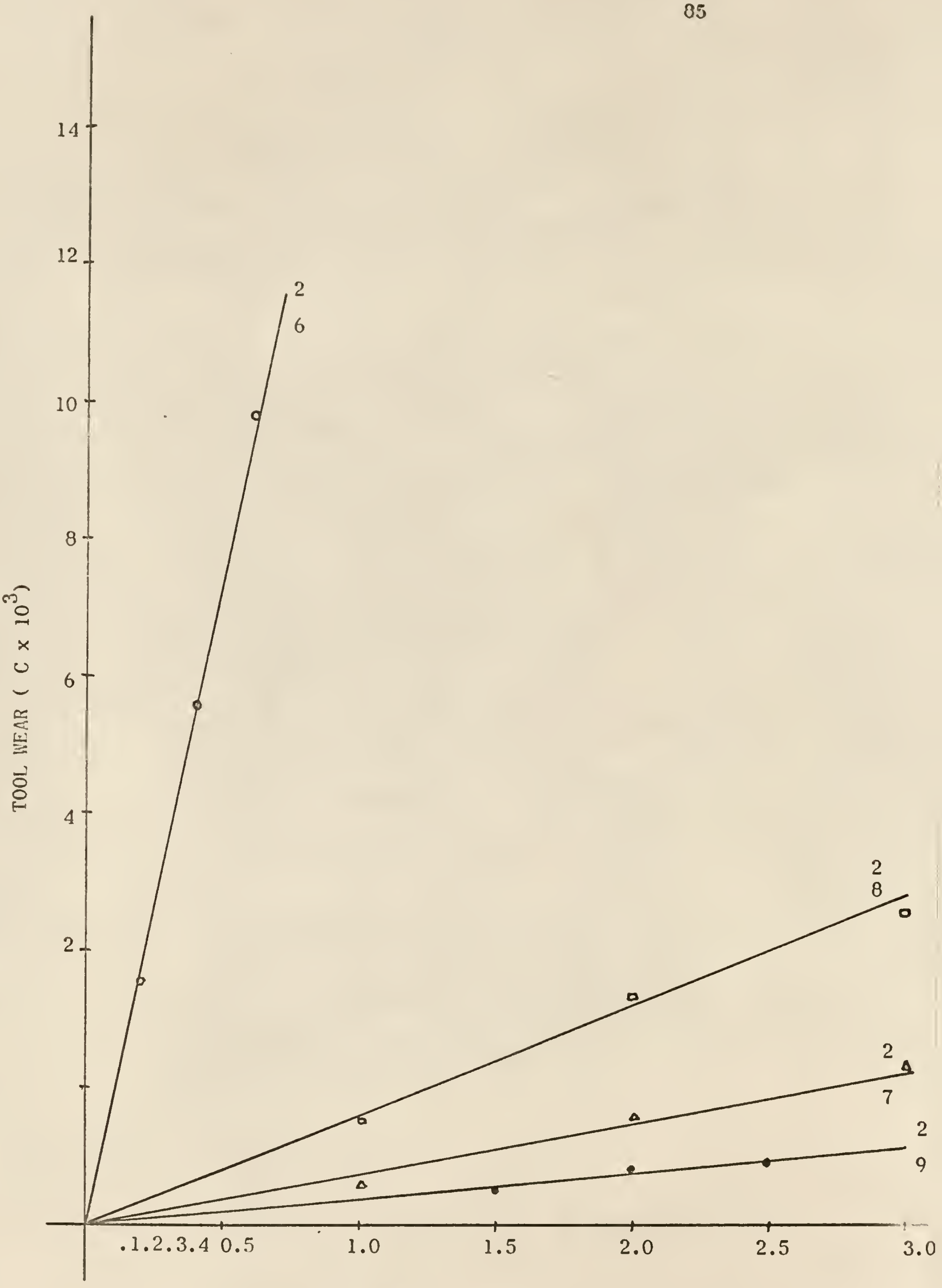


FIGURE II

TIME IN MINUTES

FIGURE III

TIME IN MINUTES

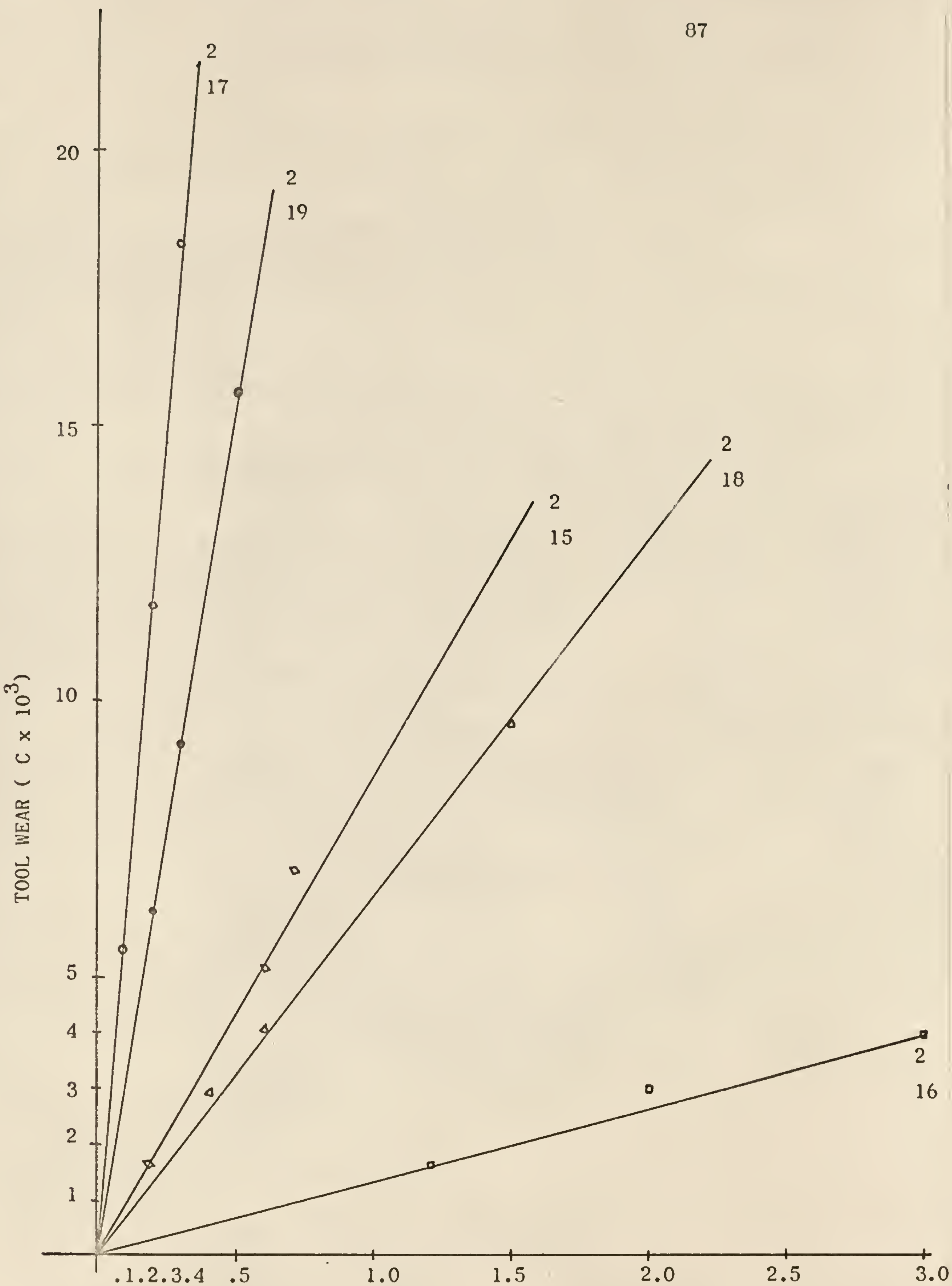


FIGURE IV

TIME IN MINUTES

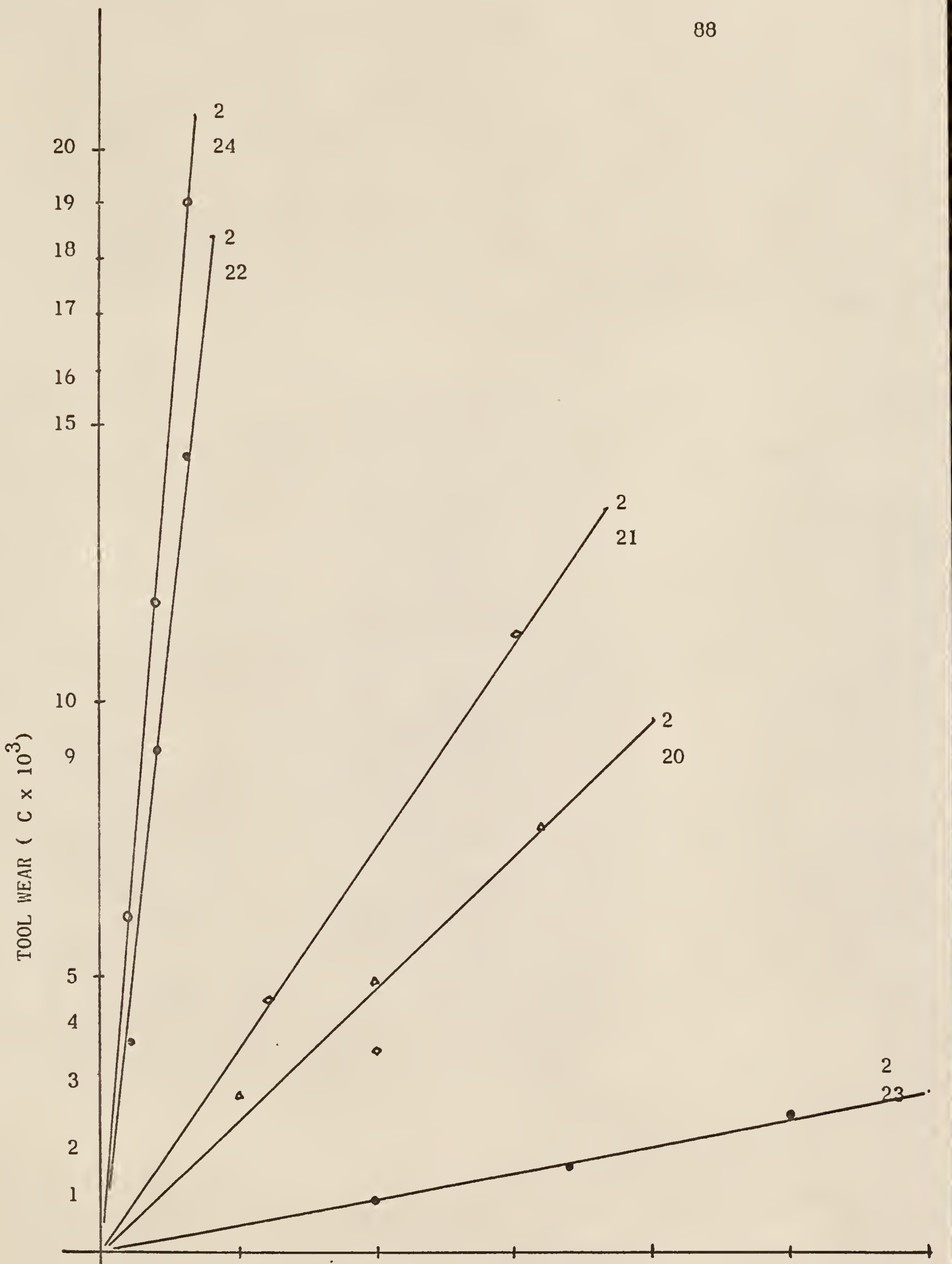


FIGURE V

TIME IN MINUTES

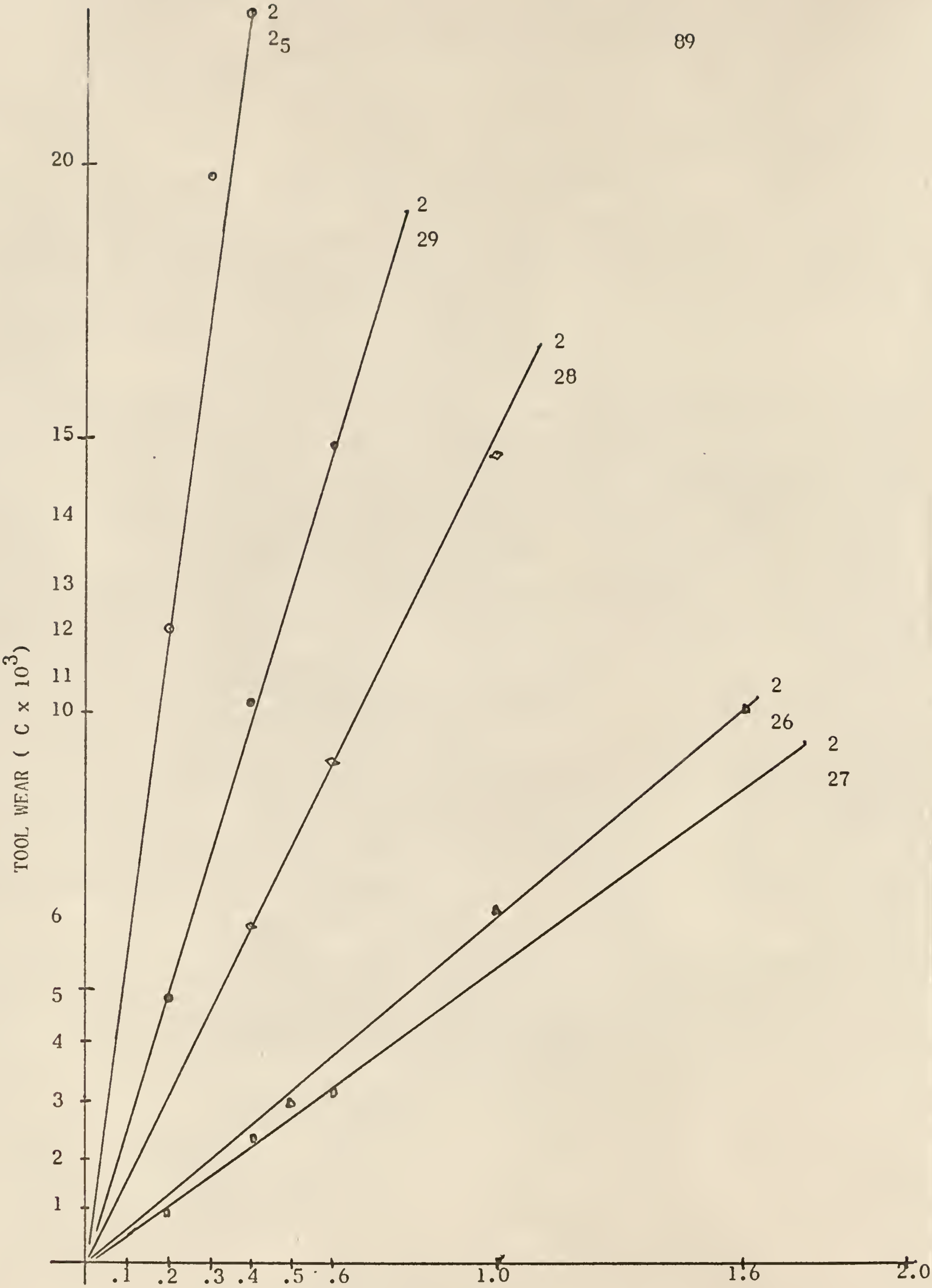


FIGURE VI

TIME IN MINUTES

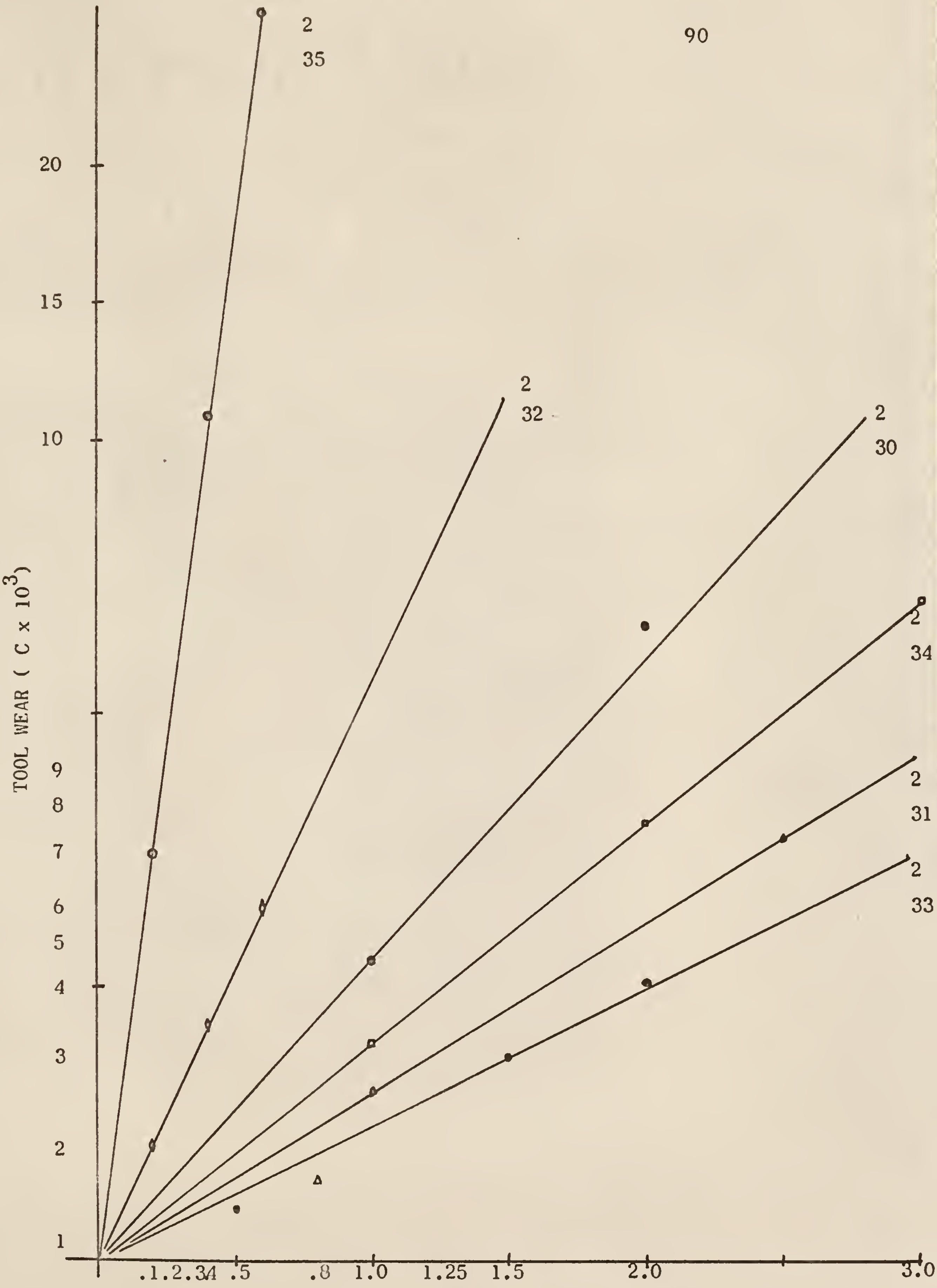


FIGURE VII

TIME IN MINUTES

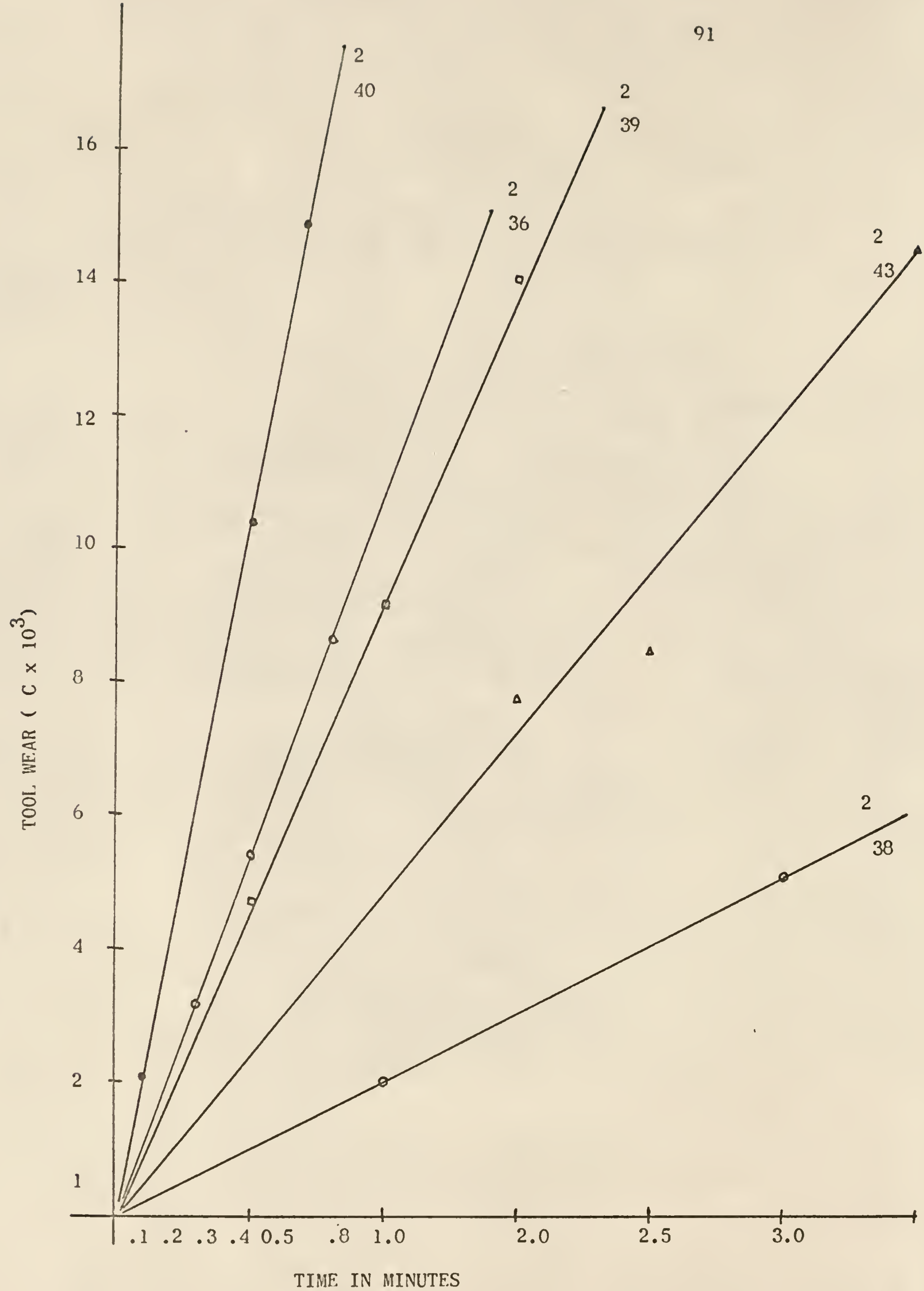
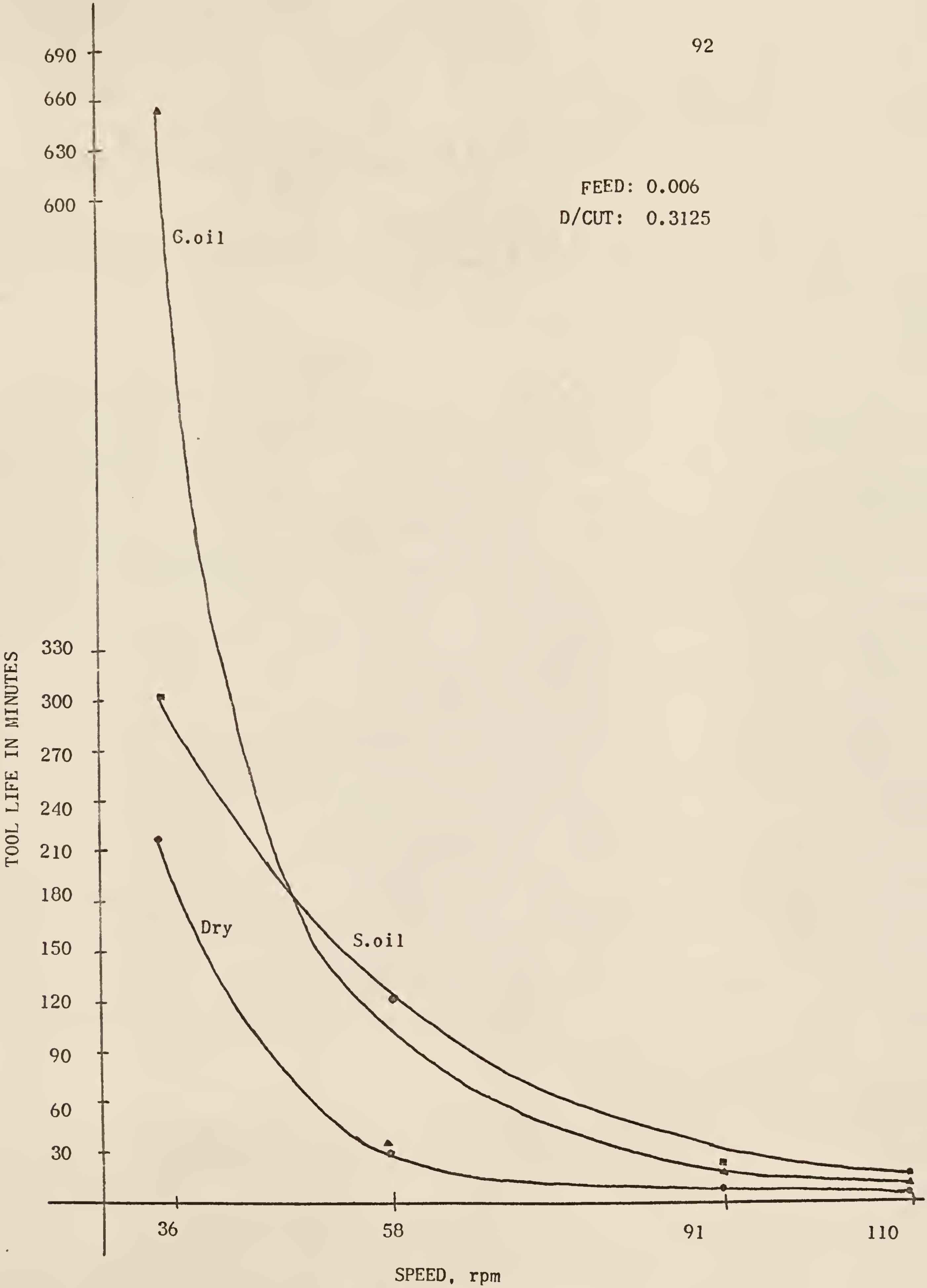
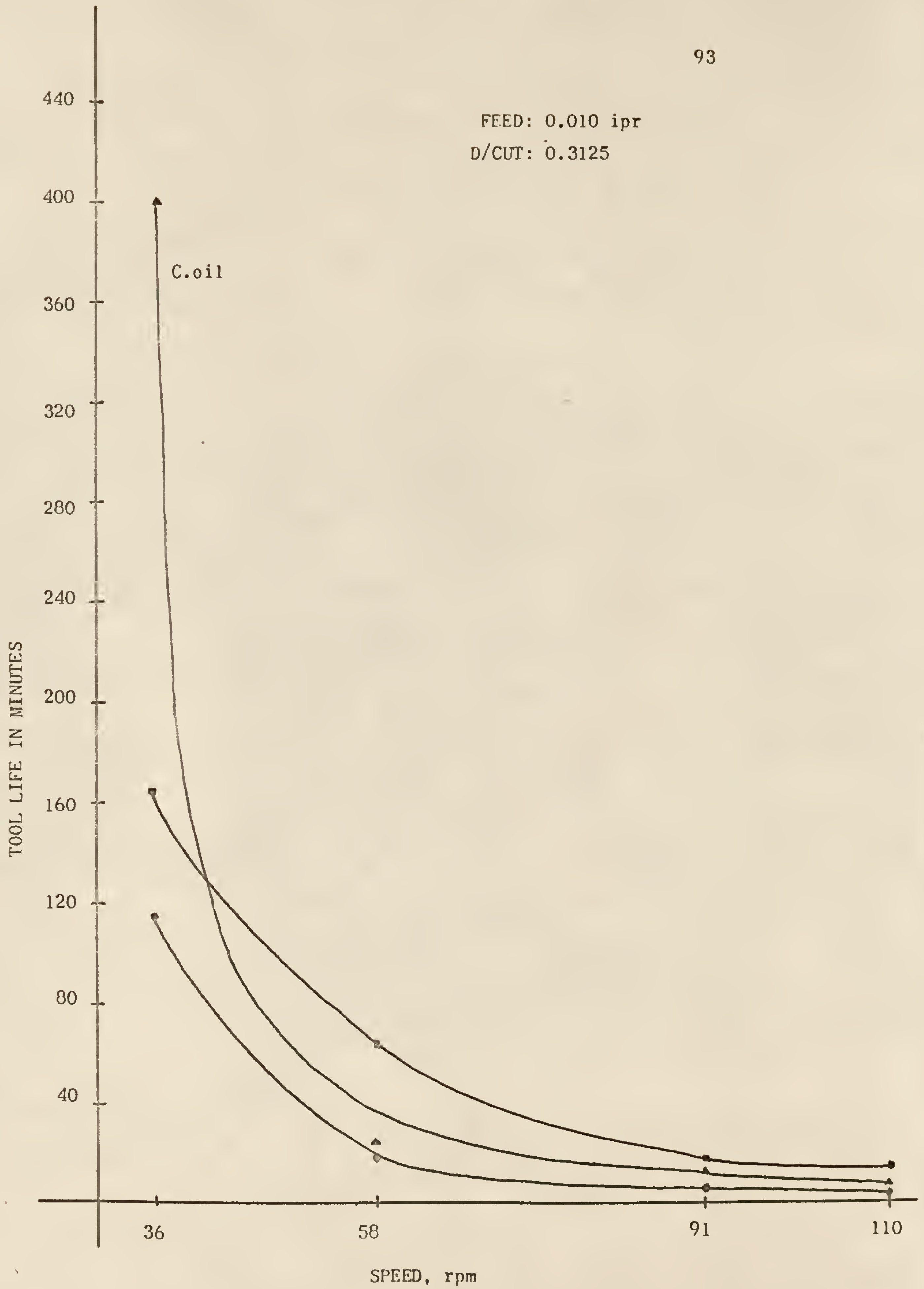
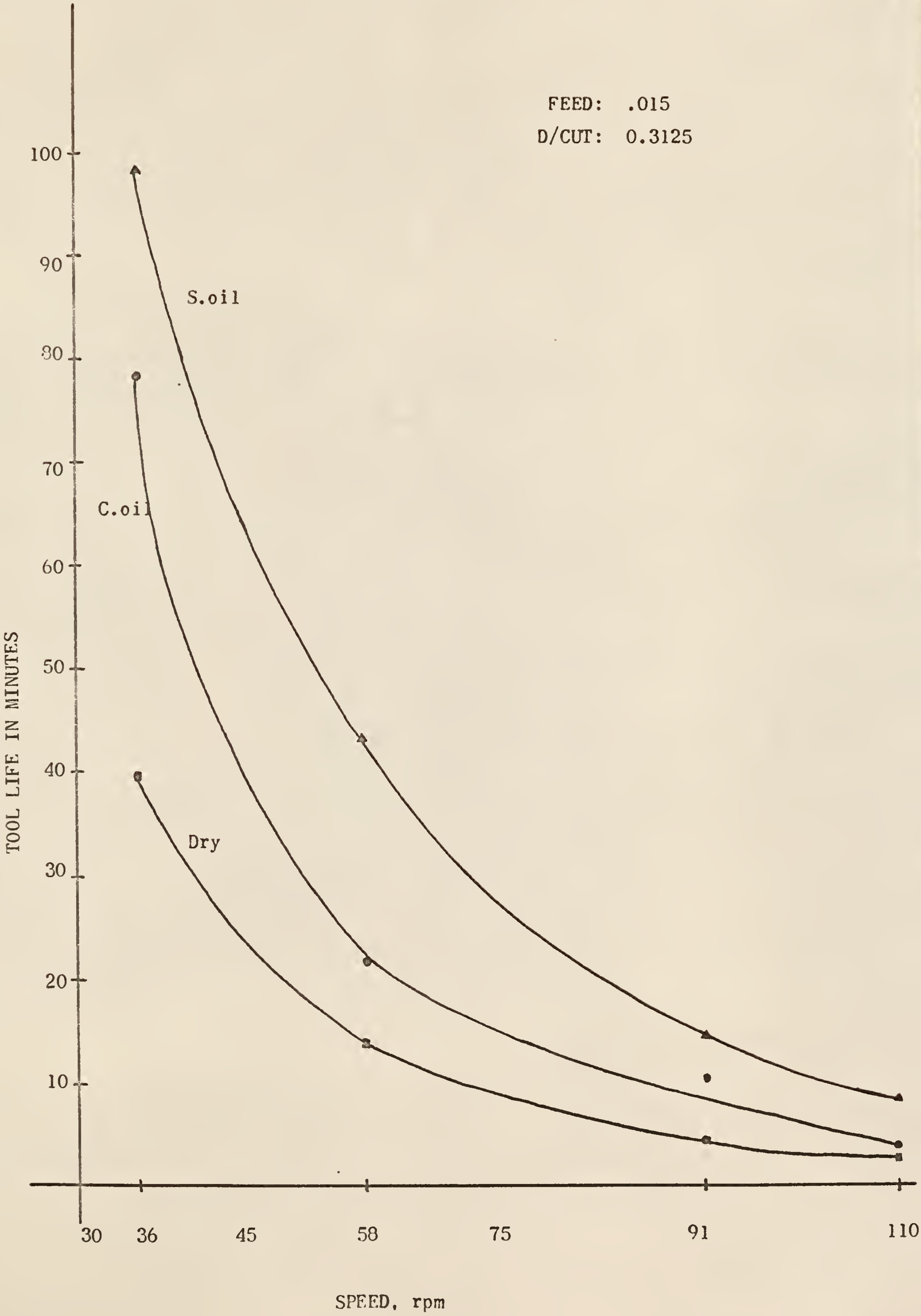
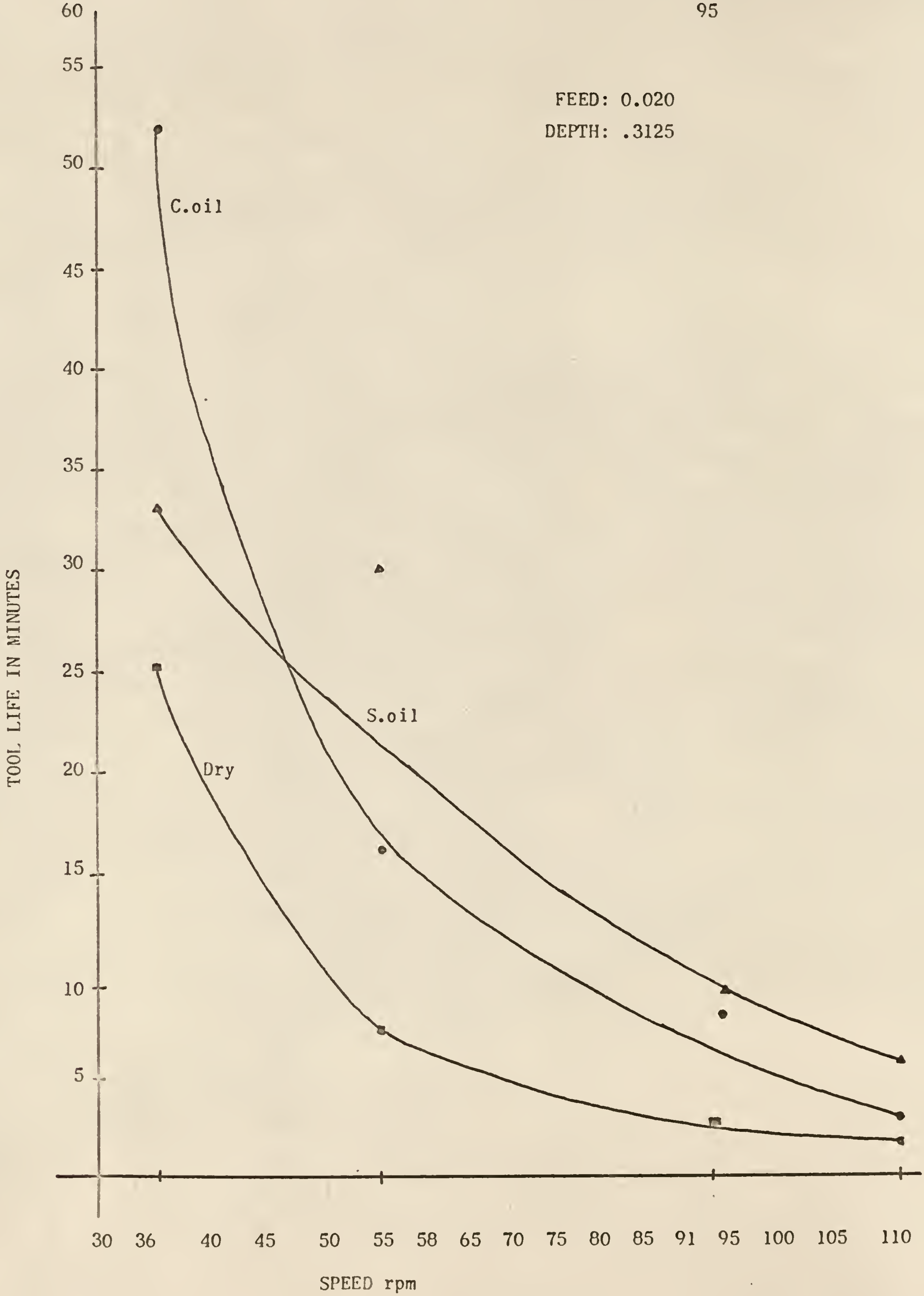

2
40
2
39
2
36
2
43
2
38
16
14
12
10
8
6
4
2
1
TOOL WEAR (C x 10^3)
.1
.2
.3
.4
0.5
.8
1.0
2.0
2.5
3.0
TIME IN MINUTES

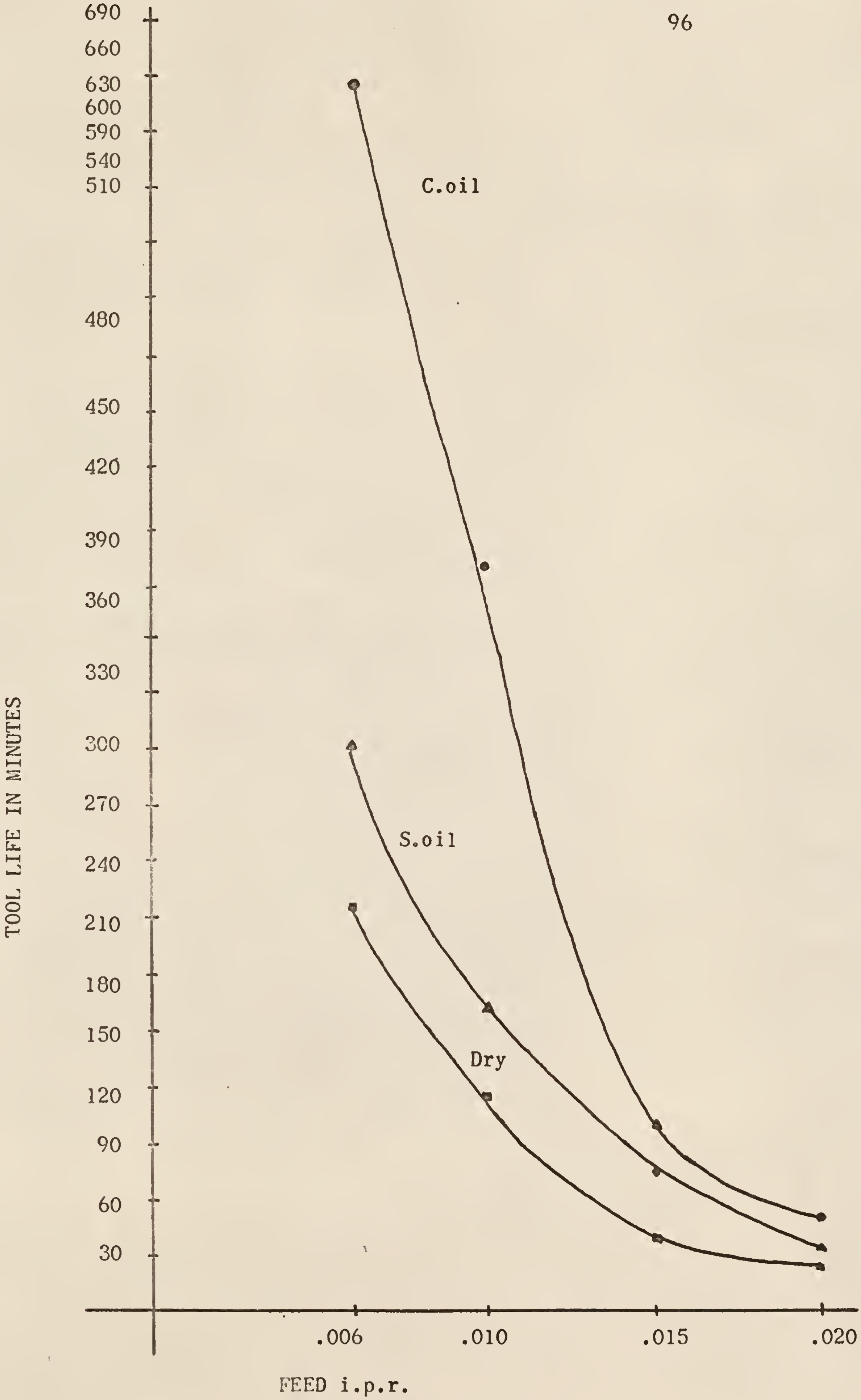
FIGURE VIII

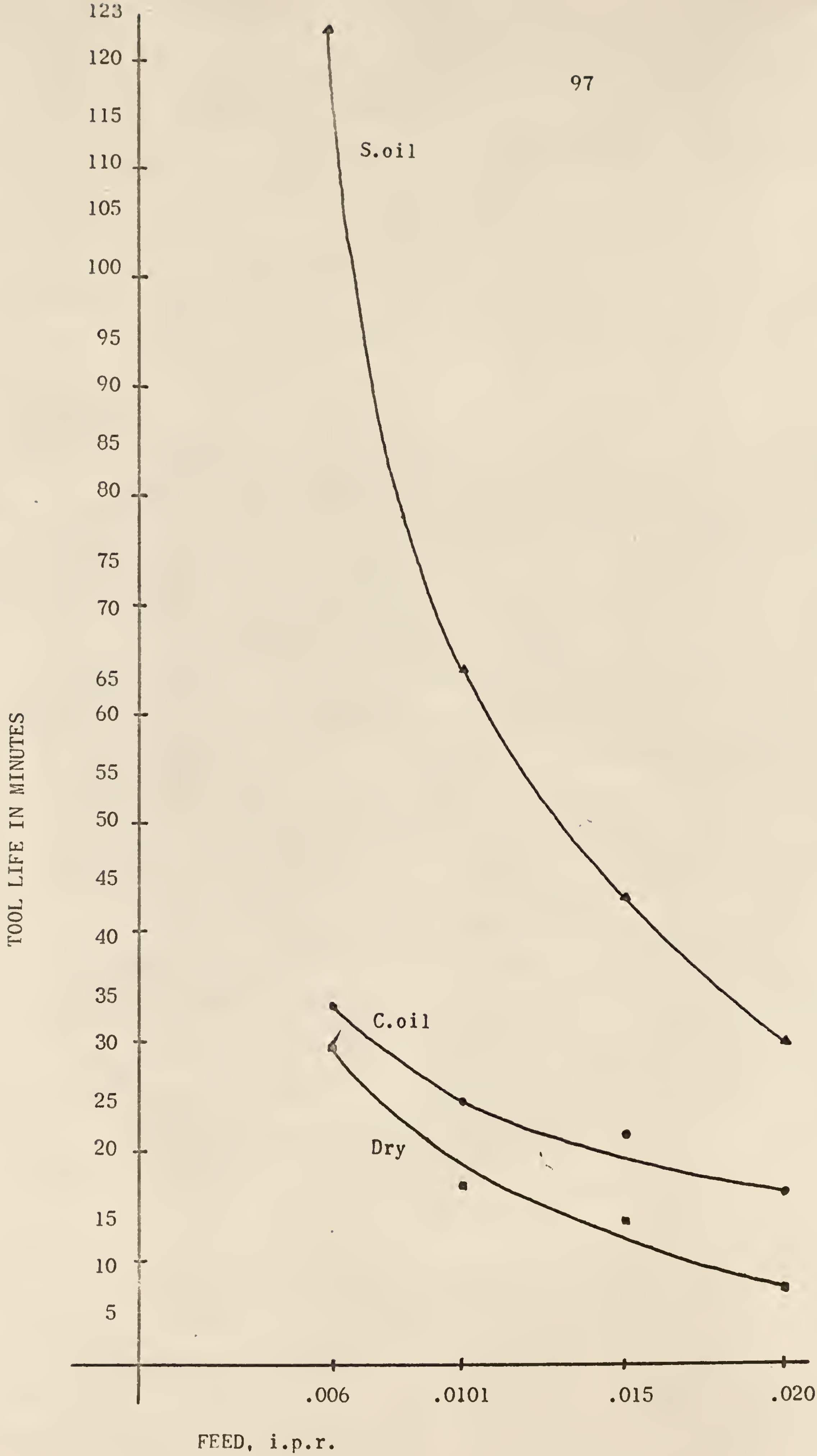

FEED: 0.006
D/CUT: 0.3125
G.oil
S.oil
Dry
TOOL LIFE IN MINUTES
690
660
630
600
330
300
270
240
210
180
150
120
90
60
30
36
58
91
110
SPEED, rpm

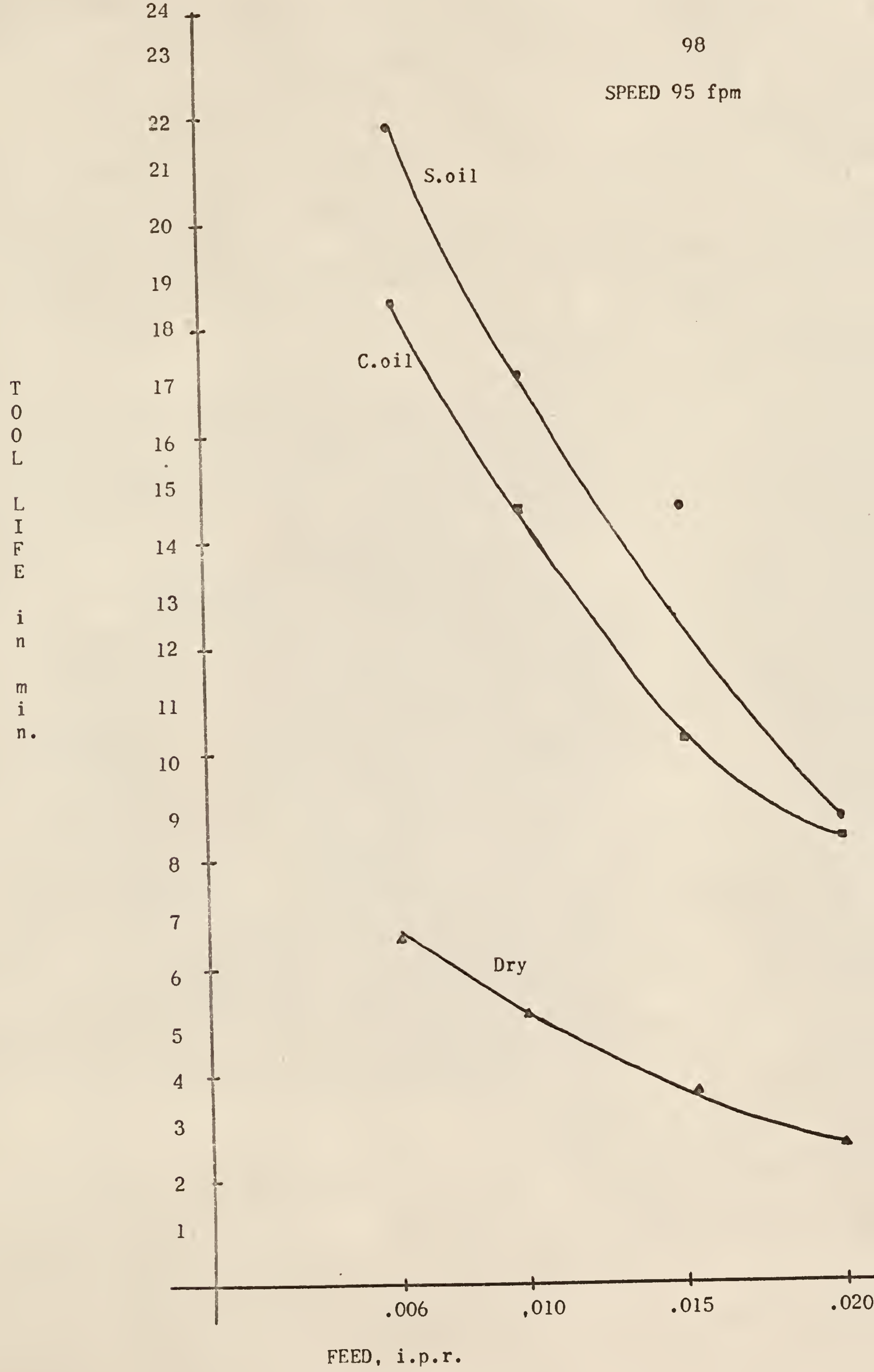

FEED: 0.010 ipr
D/CUT: 0.3125
C.oil
TOOL LIFE IN MINUTES
440
400
360
320
280
240
200
160
120
80
40
36
58
91
110
SPEED, rpm

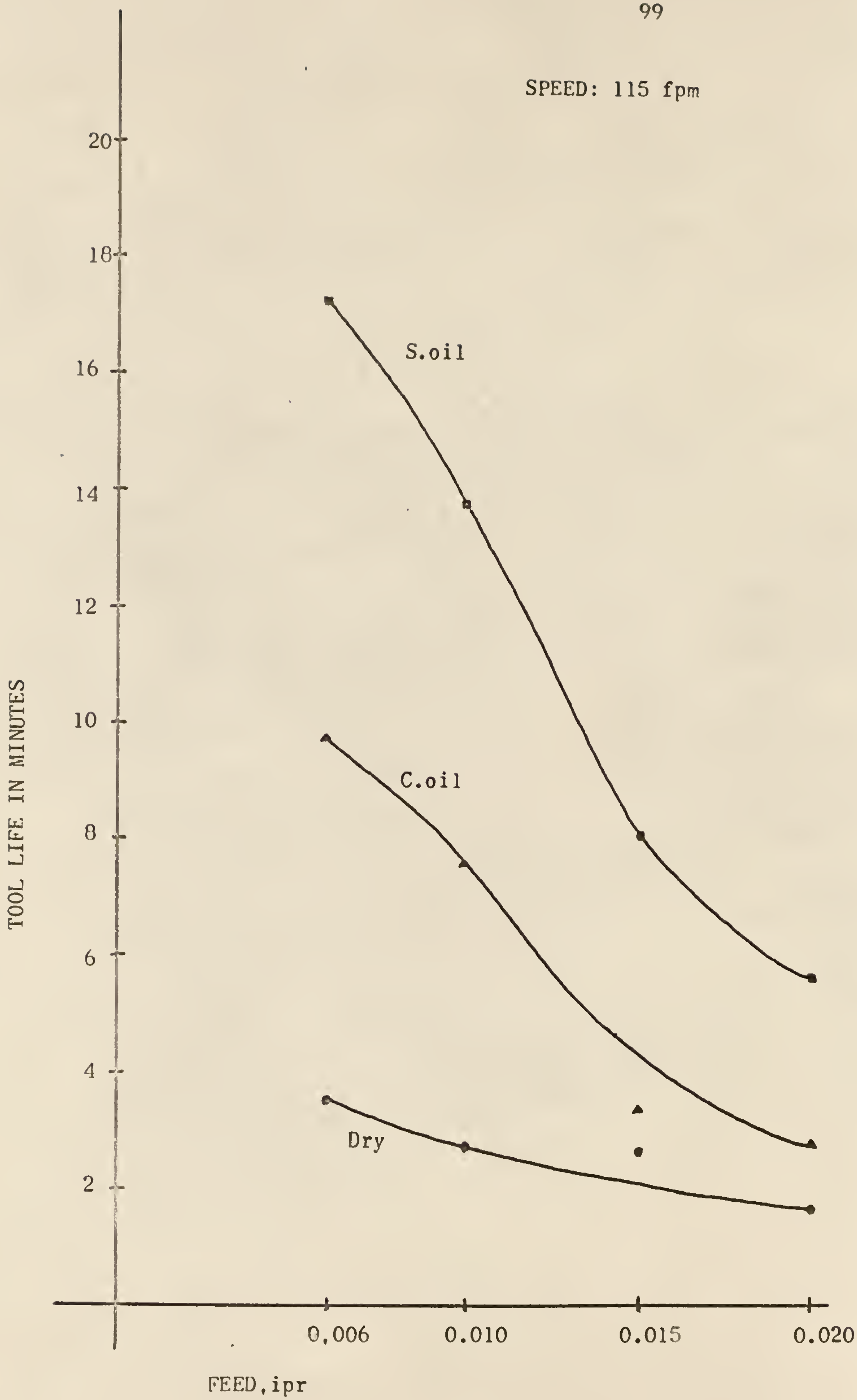

FEED: .015
D/CUT: 0.3125
S.oil
C.oil
Dry
TOOL LIFE IN MINUTES
100
90
80
70
60
50
40
30
20
10
30
36
45
58
75
91
110
SPEED, rpm


FEED: 0.020
DEPTH: .3125
C.oil
S.oil
Dry
TOOL LIFE IN MINUTES
60
55
50
45
40
35
30
25
20
15
10
5
30 36 40 45 50 55 58 65 70 75 80 85 91 95 100 105 110
SPEED rpm

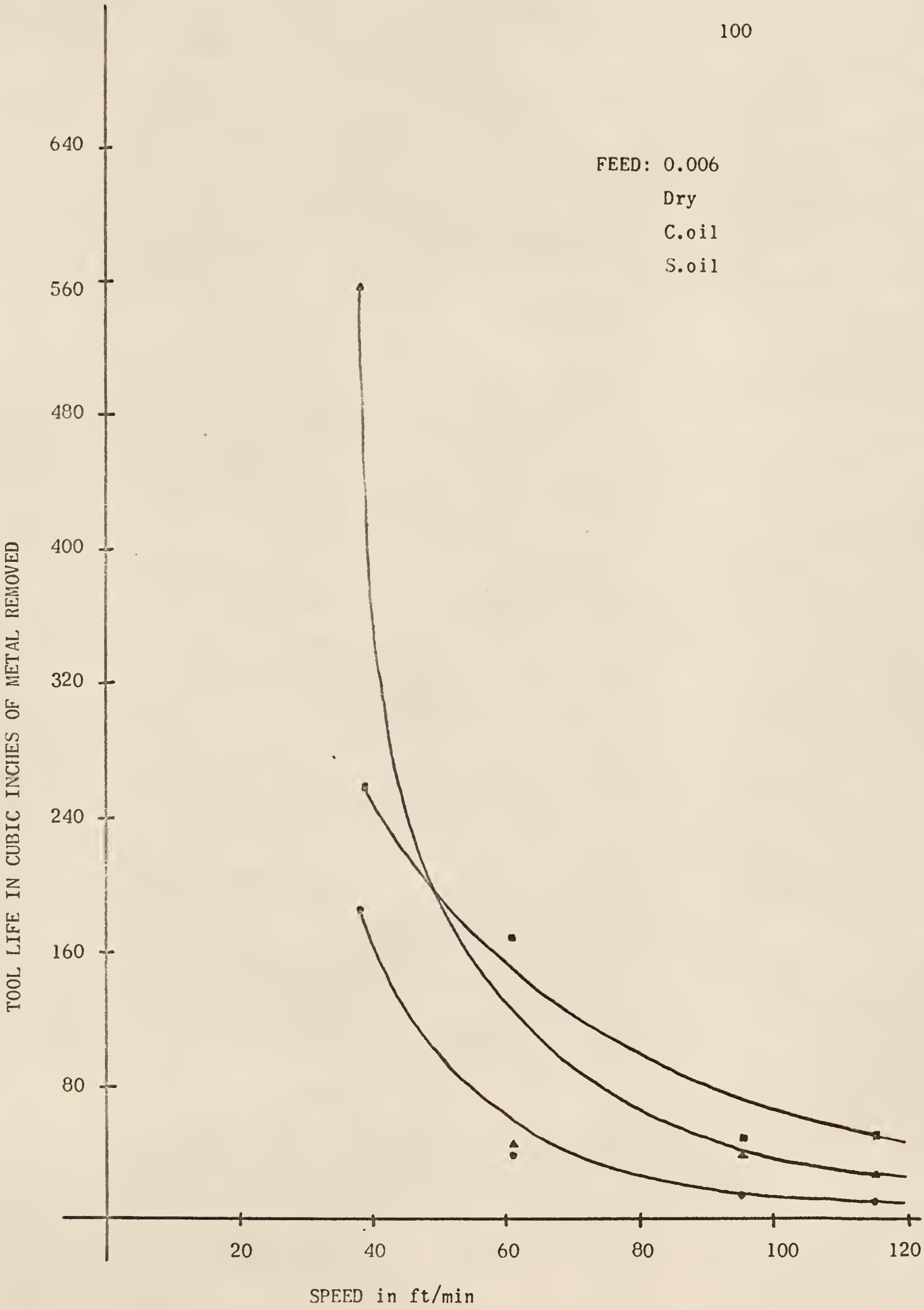

690
660
630
600
590
540
510
480
450
420
390
360
330
300
270
240
210
180
150
120
90
60
30
TOOL LIFE IN MINUTES
C.oil
S.oil
Dry
.006
.010
.015
.020
FEED i.p.r.

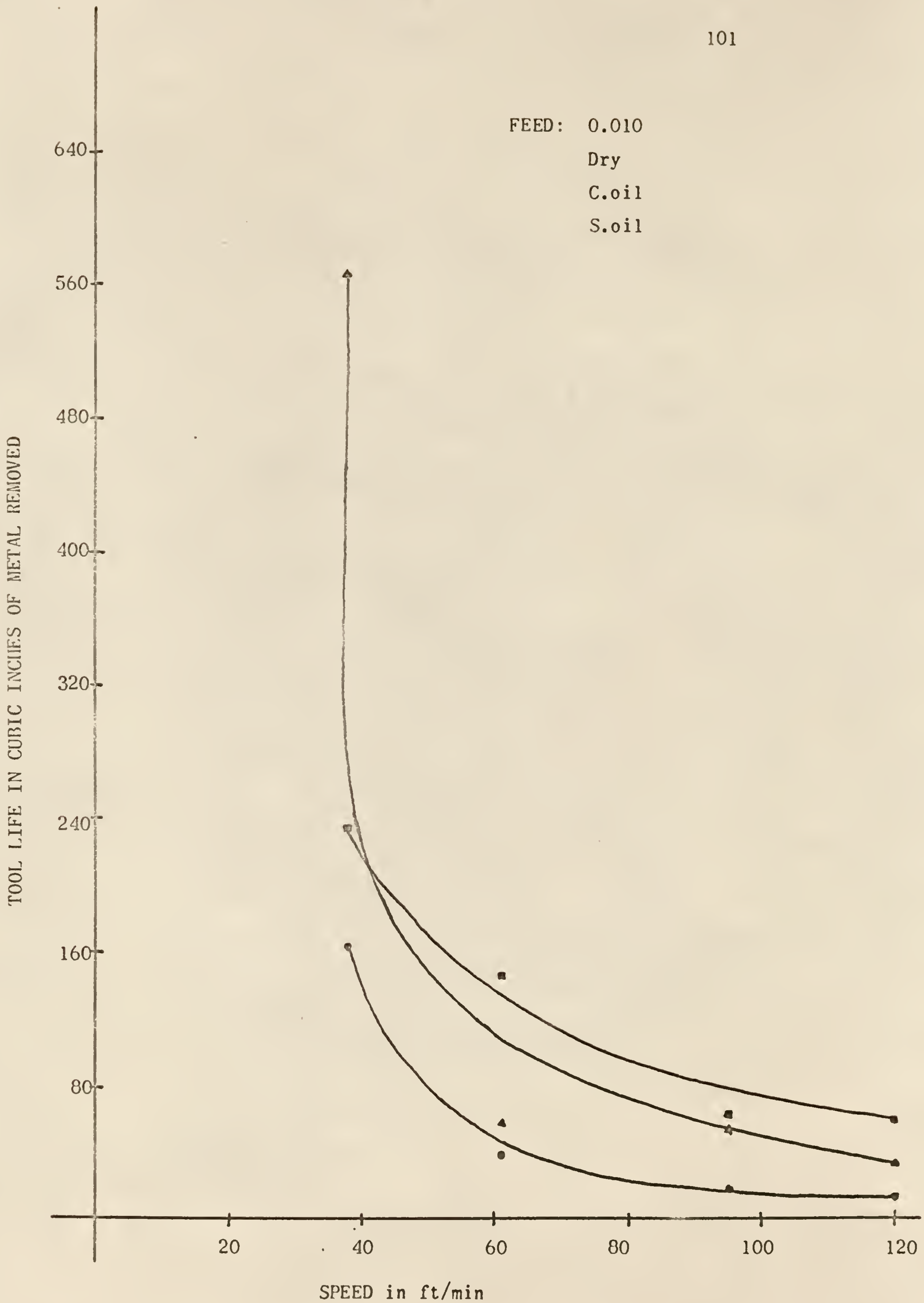

123
120
115
110
105
100
95
90
85
80
75
70
65
60
55
50
45
40
35
30
25
20
15
10
5
TOOL LIFE IN MINUTES
S.oil
C.oil
Dry
.006
.0101
.015
.020
FEED, i.p.r.

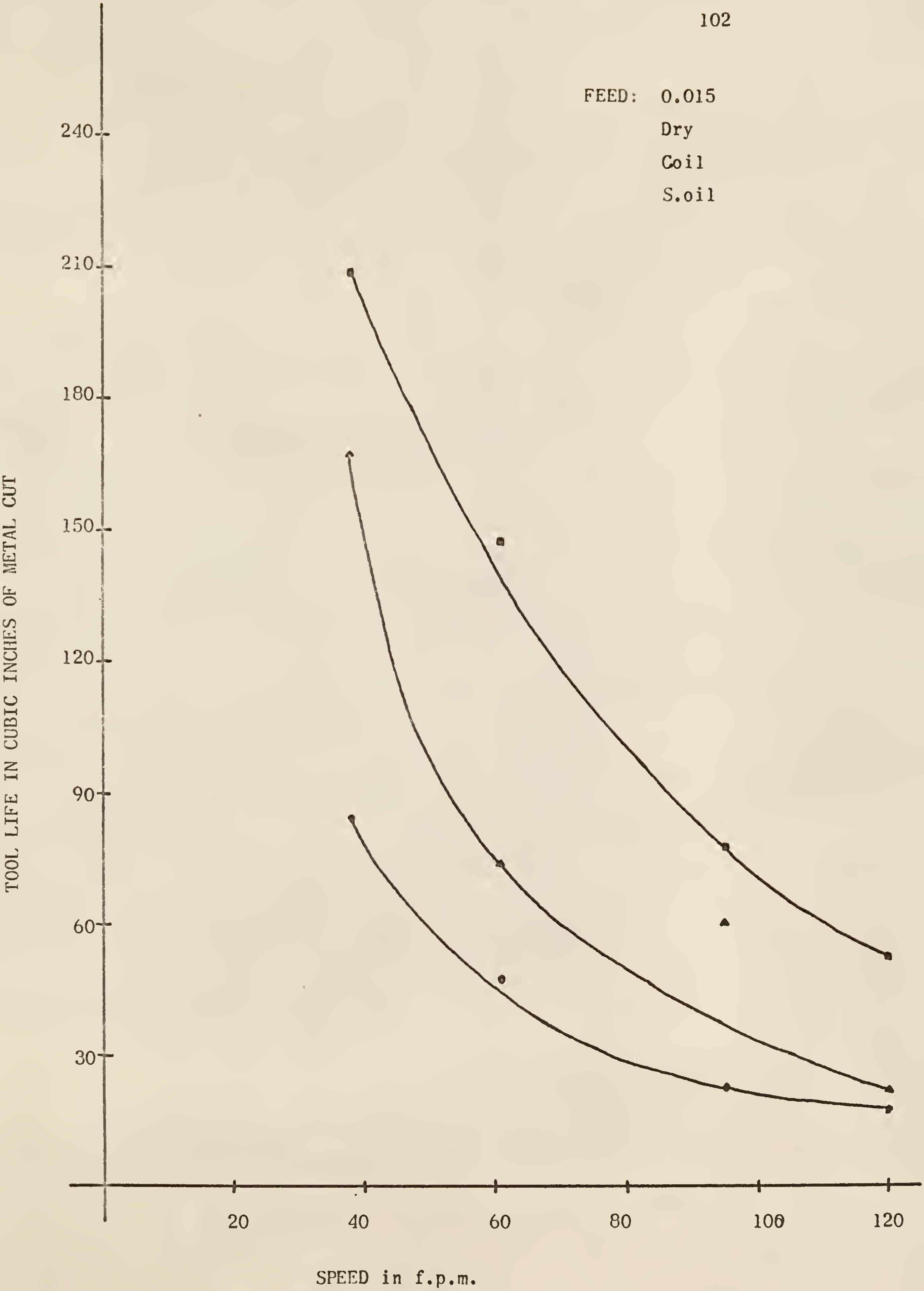

SPEED 95 fpm
S.oil
C.oil
Dry
TOOL LIFE in min.
24
23
22
21
20
19
18
17
16
15
14
13
12
11
10
9
8
7
6
5
4
3
2
1
.006
.010
.015
.020
FEED, i.p.r.



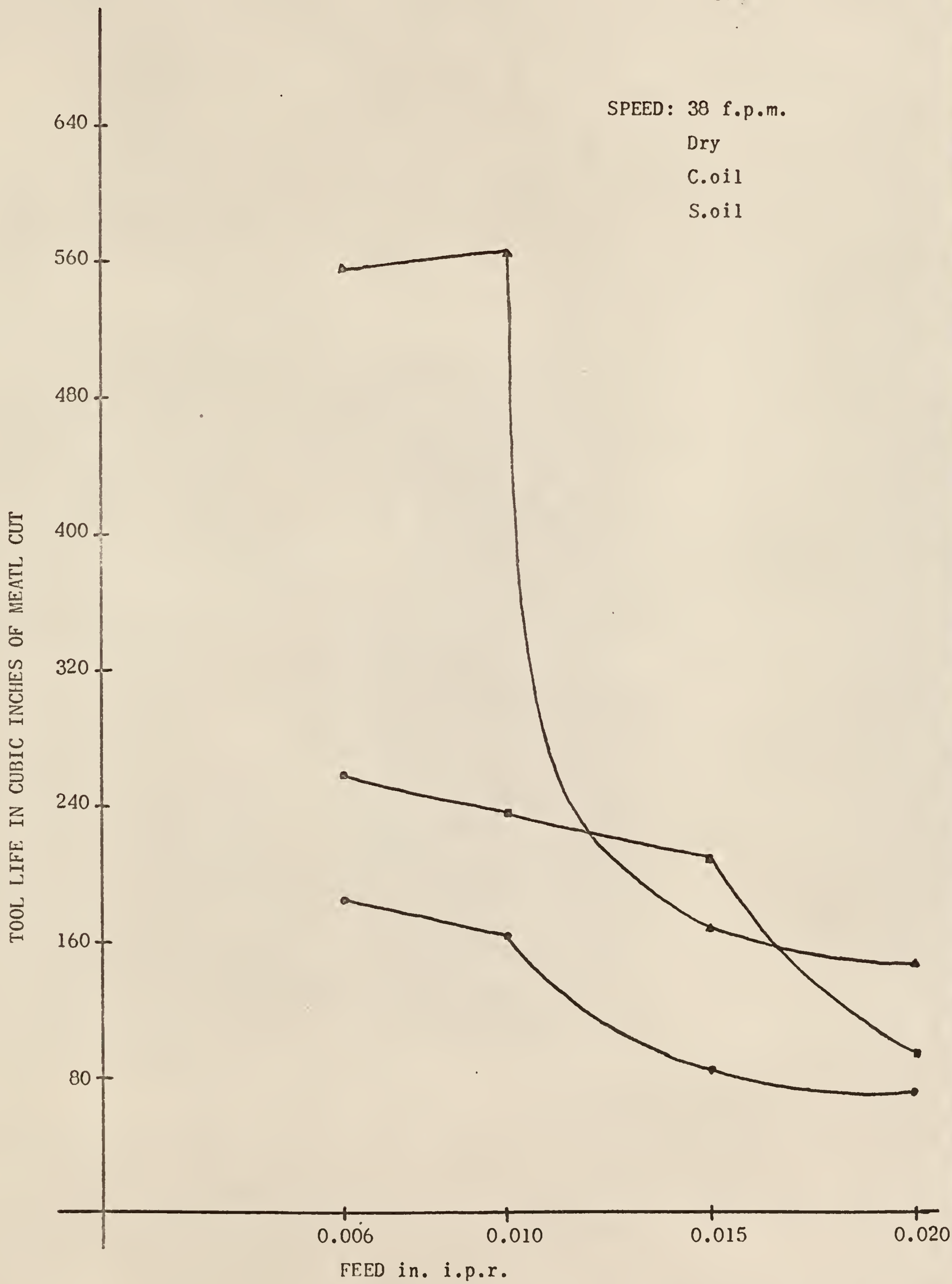
TOOL LIFE IN CUBIC INCHES OF METAL REMOVED

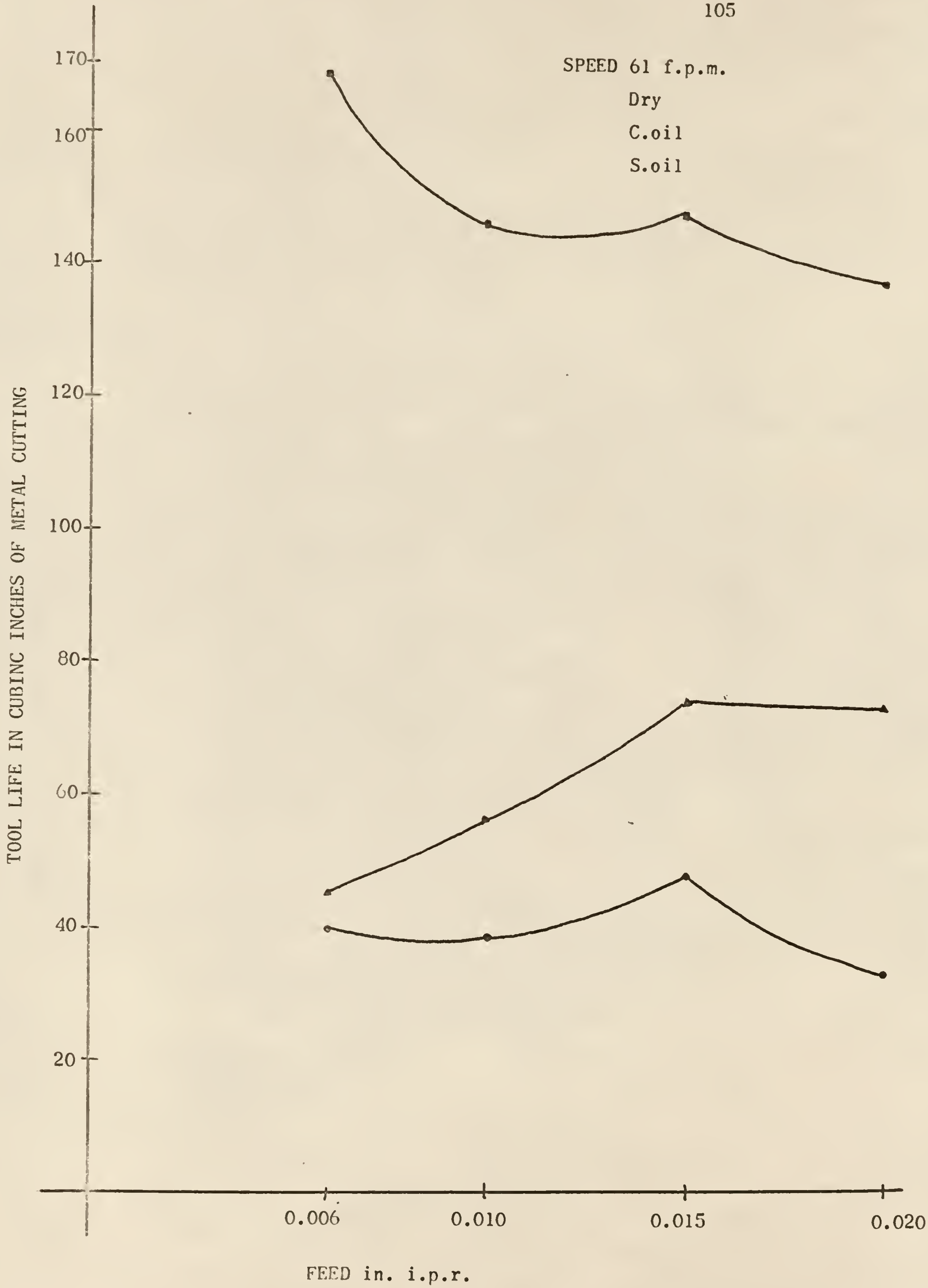

FEED: 0.006
Dry
C.oil
S.oil
TOOL LIFE IN CUBIC INCHES OF METAL REMOVED
640
560
480
400
320
240
160
80
20
40
60
80
100
120
SPEED in ft/min

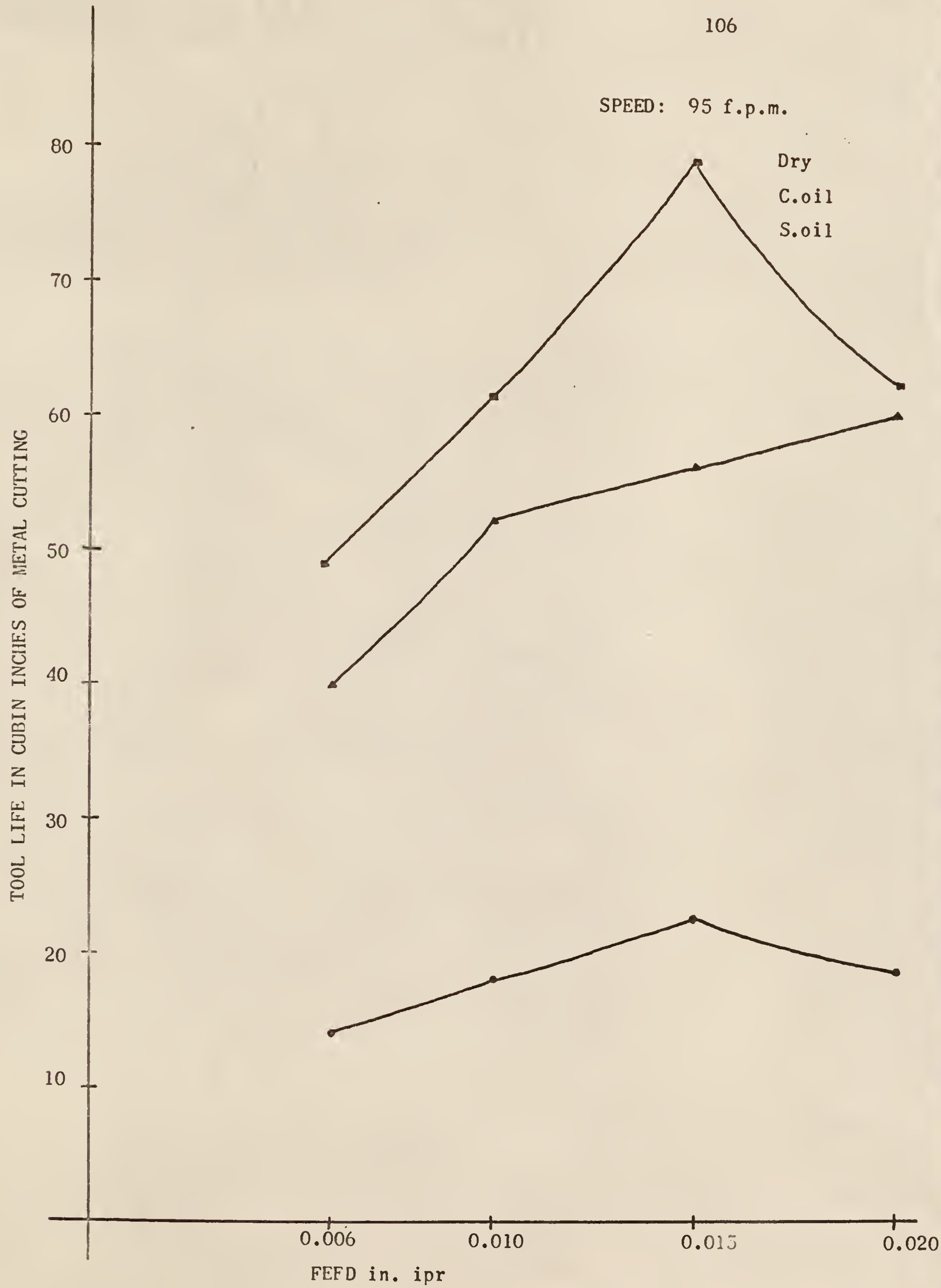

FEED: 0.010
Dry
C.oil
S.oil
TOOL LIFE IN CUBIC INCHES OF METAL REMOVED
640
560
480
400
320
240
160
80
20
40
60
80
100
120
SPEED in ft/min

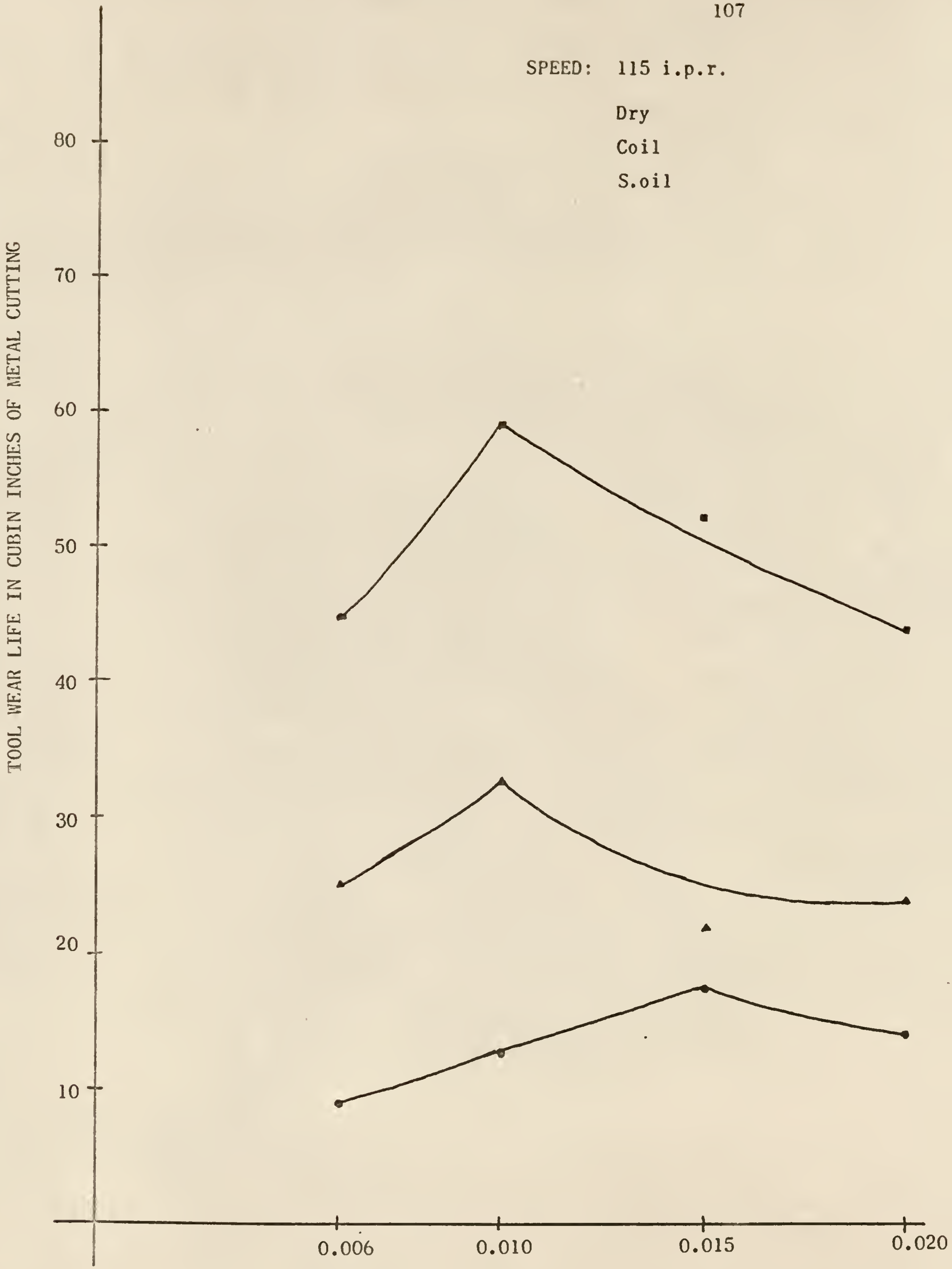

FEED: 0.015
Dry
Coil
S.oil
240
210
180
150
120
90
60
30
TOOL LIFE IN CUBIC INCHES OF METAL CUT
20
40
60
80
100
120
SPEED in f.p.m.

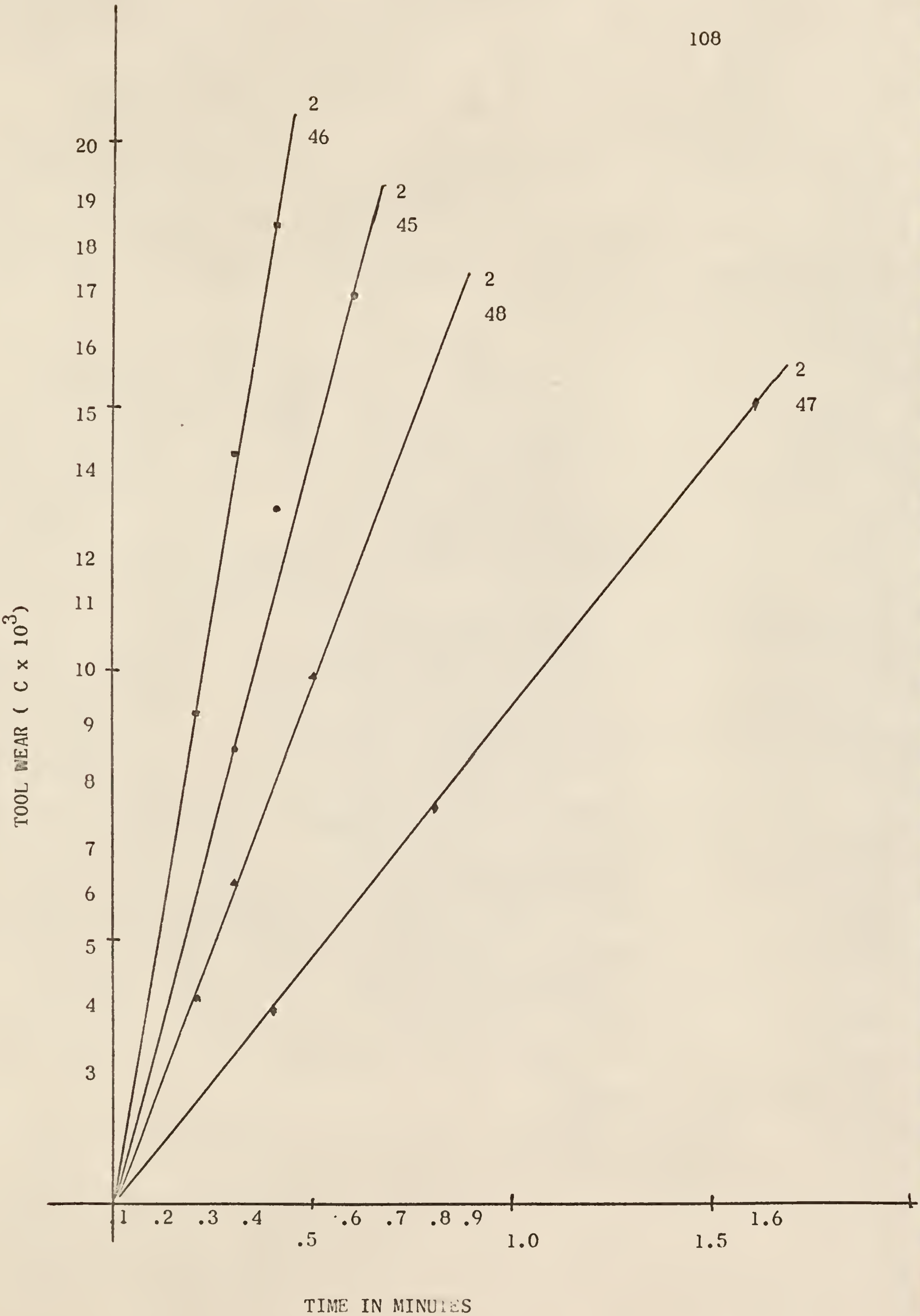

FEED: 0.020
Dry
C.oil
S.oil
160
140
120
100
80
60
40
20
TOOL LIFE IN CUBIC INCHES OF METAL CUT
20
40
60
80
100
120
SPEED in f.p.m.

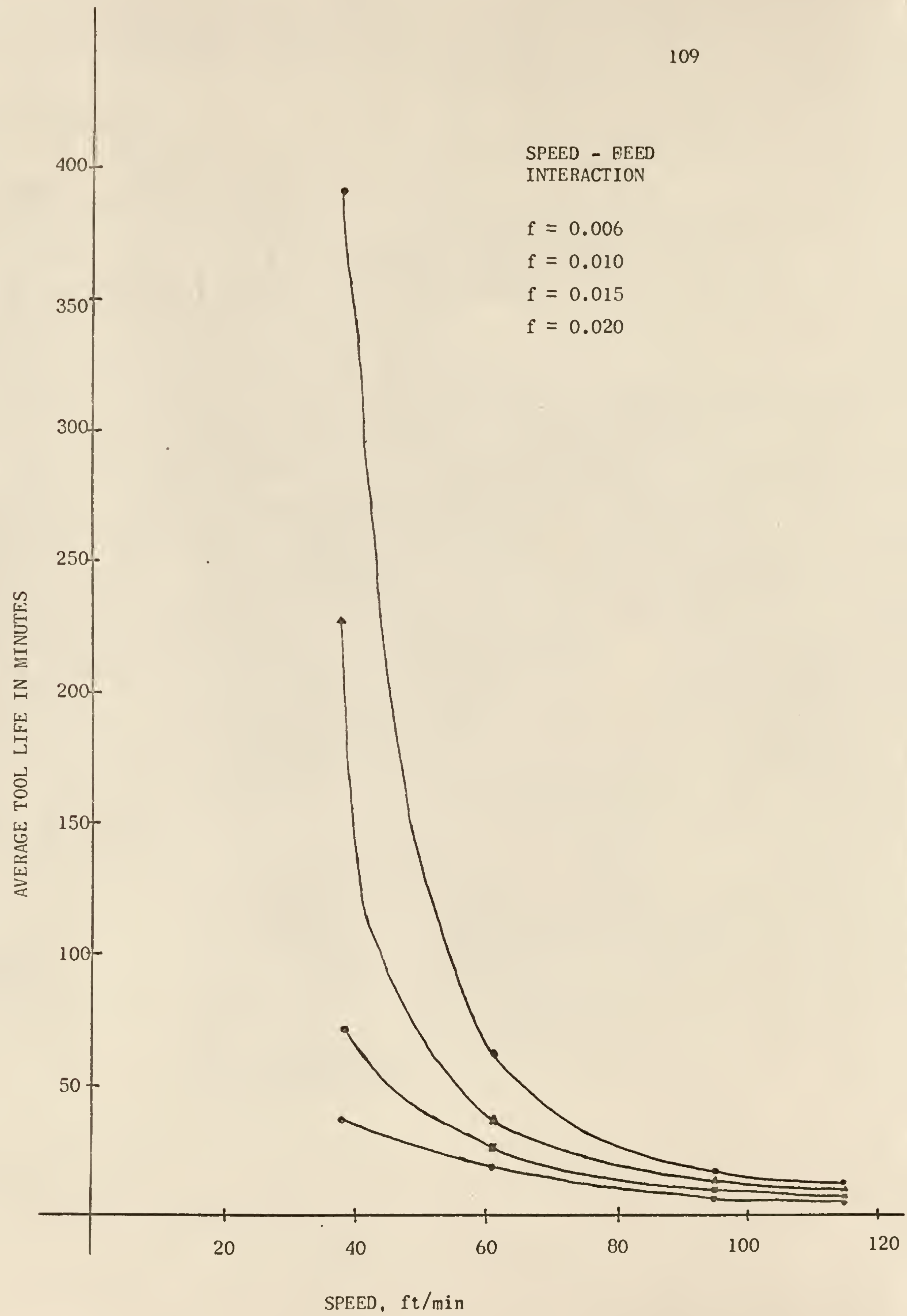

SPEED: 38 f.p.m.
Dry
C.oil
S.oil
TOOL LIFE IN CUBIC INCHES OF MEATL CUT
640
560
480
400
320
240
160
80
0.006
0.010
0.015
0.020
FEED in. i.p.r.

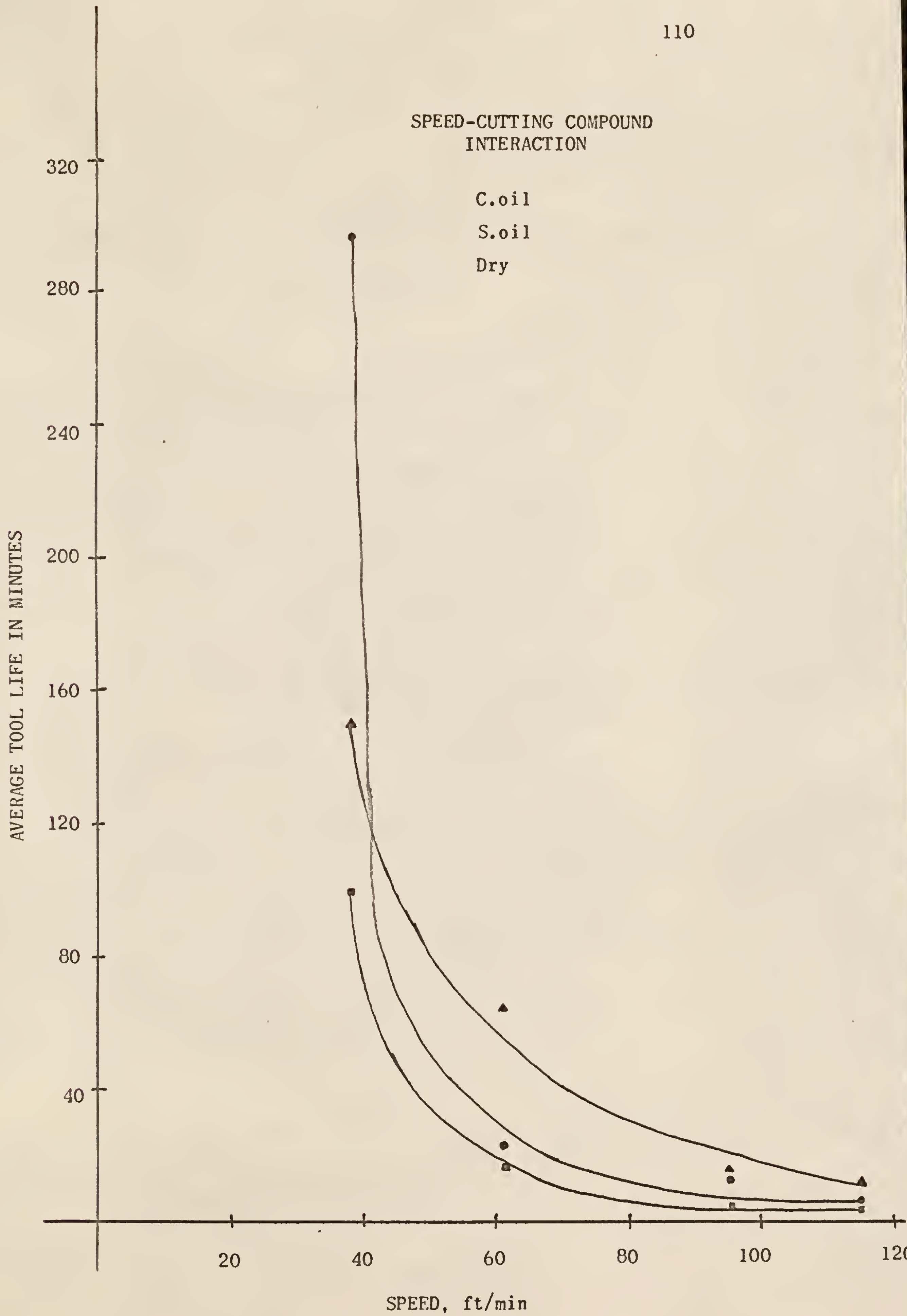

SPEED 61 f.p.m.
Dry
C.oil
S.oil
170
160
140
120
100
80
60
40
20
TOOL LIFE IN CUBINC INCHES OF METAL CUTTING
0.006
0.010
0.015
0.020
FEED in. i.p.r.

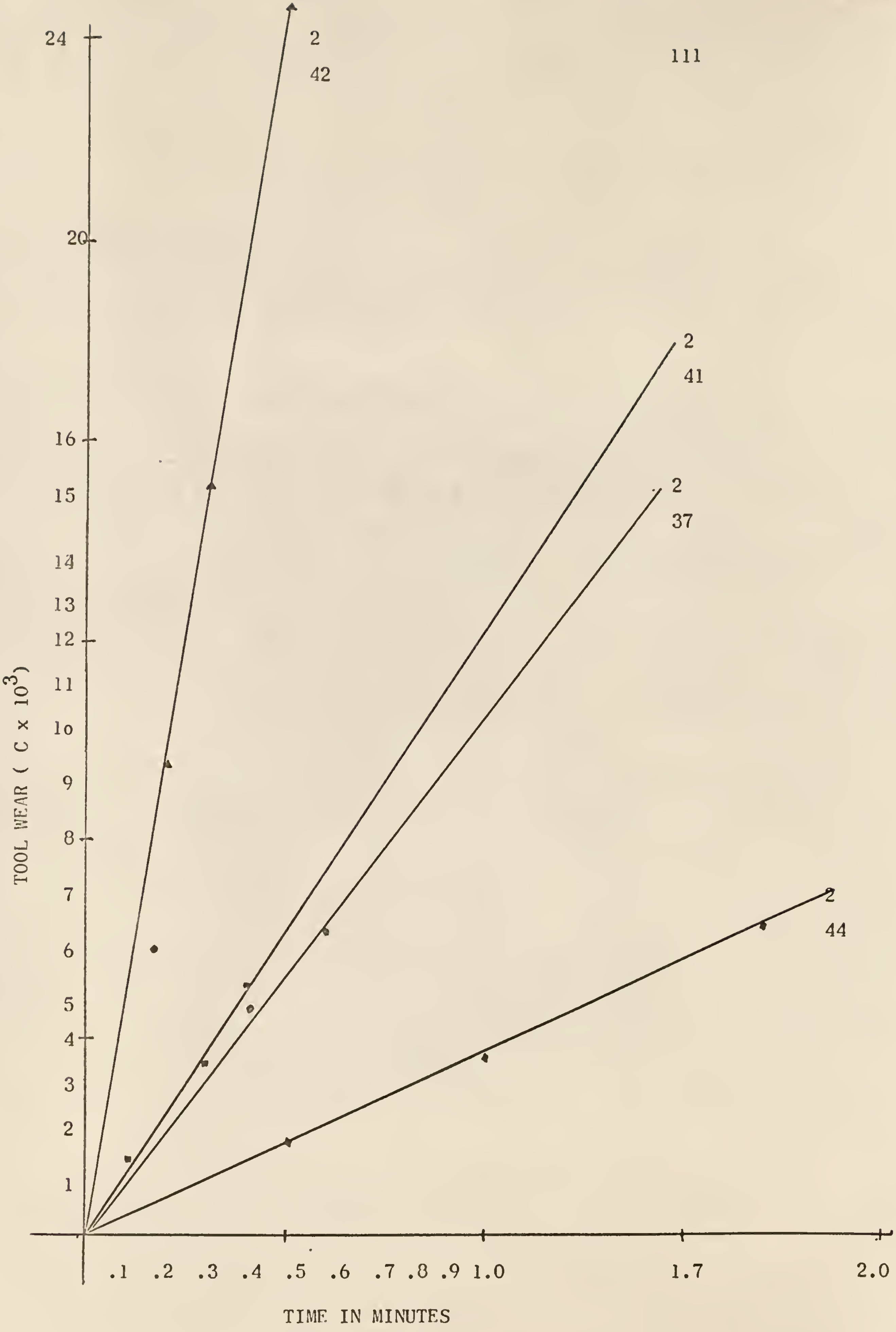

SPEED: 95 f.p.m.
Dry
C.oil
S.oil
TOOL LIFE IN CUBIN INCHES OF METAL CUTTING
80
70
60
50
40
30
20
10
0.006
0.010
0.015
0.020
FEFD in. ipr


SPEED: 115 i.p.r.
Dry
Coil
S.oil
TOOL WEAR LIFE IN CUBIN INCHES OF METAL CUTTING
80
70
60
50
40
30
20
10
0.006
0.010
0.015
0.020
FEED, i.p.r.


TOOL WEAR (C x 10^3)
20
19
18
17
16
15
14
12
11
10
9
8
7
6
5
4
3
2
46
2
45
2
48
2
47
1
.2
.3
.4
.5
.6
.7
.8
.9
1.0
1.5
1.6
TIME IN MINUTES


SPEED - FEED
INTERACTION
f = 0.006
f = 0.010
f = 0.015
f = 0.020
AVERAGE TOOL LIFE IN MINUTES
400
350
300
250
200
150
100
50
20
40
60
80
100
120
SPEED, ft/min


SPEED-CUTTING COMPOUND
INTERACTION
C.oil
S.oil
Dry
AVERAGE TOOL LIFE IN MINUTES
320
280
240
200
160
120
80
40
20
40
60
80
100
120
SPEED, ft/min


24
20
16
15
14
13
12
11
10
9
8
7
6
5
4
3
2
1
TOOL WEAR (C x 10^3)
2
42
2
41
2
37
2
44
.1
.2
.3
.4
.5
.6
.7
.8
.9
1.0
1.7
2.0
TIME IN MINUTES

APPENDIX B

The tool-life calculation is done with the use of the following equation proposed by M. C. Shaw[23].

$$T = 30.53 \frac{BC}{\cot \Theta} \quad \frac{dT}{dC}$$

where

BC = the tool-life criterion, based on land wear - 0.006

θ = clearance angle = 5^0

$\cot \theta$ = 11.43

$\frac{dT}{dC}$ = the inverse slope of the wear time graph

substituting the above values, we get:

$$T = 30.53 \times \frac{0.060}{11.43} \cdot \frac{dT}{dC}$$

$$T = 0.16 \frac{dT}{dC} \text{ minutes} \qquad (5)$$

The equation has been repeatatively used in all the 48 treatments determining the tool-life.

Treatment 1:

Initial length of the impression, 931

Length after: 1.7 min 894

2.5 min 837

1.0 min 817

TIME	WEAR	ΔC(inch)	$\Delta C \times 10^3$
1.7	931-894-37	$\frac{37}{162.75} \times .01 = 0.002195$	2.195
2.5	894-837-51	$\frac{51}{162.75} \times .01 = 0.003512$	3.512
1.0	837-817-20	$\frac{20}{162.75} \times .01 = 0.001230$	1.230

From graph 1, between $\Delta C \times 10^3$ and time, we get,

$$\frac{dT}{dC} = \frac{1.5}{0.002075}$$

Hence,

$$T_1 = 0.16 \times \frac{1.5}{0.002075}$$

$$= 115.662 \text{ minutes}$$

$$T_1 = 115.7 \text{ minutes}$$

The results of a similar calculation for other treatments are shown in Table 13.

Table 9 gives the tool-life in terms of cubic inch of metal removed. A sample calculation is shown below. Similar computations were done in order to arrive at Table figures.

L = cubic inch of material removed

= v.f.d.T.

or L = f.d. π D.N.T. cubin inch

where

D is the mean diameter of the tube cut = 4 inches

N revolution per minute

$L = (\pi.d.D)\ f.N.T = K.f.N.T$

where

$K = \pi \times 0.3125 \times 4 = 3.9263$

Hence,

L, tool-life in terms of cubin inches of metal cut equals,

$$L = 3.9263 \times f \times N \times T \qquad (6)$$

At,

f = 0.006 inches

N = 36 r.p.m.

T = 303 minutes (under Soluble oil)

$L = 3.9263 \times 0.006 \times 36 \times 303$

$= 0.0236 \times 36 \times 303$

= 257.429 cubic inch

The equation (6) can be written as:

$$L = K'T \qquad (7)$$

where

K' equals $3.9263\, fN$

The values of K' for the various combinations of f and N are given in Table 14, pp. 133.

TABLE 13
COMPUTATIONS FOR TOOL-LIFE IN MINUTES

Treatment	Wear (ΔC) inch	$\Delta C \times 10^3$	Time min	Wear Rate $\frac{dT}{dC}$	Tool-Life T min
1	0.00123 0.002195 0.003512	1.230 2.195 3.512	1.0 1.7 2.5	$\frac{1.5}{0.00208}$	115.7
2	0.009213 0.014151 0.019002	9.213 14.151 19.002	1.0 1.5 2.0	$\frac{1.2}{0.01143}$	16.82
3	0.002657 0.007813 0.012948	2.657 7.813 12.948	0.1 0.3 0.5	$\frac{0.2}{0.00447}$	7.16
4	0.0022119 0.0046082 0.0071270	2.2119 4.6082 7.1270	0.2 0.4 0.6	$\frac{0.3}{0.00351}$	013.7
5	0.0049155 0.0082334 0.0130261	4.9155 8.2334 13.0261	0.3 0.5 0.8	$\frac{0.5}{0.0082}$	9.66
6	0.0036251 0.0075576 0.011797	3.6251 7.5576 11.7970	0.2 0.4 0.6	$\frac{0.5}{0.0095}$	8.40

Table 13 Continued......

Treatment	Wear (ΔC) inch	$\Delta C \times 10^3$	Time min.	Wear Rate $\frac{dT}{dC}$	Tool-Life T min.
7	0.000512 0.001531 0.002367	0.5120 1.5310 2.3670	1.0 2.0 3.0	$^{2.5}/_{0.00184}$	217
8	0.001536 0.003379 0.004592	1.5360 3.3790 4.5920	1.0 2.0 3.0	$^{1.6}/_{0.0026}$	98.5
9	0.00 0.0004915 0.0008602	0 0.4915 0.8602	1.0 1.5 2.0	$^{4}/_{0.0016}$	400
10	0.00 0.0009216 0.001536	0 0.9216 1.5360	2.0 4.0 6.0	$^{4.9}/_{0.0012}$	654
11	0.009213 0.019521 0.029638*	9.213 19.521 29.638	0.1 0.2 0.3	$^{0.14}/_{0.0138}$	1.614
12	0.001167 0.009831 0.012783	1.167 9.831 12.783	0.3 0.5 0.7	$^{0.5}/_{0.0092}$	8.7

*A new indentation of length 933 was given at the beginning of this time.

TABLE 13 cont....

Treatment	Wear (ΔC) Inch	$\Delta C \times 10^3$	Time min	Wear Rate $\frac{dT}{dC}$	Tool-Life $T_{min.}$
13	0.002148 0.005284 0.014842	2.1480 5.2840 14.8420	0.3 0.7 2.0	$^{1.2}/_{0.0088}$	25.8
14	0.0005039 0.001047 0.001603	0.5039 1.0470 1.6030	1.0 2.0 3.0	$^{2.5}/_{0.00132}$	303.0
15	0.00159754 0.00516129 0.00688170	1.59754 5.16129 6.88170	0.2 0.6 0.8	$^{0.5}/_{0.00432}$	18.5
16	0.001597 0.003072 0.003965	1.5970 3.0720 3.9650	1.2 2.0 3.0	$^{2.0}/_{0.0026}$	123.0
17	0.005468 0.011721 0.018176	5.4680 11.7210 18.1760	0.1 0.2 0.3	$^{0.24}/_{0.0142}$	2.704
18	0.002945 0.004055 0.009574	2.945 4.055 9.574	0.4 0.6 1.5	$^{1.8}/_{0.0117}$	24.6

Table 13 Cont.....

Treatment	Wear (ΔC) inch	$\Delta C \times 10^3$	Time min	Wear Rate $\frac{dT}{dC}$	Tool-Life $T_{min.}$
19	0.0062058 0.0092165 0.0155453	6.2058 9.2165 15.5453	0.2 0.3 0.5	$^{0.4}/_{0.01257}$	5.09
20	0.002826 0.005038 0.007686	2.8260 5.0380 7.6860	0.5 1.0 1.6	$^{1.4}/_{0.0068}$	33.00
21	0.004598 0.003502 0.011121	4.598 3.502 11.121	0.6 1.0 1.5	$^{1.0}/_{0.0074}$	21.60
22	0.003808 0.009021 0.014439	3.808 9.021 14.439	0.1 0.2 0.3	$^{0.25}/_{0.0118}$	3.39
23	0.000923 0.001536 0.002457	0.923 1.536 2.457	1.0 1.7 2.5	$^{3.0}/_{0.0029}$	165.50
24	0.006121 0.011792 0.019086	6.121 11.792 19.086	0.1 0.2 0.3	$^{0.22}/_{0.0135}$	2.61

Table 13 Cont......

Treatment	Wear (ΔC) inch	$\Delta C \times 10^3$	Time min	Wear Rate $\frac{dT}{dC}$	Tool-Life T_{min}
25	0.011580 0.019784 0.022764	11.580 19.784 22.764	0.2 0.3 0.4	$0.2/_{0.0116}$	2.76
26	0.002921 0.006352 0.010123	2.921 6.352 10.123	0.5 1.0 1.6	$0.75/_{0.00476}$	25.202
27	0.000943 0.002312 0.003157	0.923 2.342 3.137	0.1 0.2 0.4	$0.3/_{0.00165}$	29.2
28	0.006144 0.009103 0.014698	6.144 9.103 14.698	0.4 0.6 1.0	$0.75/_{0.0115}$	10.44
29	0.0048121 0.010523 0.0149150	4.8121 10.1923 14.8850	0.2 0.4 0.6	$0.5/_{10.1227}$	6.524
30	0.000921 0.005468 0.011580	019210 5.4680 11.5800	0.5 1.0 2.0	$1.28/_{0.00068}$	30.10

Table 13 Cont.......

Treatment	Wear (ΔC) inch	$\Delta C \times 10^3$	Time min	Wear Rate $\frac{dT}{dC}$	Tool-Life T_{min}
31	0.001413 0.004669 0.007682	1.4130 4.6690 7.6820	0.8 1.5 2.5	$1.0/0.0031$	51.70
32	0.00208909 0.00423963 0.00651300	2.08909 4.23963 6.51300	0.2 0.4 0.6	$0.5/0.00549$	14.57
33	0.000491 0.003729 0.005002	0.4910 3.7290 5.0020	1.0 1.5 2.0	$2.0/0.005$	64.00
34	0.003995 0.007982 0.012120	3.9950 7,9820 12.1200	1.0 2.0 3.0	$2.5/0.0101$	39.60
35	0.007375 0.015362 0.022745	7.3750 15.3620 22.7450	0.2 0.4 0.6	$0.5/0.01905$	4.20
36	0.00319508 0.00540706 0.0086021	3.19508 4.50706 8.60210	0.3 0.5 0.8	$0.6/0.00652$	14.72

Table 13 Cont.......

Treatment	Wear (ΔC) inch	$\Delta C \times 10^3$	Time min	Wear Rate $\frac{dT}{dC}$	Tool-Life T_{min}
37	0.0058960 0.0046697 0.0062058	5.8960 4.0697 6.2058	0.2 0.4 0.6	$0.9/0.0096$	16.10
38	0.002032 0.002150 0.005099	2.0320 2.1500 5.0990	1.0 1.5 2.5	$2.0/0.00408$	78.50
39	0.004712 0.009128 0.014021	4.7120 9.1280 14.0210	0.5 1.0 1.5	$0.75/0.007$	17.20
40	0.00208909 0.0103840 0.0148079	2.08909 10.3840 14.8079	0.1 0.5 0.7	$0.8/0.0169$	7.57
41	0.001582 0.003498 0.005121	1.4820 3.4980 5.1210	0.1 0.3 0.4	$0.2/0.00229$	13.97
42	0.009465 0.015100 0.024780	9.4650 15.1000 24.7800	0.2 0.3 0.5	$0.25/0.01482$	2.7

Table 13 Cont......

Treatment	Wear (ΔC) inch	$\Delta C \times 10^3$	Time mn	Wear Rate $\frac{dT}{dC}$	Tool-Life T_{min}
43	0.008417 0.014562 0.007741	8.417 14.562 7.741	2 3 1.5	$2/_{0.0097}$	33
44	0.00184331 0.00374807 0.0064901	1.84331 3.74807 6.39010	0.5 1.0 1.7	$1.5/_{0.00557}$	43.10
45	0.008540 0.0046082 0.017012	8.5400 4.6082 17.0120	0.3 0.5 0.6	$0.4/_{0.0113}$	5.67
46	0.00918 0.01412 0.01841	9.180 14.120 18.410	0.2 0.3 0.4	$0.25/_{0.01153}$	3.468
47	0.00368663 0.0074961 0.0151152	3.68663 7.49610 15.11520	0.4 0.8 1.6	$0.5/_{0.00465}$	17.20
48	0.00387096 0.00608294 0.00989240	3.87096 6.08294 9.89240	0.2 0.3 0.5	$0.4/_{0.00792}$	8.08

Feed ipr / Speed rpm	0.006	0.010	0.015	0.020
36	0.8496	1.4148	2.1204	2.8260
58	1.3688	2.2794	3.4162	4.5530
91	2.1476	3.5763	4.3599	7.1435
110	2.5960	4.3230	6.4790	8.6350

TABLE 14

VALUES OF K^1 OF EQUATION 7

APPENDIX C

The detailed calculations for ANOVA are shown below.

Y_{ijk} is the observed tool-life under the speed level i, feed level j, and cutting compound k.

N equals total number of treatments equals 48.

T_{SS} is the total sum of square.

S_{SS}, F_{SS}, C_{SS} are the sum of squares for speed, feed, and cutting compound respectively.

SxF_{SS} is the sum of squares of the interaction of speed and feed.

SxC_{SS} is the sum of squares of the interaction of speed and cutting compound.

FxC_{SS} is the sum of squares of the interaction of feed and cutting compound.

$SxFxC_{SS}$ is the sum of square due to interaction of all the three factors. This is the project equals the error sum of square, assuming there is no three factor interaction.

M.S.S. is the mean sum of squares which equals the S.S. divided by the corresponding degree of freedom.

α is the level of significance, assumed.

d.f degree of freedom.

The different sum of squares are calculated with the use of following equations.

$$C.F = \left(\sum_{k} \sum_{j} \sum_{i} Y_{ijk}\right)^2 / N$$

$$T_{SS} = \sum_{k} \sum_{j} \sum_{i} (Y_{ijk})^2 - C.F.$$

$$S_{SS} = \sum_{i=1}^{4} (Y_{.jk})^2 / 12 - C.F.$$

where

$Y_{.jk}$ represents the observed values are summed up over i, i.e., each speed level, and 12 is the total number of observation added together to determine $Y_{.jk}$.

$$F_{SS} = \sum_{j=1}^{4} (Y_{i.k})^2 / 12 - C.F.$$

$$C_{SS} = \sum_{k=1}^{3} (Y_{ij.})^2 / 16 - C.F.$$

$$SxF_{SS} = \sum_{j} \sum_{i} (\sum_{j} \sum_{i} Y_{..k})^2 / 3 - S_{SS} - F_{SS} - C.F.$$

where

3 is the number of observations due to three different cutting compounds which are added together to find the square in the denominator.

$$SxC_{SS} = \sum_{k} \sum_{i} (\sum_{k} \sum_{i} Y_{.j.})^2 / 4 - S_{SS} - C_{SS} - C.F.$$

$$FxC_{SS} = \sum_{k} \sum_{j} (\sum_{k} \sum_{j} Y_{i...})^2 / 4 - F_{SS} - C_{SS} - C.F.$$

$$SxFxC_{SS} = T_{SS} - S_{SS} - F_{SS} - C_{SS} - SxF_{SS} - SxC_{SS} - FxC_{SS}$$

$$C.F. = (\sum_{k} \sum_{j} \sum_{i} Y_{ijk})^2 / N$$

$$= (2815.632)^2/48$$

$$= 7927783.559/48$$

$$= 165162.157$$

$$\sum_k \sum_j \sum_i (Y_{ijk})^2 \quad = 817671.3809$$

$$T_{SS} = 817671.3809 - 165162.157 = 652509.224$$

$$S_{SS} = \left[(2181.702)^2 + (422.65)^2 + (138.754)^2 + (78.526)^2\right]/_{12} - \text{C.F.}$$

$$= \left[4759823.6168 \pm 178633.0225 + 19252.6725 \pm 6166.3327\right]/_{12} - \text{C.F.}$$

$$= 413656.303 - 165162.157$$

$$= 248494.146$$

$$F_{SS} = \left[(1436.352)^2 + (847.454)^2 + (338.8)^2 + (193.026)^2\right]/_{12} - \text{C.F.}$$

$$= (2063107.068 \pm 718178.282 + 114785.44 + 37259.037)/_{12} - \text{C.F.}$$

$$= 244444.152 - 165162.157$$

$$= 79281.995$$

$$C_{SS} = \left[(1354.79)^2 + (967.27)^2 + (493.572)^2\right]/_{16} - \text{C.F.}$$

$$= (1835455.944 + 936611.253 + 243613.319)/_{16} - \text{C.F.}$$

$$= 188417.532 - 165162.157$$

$$= 23255.375$$

$$SxF_{SS} = \left[(1174)^2 + (681.2)^2 + (216.6)^2 \_ (109.902)^2 + (185.2)^2 + (78.67)^2\right.$$

$$+ (53.36)^2 + (46.824)^2 + (36.86)^2 + (29.36)^2 + (19.71)^2 + (23.974)^2$$

$$\left. + (14.17)^2 + (10.054)^2 \right]/_3 - \text{C.F.} - S_{SS} - F_{SS}$$

$$= \frac{1962350.177}{3} - \text{C.F.} - S_{SS} - F_{SS}$$

$$= 654116.725 - 165162.157 - 248494.146 - 79281.995$$

$$= 161178.427$$

$$SxC_{SS} = \left[(1184.2)^2 + (600)^2 + (397.502)^2 + (95.3)^2 \pm (260.2)^2 + (67.15)^2 + (51.91)^2\right.$$

$$\left. + (62.42)^2 + (18.424)^2 + 23.38)^2 + (44.65)^2 + (10.496)^2 \right]/_4$$

$$- \text{C.F.} - S_{SS} - C_{SS}$$

$$= \frac{2014264.495}{4} - C.F. - S_{SS} - C_{SS}$$

$$= 503566.123 - 165162.157 - 24894.146 - 23255.375$$

$$= 66654.445$$

$$FxC_{SS} = \Big[(715.16)^2 + (464)^2 + (256.192)^2 + (446.74)^2 + (260.4)^2 + (140.314)^2$$

$$+ (113.93)^2 + (164.4)^2 + (60.47)^2 + (78.96)^2 + (77.47)^2 + (36.596)^2\Big]/_4$$

$$- C.F. - F_{SS} - C_{SS}$$

$$= \frac{1137625.5482}{4} - CF - F_{SS} - C_{SS}$$

$$= 284406.387 - 165162.157 - 79281.995 - 23255 . 375$$

$$= 16706.860$$

$$SxFxC_{SS} = 652509.224 - 248494.146 - 79281.995 - 23255.375 - 161178.427$$

$$- 66654.445 - 16706.860$$

$$= 56937.976$$

Degree of Freedom:

Total d.f. = 48 - 1 = 47

Speed d.f. = 4 - 1 = 3

Feed d.f. = 4 - 1 = 3

C.comp d.f. = 3 - 1 = 2

SxF d.f. = (4-1)(4-1) = 9

SxC d.f. = (4-1)(3-1) = 6

FxC d.f. = (4-1)(3-1) = 6

Hence, SxFxC d.f. = 47 - (3+3+2+9+6+6) = 18

$$\text{Mean sum of squares} = \frac{\text{Sum of Squares}}{\text{D.f.}}$$

The values of M.S.S. are tabulated in Table .

The test is done under a level of significance

$\alpha = 0.05$ and 0.01

Refering to statistics tables [26]

$F_{.05,\ 6,\ 18} = 2.66$

$F_{.05,\ 2,\ 18} = 3.55$

$F_{.05,\ 9,\ 18} = 2.46$

$F_{.05,\ 3,\ 18} = 3.16$

$F_{.01,\ 6,\ 18} = 4.01$

$F_{.01,\ 2,\ 18} = 6.01$

$F_{.01,\ 9,\ 18} = 3.60$

$F_{.05,\ 3,\ 18} = 4.25$

These values are compared with the F ratio of Table 10, and the significance test was done.