STUDY OF EFFECT OF SPEED, FEED, AND TOOL RAKE ANGLE IN MACHINING PLASTICS

by

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TABLE OF CONTENTS

INTRODUCTION

Working with any material, a product engineer is faced with many problems concerning the machining conditions, such as:

1. What speed should be used?
2. What feed and depth of cut should be used?
3. What tool and tool-geometry should be used?

and many others.

Along with these questions there are certain economic aspects of a machining operation which have to be considered. They are:

1. Productivity
2. Quality
3. Tool life.

To answer these questions and to solve the many other problems to determine an effective machining condition, experiments should be carried out before actually working with the material. This project was designed to determine optimum conditions for machining certain industrial plastics. Since the cutting conditions are mainly based on the shop worker's past experience, these are not necessarily economical and reasonable. To determine optimum cutting conditions, tool-bit forces and tool-wear studies were made and will be discussed in this project.

Why Plastic Machining is Necessary

Plastic machining is often required due to its wide usage. Modern plastic materials are turning up in literally hundreds of industrial uses today. They are found in all kinds of mechanical, electrical, and chemical applications, from microminiature bearings and insulators to structural parts of rockets and missiles. Some parts are so small that a hatful represents a day's work on an automatic. Some are so large that the blank must be chucked on a large lathe.

More and more, too, they are being used in conjunction with metals. As a result, many metal working shops are having to learn how to work with these new materials--how best to cut, shear, saw, turn, drill, tap, thread, plane, punch, broach, form, draw, and otherwise process them into useful products.

Whenever possible, dies and molds for plastic fabrication should be designed to eliminate or minimize any finishing operation. Sometimes supplementary operations are necessary, such as improving the surface, removing flash, gates, or sprues, or drilling or threading. Machining is occasionally used as a primary fabrication operation when the cost would not warrant the procurement of an expensive die or when only a limited number of units is required. Dies for fabrication operations are expensive, and amortization costs are high.

Also, when extreme tolerances must be specified or when product shapes are very complex or when just one or two parts are required (e.g., in rockets or missiles), machining becomes a logical means of fabrication.

What is Plastic?

Before going any further it is important to know something about plastics. The accepted definition of plastics is "a large and varied group of materials which consist of, or contain as an essential ingredient, a substance of high molecular weight which, while solid in the finished state, at some stage in its manufacture is soft enough to be formed into various shapes, most usually through the application, either singly or together, of heat and pressure." (1)*

For the purposes of simplification, most plastics can be classified under one of several recognized basic family groups. These groups, in turn, can be generally classified under one of two major subdivisions--thermosetting or thermoplastic.

Thermosetting. A material that is permanently insoluble and infusible as a result of some chemical reaction that has taken place, e.g., epoxy, phenolic (1).

Thermoplastic. Capable of repeatedly becoming soft when exposed to heat, and hard when cooled, e.g., polystyrene or wax (1).

Laminated and Reinforced Plastics. The terms "laminated plastics" or "plastics laminates" are used loosely to cover a broad range of resin-impregnated filler materials which have been bonded together by heat and pressure to form a solid mass. Resins used are the thermosetting type and include phenolics, melamines, etc.

Laminated plastics are generally divided into groups according to the pressure used in their manufacture. "High-

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*Numbers in parenthesis indicate references at the end of report.

pressure laminates" are those formed at pressures of 1,100 to 1,200 p.s.i. and temperatures of 300 to 350 deg. F. "Low-pressure laminates" are generally glass-fiber base, polyester-impregnated laminates formed at pressures under 400 p.s.i. and temperatures of about 300 deg. F. The term "reinforced plastic" should logically apply to any laminated or molded product made from a fibrous filler impregnated with a thermosetting resin binder; actually it seems to be limited to low-pressure glass-fiber base laminates.

Applications of laminated plastics are very wide. They include: Aircraft industry, automotive, compressor, diesel locomotive, farm equipment, furniture, machinery, marine industry, radio and television, and many others.

REVIEW OF LITERATURE

Little work has been done in laboratories to study the cutting mechanisms and measurement of tool-bit forces. This is due to two main reasons:

1. Only recently was it felt necessary to fabricate plastic materials on machines like lathes, mills, etc.

2. There are so many types of plastics used in industries, and they differ in many ways.

The articles published on machining plastics are based on past experience. Kobayashi (2) has done some work in studying the cutting phenomena, magnitude of forces, and the strains of the work material during cutting.

It was possible to obtain the film taken by Dr. Kobayashi to study the types of chip formation. Some interesting results are included under "The Cutting Action in Plastics Machining" (Sec. 6). He studied three kinds of plastics: 1. Polytetrafluoroethylene (PTFE), 2. Polystyrene (PSL), and 3. Polymethylmethacrylate (PMMA). While cutting he found that five types of chips appeared. Chips varied from continuous to discontinuous type at higher speeds due to the decrease of the rake angles. The rake angle of the tool was the only factor influencing the work deformation and cutting forces.

Fleming (3) discusses the importance of the study of plastics machining.....

> As a rule, machining of industrial plastics is no more difficult than machining metal, but it _is_ different. For one thing, machinability varies tremendously among plastics. There are four major problem areas to be considered in the machining of plastics: clamping and holding, feeds and speeds, coolants and cooling rates, and finishing operation. .....chip removal is a problem when machining nylons, and chip-breakers are seldom effective.

He recommended high speeds, low feeds and the use of coolants.

Wason (4) discusses the characteristics of plastics in order to understand the machining of plastics.

> .....Although thermosetting plastics can be machined, with less attention to heat build-up than thermoplastics, all plastics are poor heat conductors and introduce heat problems. Poor tool design leads to friction, and friction leads to heat. Since the workpiece cannot conduct the heat away, heat must localize in the tool. This leads to short tool life and eventual gumming or burning of the plastics. The use of abrasive fillers in various plastic formulation compounds the problems of heat build-up and tool-wear. .....Today plastics are being applied in accordance with their capabilities and, based on extensive experience, the machining of plastics does not appear so formidable. They can be machined readily if their basic properties and characteristics are taken into account.

He supplies the machining tips for some plastics, like: Acrylic resins, polystyrenes, nylons, rigid vinyl plastics, polyethylene, phenolic moldings, laminated plastics, etc.

Martin (5) discusses the machining of laminates. He suggests certain effective machining techniques.....

> Care must be taken to see that tools are properly ground and chips are removed from cutting points. ..... being more resilient than metals, laminates require greater clearance and less rake on cutting tools. ..... it is extremely important to keep tools sharp. .....because of the heat generated in laminates, both tool and work must be flooded in a stream of coolant.....

Hans Reinsch (6) stresses the importance of the plastics working.....

> It makes a great difference whether the material in question is a thermoplastic or thermosetting resin. .....the evaluation of the workability is as important as that of the properties for the selection of a plastic material for a certain purpose.

Kipnes (7) gives some interesting facts in the machining of TFE (Tetra Fluoroethylene) resins.....

> The fact that it is difficult to mold the material to close tolerances at high temperatures, TFE parts must be machined. .....Soft, waxy, and springy TFE resins, according to machinists, have the cutting "feel" of brass, and surprisingly, the abrasiveness of stainless steel. .....in cutting TFE resin, cutting oils are required for rapid removal of frictional heat from the cutting zone.

Silk (8) gives some machining tips for laminated plastics. Sharp tools or the use of carbide-tipped tools is emphasized. Operations parallel to laminates should be avoided. He discusses different types of machining processes for fabricating laminated plastics. For turning on a lathe, he suggests a speed of 400 surface feet per minute with H.S.S. tool and rake angles up to 10 deg. negative.

INSTRUMENTATION

A Reed & Prentice 14-inch lathe shown in Fig. 1 was used for machining. It provided many different speeds. The highest speed available was 576 r.p.m. Various feeds were available. For the measurement of tool-bit forces, a lathe tool dynamometer mounted on the tool-post, and a Sanborn Strain Gage Amplifier Model 64-500B were used. The dynamometer was designed for three forces acting on the tool-tip. But the Strain Gage Amplifier had the facility to record only two forces at a time, so the orthogonal cutting condition was adopted.

Force Dynamometry

A three-dimensional lathe dynamometer was used to measure the forces acting on the lathe tool. The dynamometer consisted of a unit machined carefully from a single steel block in order to provide the maximum possible stiffness for the required sensitivity and to achieve also a high degree of linearity and freedom from hysterisis effects. All the deflections that take place under load are purely elastic and free of friction, and it is their measurement with suitably placed resistance strain gages that provided the means for converting forces into a conveniently measured electrical quantity. A photograph of the complete unit is shown in Fig. 2. Figure 3 shows the locations of the strain gages on the unit, and Fig. 4 shows the diagrammatic sketch of the dynamometer and a representative Wheatstone bridge for a force.

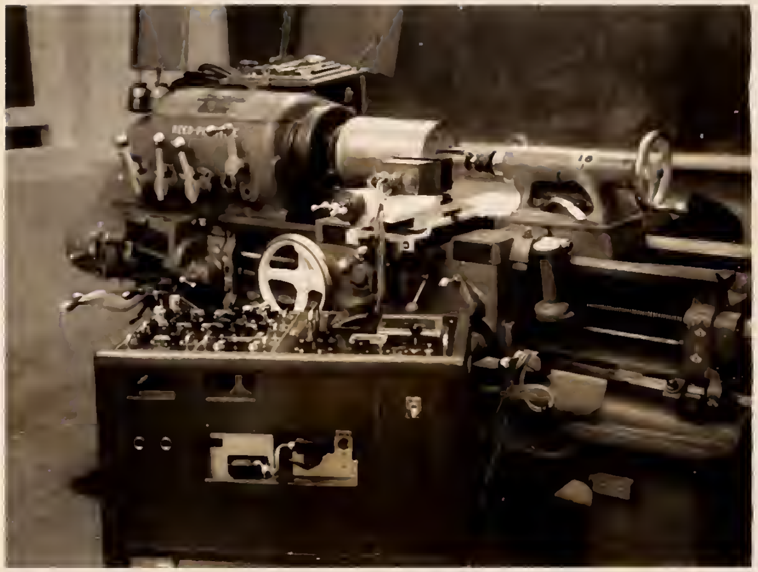


Fig. 1. General experimental setup.

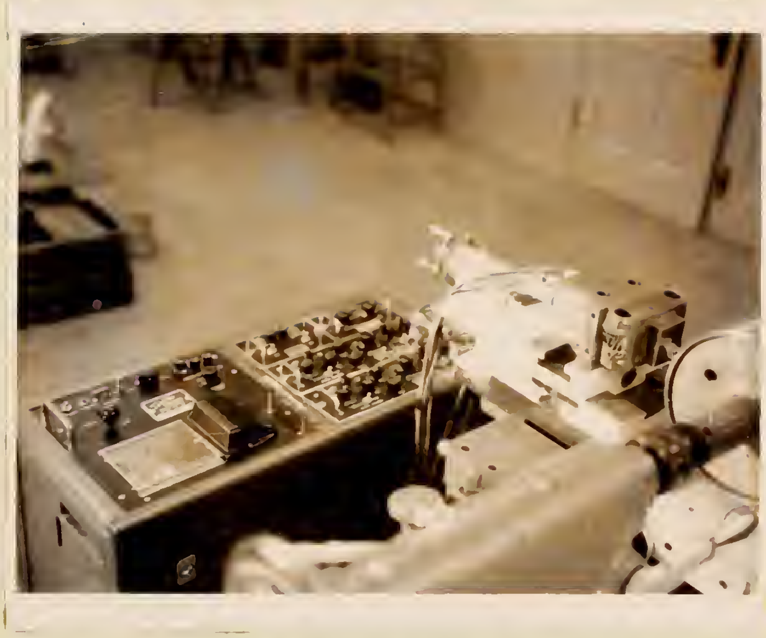


Fig. 2. Lathe dynamometer and recorder.

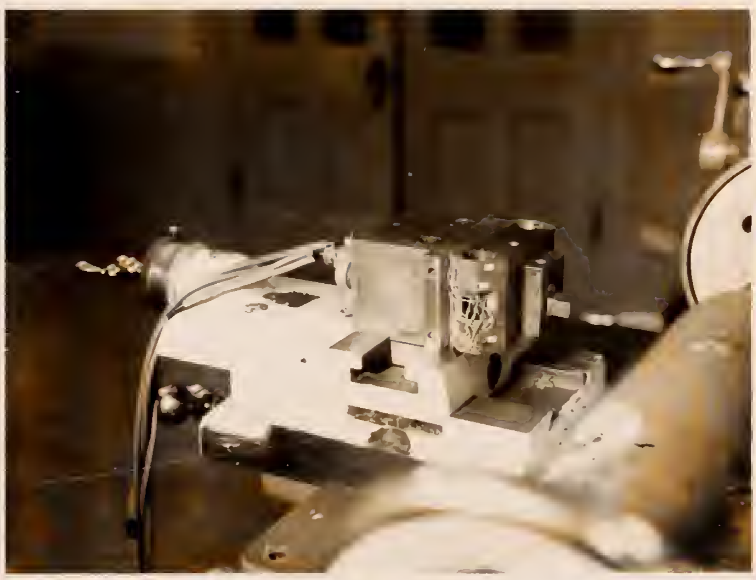


Fig. 3. Lathe dynamometer showing strain gages.

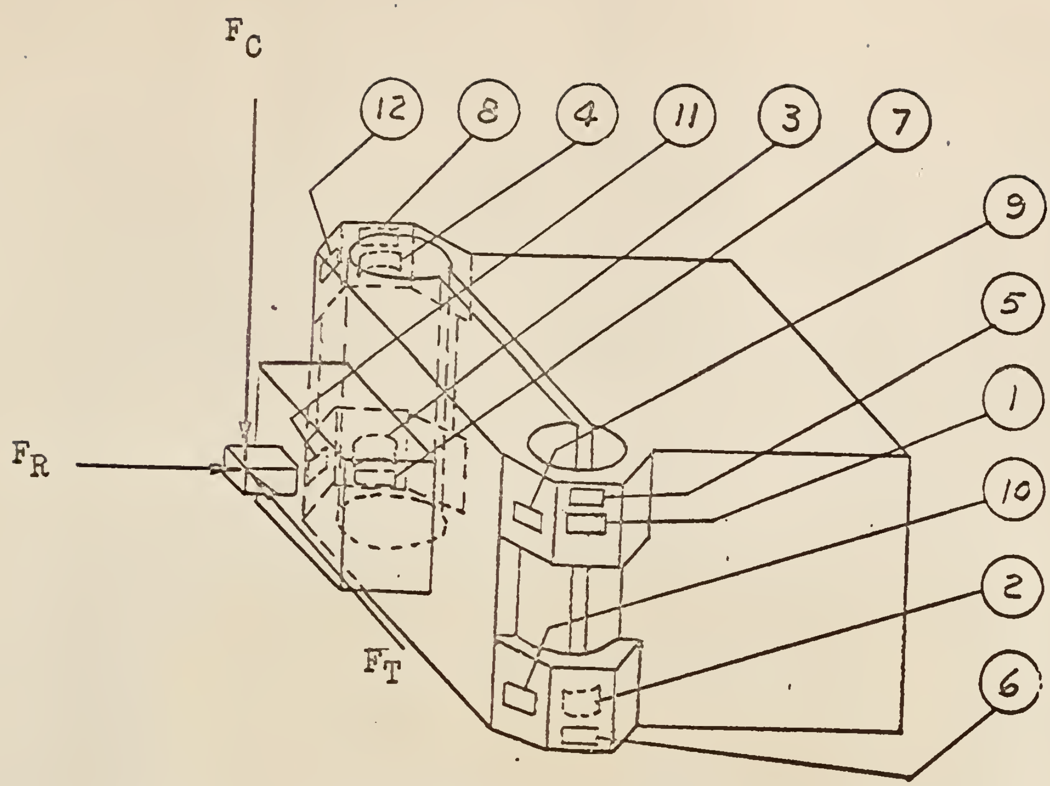


Fig. 4a. Diagrammatic sketch of Lathe Dynamometer.

Gages 1 to 4 are used to measure radial force F_R
Gages 5 to 8 are used to measure cutting force F_C
Gages 9 to 12 are used to measure thrust force F_T

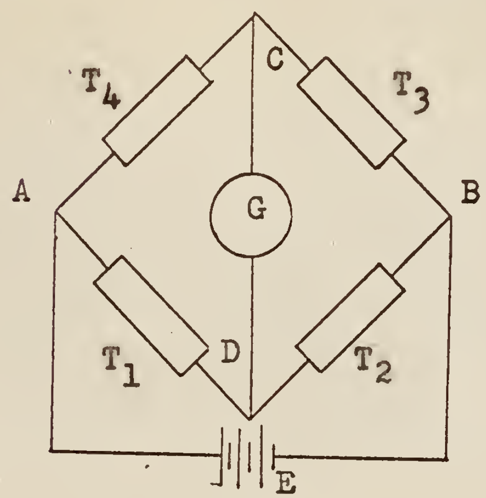


Fig. 4b. A representative Wheatstone Bridge.

Strain Gage and Wheatstone Bridge

The fact that the electrical resistance of a wire is changed when it is stretched has led to the development of extremely useful wire resistance strain gages. A strain gage is made of a fine wire in the form of a flat coil which is cemented to the member, dynamometer block in this case. In the present case, the strain gages forming a Wheatstone bridge are located on the dynamometer block as shown in Fig. 4a.

The change in resistance of a strain gage is usually less than .5 per cent. Measurements of this order of magnitude may be made by means of the Wheatstone bridge. To understand the function of the Wheatstone bridge, shown in Fig. 4b, if T_1 is stretched so that its resistance increases by one unit ($+\Delta R$), the voltage at point D will be increased from zero to plus one unit of voltage ($+\Delta V$), and there will be a voltage difference of one unit between C and D, which will give rise to a current through G. Now if T_2 changes by $-\Delta R$ at the same time, the voltage at D will move to $2\Delta V$. Also, if at the same time T_3 changes by $-\Delta R$, and T_4 changes by $+\Delta R$, then the voltage of point C will move to $-2\Delta V$, and the voltage difference between C and D will now be $4\Delta V$. It is then apparent that although a single gage can be used, the sensitivity will be increased fourfold if two gages are used in tension while two others are used in compression. The same principle is used here to form the bridge.

Under the particular force on the tool, a bending moment will be caused. Due to this moment, there will be strain in the member. This strain will be distributed at a section maximum +ve at one end to maximum -ve at the other end.

This potential difference will be amplified by the Sanborn Amplifier and recorded on the running graph paper.

Balancing of Amplifier

In order to compensate for the residual unbalance of the bridge circuit and its cabling, the unit was balanced in the following manner:

1. Connect the amplifier and warm up for 30 min. Set the panel controls:

R/T.....T   ATTENUATOR.....OFF   GAIN.....FULL RIGHT

2. Set the FINE/COARSE switch to FINE. Center the stylus with the ZERO control, then set the FINE/COARSE switch to COARSE.

3. Remove all strain from the bridge. Turn the ATTENUATOR to the right for a stylus deflection. Bring the stylus to its null position with the RES BAL and CAP BAL controls. Continue advancing the ATTENUATOR and bringing the stylus back to its null position until the ATTENUATOR is at X1.

4. Set the FINE/COARSE switch to FINE. Now make a final adjustment of the RES BAL control, so the stylus does not move when turning the ATTENUATOR between X1 and OFF. Then return the ATTENUATOR to OFF.

5. The full bridge is now balanced, and the system is ready for calibration.

Calibration

After balancing the unit, the calibration was done. The method employed to calibrate the unit was to provide a known, varying force at the tool-tip and to measure the deflection of the stylus at desired force intervals, so that graphs may be drawn with the stylus deflection on the horizontal axis and the force responsible for that deflection on vertical axis. These graphs are called calibration curves and can be used any time during the experiment.

The following steps were observed for the calibration:

1. The dynamometer was firmly affixed to the base plate of Universal (hydraulic) testing machine. A tool of 5/8 in. sq. was inserted into the dynamometer and was securely clamped by means of screws.

2. One inch of overhang of the tool was kept, and a small hole of 1/16" diameter was made on the tool tip at a distance of ¼" from the tool end. This hole would, very closely, give the cutting condition point. This overhang was constant throughout the project.

3. In order to apply a concentrated force, a ball bearing of 1/8" diameter was placed in the hole. On this ball a cylindrical steel rod of ½" diameter and three inches long was placed over the ball and was kept in the vertical position as to touch the machine ram. The idea was to transmit the force from the ram through this cylindrical rod to the ball, so a vertical force would be acting on the tool.

The ram touched the rod in such a way that it would give a zero reading on the graph paper.

4. The ATTENUATOR was set on X1 and GAIN was set to give 32 lines of calibration under no load condition. This was measured by the CAL button.

5. The motor was started to run the graph paper and the known load applied at fixed intervals of five pounds. At the end of the interval, it was marked on the paper with the help of MARKER.

6. The load was applied up to 150 pounds and then was decreased by the same interval as before and was marked on the graph paper. Averaging these two readings gave a deflection of the stylus for a particular force. From this average a calibration graph was drawn as shown on page 17.

7. The dynamometer was tilted to 90 deg. so as to calibrate for horizontal force. The Steps 4, 5, and 6 were followed to get a calibration graph for horizontal force (F_T) and shown on page 19. The GAIN was set to give 20 lines of calibration under no load condition. This force was calibrated up to 100 pounds. These upper limits for forces (150 pounds for F_C and 100 pounds for F_T) were found from a preliminary survey.

The whole system was then ready for the experiment.

EXPLANATION OF PLATE I

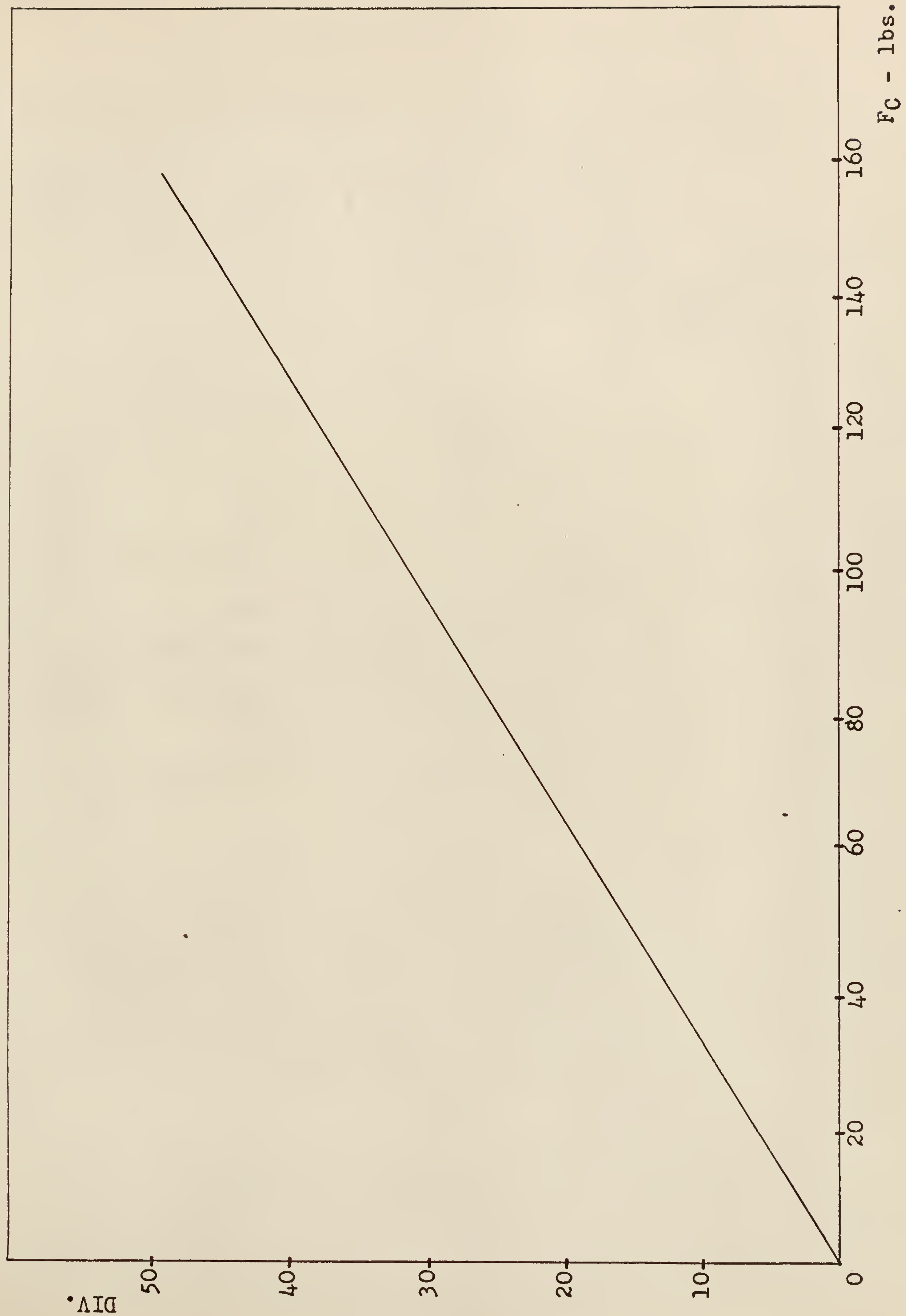
Calibration curve for cutting force, F_C

ATTENUATOR - XI, CAL - 32 lines

Scale: X-axis 1 in. = 20 lbs. - F_C

Y-axis 1 in. = 10 divisions on graph

PLATE I



EXPLANATION OF PLATE II

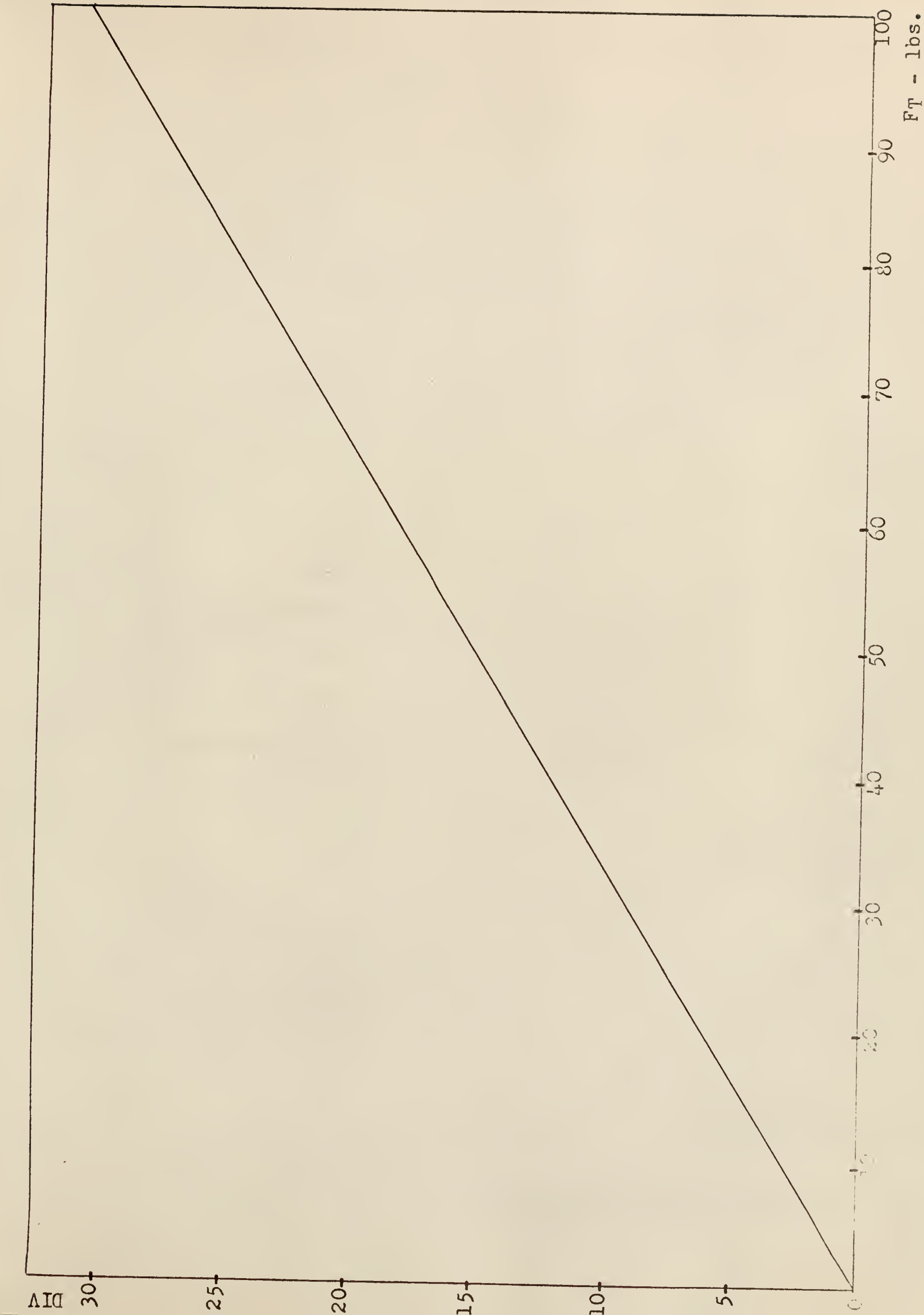
Calibration curve for feeding force, F_T

ATTENUATOR - XI, CAL - 20 lines

Scale: X-axis 1 in. = 10 lbs. - F_T

Y-axis 1 in. = 5 divisions on graph

PLATE II



MATERIALS--WORK AND TOOL

Work Materials

The following work materials were used for the project:

1. PVC with GEON RIGID VINYL
2. CYCOLAC LL, ABS PLASTIC
3. FORMICA GRADE CN (Fabric Base)
4. DILECTO XX-79 (Paper Base)

All these plastics were in the form of tubes of various diameters. A brief description for each plastic is given below:

1. PVC with Geon Vinyl. PVC or Poly Vinyl Chloride is one of the more important synthetic plastics. The pure resin is a clear thermoplastic that is hard and rigid. PVC with Geon Vinyl is unplasticized polyvinyl chloride formulations and definitely superior, both chemically and physically, to modified compositions. The unplasticized materials have been widely used in Germany for construction of chemical process equipment in which they replace corrosion-resistant alloys, such as stainless steel.

Unplasticized polyvinyl chloride is available commercially as extruded sheets, tubes, or rods. These are easily fabricated into pieces of equipment by shop methods used for light metals.

Due to chemical resistance, high strength, weather resistance, light weight, smooth surface, and easy fabrication properties, PVC with rigid vinyl is used in irrigation, water handling, petroleum, gas, air conditioning, swimming pool, drainage, marine, etc., pipe works.

2. Cycolac, LL. Cycolac, LL is an ABS type material. ABS is the industry designation for Acrylonitride-butadiene-styrene

polymers. In general, all standard ABS materials are light, strong, tough, and highly resistant to attack by corrosive gases or liquids.

Due to these properties, Cycolac, LL has been widely used in the form of pipe. Main applications include water pipe, gas pipe, electrical conduit, uses in cars, etc.

3. Formica Grade CN (Fabric Base). Formica is an industrial decorative laminate. It is a fabric base phenolic resin high pressure laminate. Where toughness and high impact strength are required, these laminates are used. It has very good machining characteristics. Main applications include cams, switchboard panels, pullies, fine pitch gears, pinions, etc.

4. Dilecto XX-79. Dilecto XX-79 is a laminate made by combining a thermosetting resin with a paper reinforcement at high temperature and pressure to produce a structural material. These laminates are light, strong, wear resistant, and an electrical insulator.

They are widely used for electrical insulators such as in bushings, switch, relays, and coil forms. They are used in motors, generators, switch gear, transformers, and television also. Mechanical applications include silent gears, bearing surfaces, pump rotor vanes, cams, etc.

Tool Material

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

C - .80%   Mn - .30%   Si - .30%   Ci - 4.0%

V - 2.0%   W - 14.0%   Mo - .75%   Co - 5.25%

Rex-95 is 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 relief angle shown in Fig. 12 (p. 34) was 10° for all cases and rake angles were varied. There were five types of rake angles used: 10°, 5°, 0°, -5°, and -10°.

EXPERIMENTAL PROCEDURE

The experimental setup for this project is shown in Fig. 1.

The tools were ground to the required angles with closest accuracy. There were five tools with five different rake angles. A relief angle of ten degrees was kept the same for all tools. The rake angles were 10, 5, 0, -5, and -10 degrees.

The PVC pipe was cut into 2-foot lengths, and an aluminum slug 2½ inches long was fitted into one end to hold it in a three-jaw chuck. The steady rest was kept at a distance approximately 8 inches from the tool to eliminate vibrations. Forces were recorded for four of the highest speeds at four different feeds. For every new cut care was taken to see that the recording stylus was on the base line. Actual magnitudes of the forces were obtained from the calibration curves on pages 17-19. The forces were recorded and shown on pages 36-46.

For Formica laminate a fixture was made to hold the work between centers. On a steel shaft 2 inches in diameter by 18 inches long, two plates 9½ inches in diameter and 1½ inches thick were fitted. One plate was a tight fit at one end and was a little larger in diameter than the internal diameter of the formica pipe. The other plate was a loose fit on the shaft as well as on the formica pipe. This was kept loose so that it could be pushed whenever needed, to give some room for machining, but still giving good support to the pipe. Readings were taken for all five tools and four speeds but at a constant feed of .012 i.p.r. (Inches per Revolution).

For Dilecto XX-79 a similar fixture was made. The data collection was the same as for PVC pipe. Particular care was taken to see that there was no chatter.

A brief tool-wear study was carried out on Cycolac-LL material. At first a microscopic study of the tool was tried, but it was not very effective. Due to time limitation, another method was adopted. In this method the material was machined continuously, and at the same time, the forces on the tool bit were recorded. Due to the chip problem, it was not very convenient to machine the piece all at once. Still, as far as possible, a 2-foot length was machined at the same speed and feed with a same tool (+5 deg.). Every 30 seconds with the help of a marker on the recorder, the time was marked. The total machining time was 40 minutes. Tool forces at the end of every 30 seconds were recorded and tabulated as shown on page 97. Conclusions drawn as a result of this test will be found in the discussion section of this paper titled: Tool-Wear Study.

CUTTING ACTION IN PLASTICS MACHINING

There are two types of studies in machining any material--one is to answer the questions mentioned in the Introduction, and the other kind is to answer the fundamental questions such as "What?" and "Why?".

The first type is concerned with obtaining information on how to carry out routine machining operations economically--the proper feeds, speeds, rate of material removal and tool angles to use, the power required for machining, the surface finish obtainable, etc. The information obtained from such research is very necessary for choosing proper machines, tools, and cutting conditions for routine machining operations. As mentioned earlier, this project deals with this kind of a research work.

The second type of research is concerned with obtaining information on what happens when material is cut and why it happens--the action of the cutting tools in machining, the behavior of the material in that process, the action of cutting fluids, etc. Such study is necessary for basic information and concerns itself with the mathematics, geometry, mechanics and physics of cutting in general, irrespective of the type of machining operation. Such research is very necessary for solving the problems that arise in machining when departures from routine practice are made, and in providing basic information for which major advances in the practice of machining can come (9). In this section, this second type of study will be discussed. The actual study was carried out by Kobayashi (2). Photos, shown in the following pages, are taken from a film received from the Dow Chemical Co. The Figs. 5 through 11 are shown for the kind of chip deformation for different tool rakes. The material was Polytetrafluoroetheylene (PTFE).

By examining the chip very closely it is found that the deformation takes place along a narrow band which extends from the cutting edge to the workpiece surface. The chip, after separation from the workpiece by the cutting edge, slides over the rake face of the tool. During this sliding over the surface of the tool, the chip undergoes certain deformation and finally curls away from the tool, thereby breaking contact with the tool.

From these photos there seem to be three main areas of interest. One is the narrow band which extends from the cutting edge to the workpiece surface. This band is called the shear plane. This area plays an important role in determining the direction of the shear plane and the shear stress and strain on this plane. The second area is the contact between chip and tool surface. This will determine the frictional condition on the tool face. The third area is the machined surface on the workpiece. The type of formation of the chip will greatly determine the finish of the surface. The condition in these three areas is greatly determined by the variables, such as feed, speed, angle of tool, and work material.

Photos shown in Figs. 5, 6, and 7 are for rake angles 40 deg., 20 deg., and 0 deg. at the same speed of .037 m/min

Fig. 5. Deformation of work material during cutting (PTFE).

Work material: Teflon No. 5
Cutting speed: .037 m/min
Depth of cut: 1.0 mm
Tool angle: 40 deg. (Kobayashi)

Fig. 6. Deformation of work material during cutting (PTFE).

Work material: Teflon No. 5
Cutting speed: .037 m/min
Depth of cut: 1.0 mm
Tool angle: 20 deg. (Kobayashi)

Fig. 7. Deformation of work material during cutting (PTFE).

Work material: Teflon No. 5
Cutting speed: .037 m/min
Depth of cut: 1.0 mm
Tool angle: 0 deg. (Kobayashi)

and depth of cut 1.0 mm. There is a considerable change in the formation of the chip from a 40 deg. to a 0 deg. rake angle. A very smooth and long chip is observed at a higher positive angle. Chips at 0 deg. rake angle seem to be under more strain thus requiring more power to remove them from the workpiece.

Photos shown in Figs. 8, 9, 10, and 11 are different types of chips found at various conditions. They are:

1. Crack type
2. Shear with crack type
3. Shear zone type
4. Tear type

Observing these photos, the effect of rake angles on machined surface is easily understood.

Kobayashi concluded from these photos, "Types of chips are influenced by the rake angles. The deformation of work material was greatly influenced by the rake angle."

DISCUSSION OF RESULTS

The schematic diagram of the orthogonal cutting forces adopted is shown in Fig. 12. In this figure the known quantities were F_C, F_T, and rake angle d. The calculated quantities were R, β , and coefficient of friction, μ , (only for PVC pipe). They are calculated from the following equations:

$$R = \sqrt{F_C^2 + F_T^2} \quad \text{- - - - - - - - - - - - - (1)}$$

$$\beta = \tan^{-1} \left(\frac{F_T}{F_C}\right) \quad \text{- - - - - - - - - - - - - (2)}$$

$$\mu = \tan (\beta + \alpha) \quad \text{- - - - - - - - - - - - - (3)}$$

Fig. 8. Crack type chip formation. (Kobayashi)

Fig. 9. Shear with crack type chip formation.

(Kobayashi)

Fig. 10. Shear zone type chip formation. (Kobayshi)

Fig. 11. Tear type chip formation. (Kobayashi)

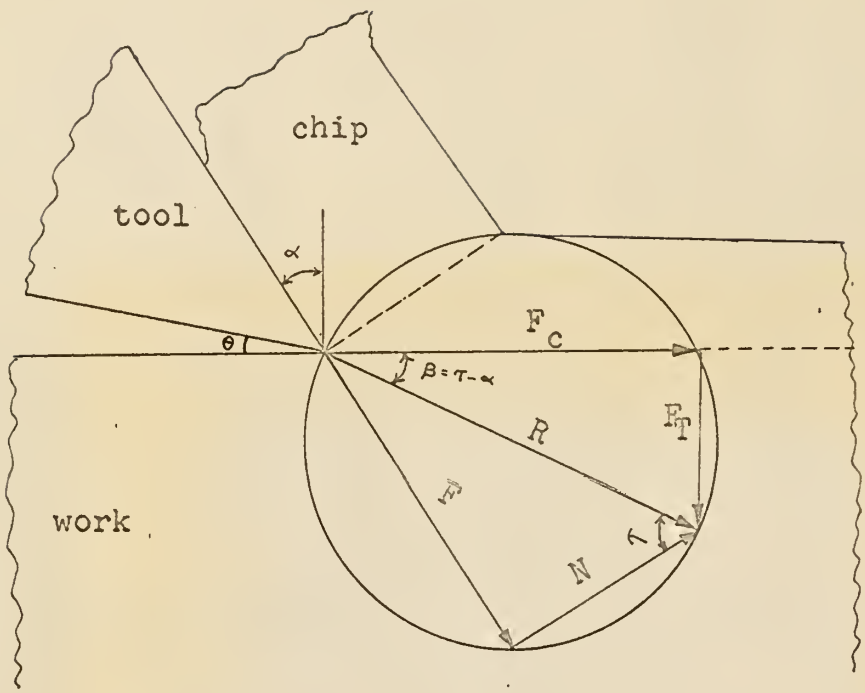


Fig. 12. Schematic Diagram of Orthogonal Cutting.

R - Resultant cutting force, lb.

F_c - Cutting force, lb.

F_T - Feeding force, lb.

F - Frictional force on tool surface, lb.

N - Normal force on tool surface, lb.

α - Tool rake angle, deg.

β - Direction of resultant force, deg.

τ - The frictional angle, deg.

θ - Relief angle, deg.

In the above analysis certain assumptions are made. One is that a continuous chip is formed when cutting. In the case of PVC pipe the chip formation was a continuous one, while in the case of Formica grade CN and Dilecto XX-79 the chip was discontinuous. So the frictional condition on tool face could not be calculated from Equation 3.

The information from the collected data is arranged in the following way:

(1) Tables I through V show the recorded forces, F_C and F_T, and calculated quantities, R, μ and β for various speeds, feeds and rake angles for PVC pipe.

(2) Table VI shows the measured forces F_C and F_T and calculated R and β for various speeds and tool angles. This table is constructed for Formica grade CN material. The feed was kept constant, .012 i.p.r.

(3) Tables VII through XI show the measured forces, F_C and F_T, and calculated R and β for various feeds, speeds and tool angles. These tables are constructed for Dilecto XX-79 material.

(4) Table XII shows the tool forces measured at every 30 seconds when machining continuously ABS pipe at 254.0 fpm and .003 i.p.r.

Cutting Force, F_C

It is very important to know the cutting force, F_C, because of the following reasons:

1. It determines the stiffness requirements of the tool and the tool-support structure, and the chatter control character-

Table 1. Summary of machining data.

Speed	Feed	F_C	F_T	R	μ	β
325.0	.003	12	4	12.6	.54	18.4
	.006	22	0	22	.17	0
	.012	48	0	48	.17	0
	.018	70	0	70	.17	0
403.0	.003	12	6	13.4	.74	26.6
	.006	20	4	20.4	.38	11.3
	.012	48	0	48	.17	0
	.018	77	-15	78.5	0	-11.0
509.0	.003	12	12	17.0	1.42	45.0
	.006	20	6	20.8	.50	16.7
	.012	48	- 4	48.2	.09	-4.8
	.018	76	-12	76.9	.01	-9.0
631.0	.003	16	12	20.0	1.06	36.9
	.006	20	8	21.5	.61	21.8
	.012	50	0	50.0	.17	0
	.018	76	- 6	76.3	.09	-4.5

Work material: Pvc with Geon Vinyl
Tool material: Rex-95
Condition: Orthogonal
Tool angle: $+10^{\circ}$ Back rake
Cutting: Dry
Work diameter: $4\frac{1}{2}$ in OD
Wall thickness: 3/8 in.
F_C: Cutting force, lb.
F_T: Thrust force, lb.
R: Resultant force, lb.
μ : Coefficient of friction
β : Direction of resultant force, deg.

Table 2. Summary of machining data.

Speed	Feed	F_C	F_T	R	μ	β
325.0	.003	12	4	12.6	.43	18.4
	.006	26	4	26.3	.24	8.8
	.012	48	0	48.0	.08	0
	.018	74	0	74.0	.08	0
403.0	.003	12	8	14.4	.80	33.7
	.006	26	4	20.3	.24	8.8
	.012	50	2	50.0	.12	2.3
	.018	74	0	74	.08	0
509.0	.003	12	12	17.0	1.19	45.0
	.006	28	10	29.7	.45	20.0
	.012	54	4	54.2	.16	4.2
	.018	80	0	80.0	.08	0
631.0	.003	12	15	19.2	1.50	51.4
	.006	28	15	31.8	.65	28.2
	.012	54	10	54.9	.27	10.5
	.018	68	2	68.0	.11	1.7

Work material: Pvc with Geon Vinyl
Tool: Rex-95
Condition: Orthogonal
Tool Angle: +5°Back rake
Cutting: Dry
Work diameter: 4½ in OD
Wall thickness: 3/8 in.
F_C: Cutting force, lb.
F_T: Thrust force, lb.
R: Resultant force, lb.
μ: Coefficient of friction
β: Direction of resultant force, deg.

Table 3. Summary of machining data.

Speed	Feed	F_C	F_T	R	μ	β
325	.003	10	14	17.2	1.4	54.5
	.006	27	14	30.4	.52	27.4
	.012	54	18	37.0	.33	18.4
	.018	72	14	73.4	.20	11.0
403.0	.003	16	18	24.1	1.13	48.4
	.006	28	18	33.3	.64	32.8
	.012	53	18	56.0	.34	18.8
	.018	76	18	78.1	.27	13.3
509.0	.003	16	21	26.4	1.31	52.7
	.006	28	21	35.0	.75	37.0
	.012	54	18	57.0	.33	18.4
	.018	80	18	82.0	.23	12.7
631.0	.003	16	30	34	1.88	62.0
	.006	31	30	43.14	.97	44.0
	.012	58	30	65.3	.52	27.4
	.018	80	30	85.4	.37	20.6

Work material: Pvc with Geon Vinyl
Tool: Rex-95
Condition: Orthogonal
Tool angle: 0^{o} Back rake
Cutting: Dry
Work diameter: $4\frac{1}{2}$ in OD
Wall thickness: 3/8 in.
F_C: Cutting force, lb.
F_T: Thrust force, lb.
R: Resultant force, lb.
μ: Coefficient of friction
β: Direction of resultant force, deg.

Table 4. Summary of machining data.

Speed	Feed	F_C	F_T	R	μ	β
325	.003	16	14	21.3	.73	41.2
	.006	29	18	34.1	.50	32.0
	.012	54	21	60.0	.29	21.3
	.018	76	28	81.0	.27	20.2
403.0	.003	16	18	24.1	.94	48.4
	.006	32	21	38.3	.53	33.3
	.012	57	30	63.5	.42	28.2
	.018	86	33	92.1	.28	21.0
509.0	.003	16	21	26.4	1.09	52.7
	.006	32	24	40.0	.62	37.0
	.012	57	36	67.4	.51	32.3
	.018	86	40	94.9	.36	25.0
631.0	.003	16	24	28.8	1.24	56.3
	.006	32	28	42.5	.73	41.2
	.012	64	34	72.5	.42	28.0
	.018	90	40	98.5	.34	24.0

Work material: Pvc with Geon Vinyl
Tool: Rex-95
Condition: Orthogonal
Tool Angle: -5° Back rake
Cutting: Dry
Work Diameter: 4½ in OD
Wall thickness: 3/8 in.
F_C: Cutting force, lb.
F_T: Thrust force, lb.
R: Resultant force, lb.
μ : Coefficient of friction
β : Direction of resultant force, deg.

Table 5. Summary of machining data.

Speed	Feed	F_C	F_T	R	μ	β
325	.003	16	21	26.4	.92	52.7
	.006	28	26	38.2	.64	43.0
	.012	61	40	73.0	.42	33.3
	.018	90	51	103.4	.35	30.0
403.0	.003	16	21	26.4	.92	52.7
	.006	32	30	43.9	.65	43.2
	.012	61	42	74.0	.45	34.0
	.018	93	55	108.1	.37	31.0
509.0	.003	20	27	33.6	.94	53.5
	.006	35	35	49.5	.70	45.0
	.012	65	49	81.4	.50	37.0
	.018	96	61	113.7	.41	32.4
631.0	.003	20	27	33.6	.94	53.5
	.006	35	36	50.2	.72	45.8
	.012	65	52	83.2	.54	39.0
	.018	100	64	118.7	.41	32.7

Work material: Pvc with Geon Vinyl
Tool: Rex-95
Condition: Orthogonal
Tool angle: -10° Back rake
Cutting: Dry
Work diameter: $4\frac{1}{2}$ in OD
Wall thickness: 3/8 in.
F_C: Cutting force, lb.
F_T: Thrust force, lb.
R: Resultant force, lb.
μ : Coefficient of friction
β : Direction of resultant force, deg.

Table 6. Summary of machining data.

Speed	Angle	F_C	F_T	R	β
740.0	10	31	0	31	0
	5	38	4	38.2	6.0
	0	44	20	51.5	24.5
	- 5	47	21	48.3	24.0
	-10	61	45.5	76.1	36.7
914	10	35	0	35	0
	5	38	4	38.2	6.0
	0	46	21	50.6	24.5
	- 5	47	20	51.1	23.0
	-10	61	45.5	76.1	36.7
1125	10	35	0	35	0
	5	38	4	38.2	6.0
	0	44	21	48.8	25.5
	- 5	50	20	53.9	22.0
	-10	63	45.5	77.7	36.0
1415	10	35	0	35	0
	5	37	4	37.3	6.2
	0	46	23	51.4	26.6
	- 5	50	20	53.9	22.8
	-10	63	27	68.5	23.2

Work material: Formica Grade CN (Fabric base)
Tool: Rex-95 H.S.S.
Condition: Orthogonal
Feed: .012 i.p.r.
Cutting: Dry
Work diameter: 10¼ in OD
Wall thickness: 3/8 in.
F_C: Cutting force, lb.
F_T: Thrust force, lb.
R: Resultant force, lb.
β: Direction of resultant force, deg.

Table 7. Summary of machining data.

Speed	Feed	F_C	F_T	R	β
450	.003	19	62	64.9	73.0
	.006	33	81	87.5	68.0
	.009	44	91	101.1	64.2
	.012	50	91	103.9	61.2
560	.003	19	81	83.2	76.8
	.006	31.5	86	91.6	70.0
	.009	42.5	95.5	104.5	66.0
	.012	47	97.5	108.2	64.3
705	.003	19	68.5	71.1	74.5
	.006	31.5	79.5	85.5	68.4
	.009	41	94.0	102.6	66.5
	.012	47	92.5	103.8	63.1
875	.003	19	81	83.2	76.8
	.006	31.5	84.5	90.2	70.0
	.009	41	95.5	103.9	67.0
	.012	47	95.5	106.5	64.0

Work material: Dilecto XX-79
Tool material: Rex-95 H.S.S.
Condition: Orthogonal
Work diameter: 6¼ in O.D.
Wall thickness: 3/8 in.
Tool angle: +10° Back rake
Cutting: Dry
F_C: Cutting force, lb.
F_T: Thrust force, lb.
R: Resultant force, lb.
β: Direction of resultant force, deg.

Table 8. Summary of machining data.

Speed:	Feed	F_C	F_T	R	β
450	.003	19	37.5	42.5	63.2
	.006	35	39.0	52.4	48.1
	.009	47	42.5	63.4	42.1
	.012	54	39.0	66.6	36.0
560	.003	19	40.5	44.7	65.0
	.006	35	42.5	55.1	50.6
	.009	50	49	70.0	44.4
	.012	60	49	77.5	39.3
705	.003	19	42.5	46.5	66.0
	.006	33	45.5	56.2	54.1
	.009	50	49	70.0	44.4
	.012	50	62	79.7	51.1
875	.003	19	44	48	66.7
	.006	33	49	60.0	56.0
	.012	50	58.5	77.0	50.0
	.018	60	55.5	81.7	43.0

Work material:	Dilecto XX-79
Tool material:	Rex-95 H.S.S.
Condition:	Orthogonal
Work Diameter:	$6\frac{1}{4}$ in O.D.
Wall thickness:	3/8 in.
Tool angle:	$+5^{o}$ Back rake
Cutting:	Dry
F_C:	Cutting force, lb.
F_T:	Thrust force, lb.
R:	Resultant force, lb.
β :	Direction of resultant force, deg.

Table 9. Summary of machining data.

Speed	Feed	F_C	F_T	R	β
450	.003	22	35	41.3	58.0
	.006	28	39	48.0	54.4
	.009	54	42.5	68.7	38.2
	.012	63	42.5	76.0	34.0
560	.003	22	42.5	47.9	62.7
	.006	28	45.5	53.4	58.4
	.009	54	45.5	70.6	40.1
	.012	63	52	81.7	40.0
705	.003	24	44	50.1	61.4
	.006	29	49	57.0	59.4
	.009	69	57	89.5	39.6
	.012	63	55.5	84.0	41.4
875	.003	22	53.5	57.8	67.7
	.006	28	57	63.5	63.9
	.009	54	61	81.5	48.5
	.012	61	66	90.0	47.3

Work material: Dilecto XX-79
Tool material: Rex-95 H.S.S.
Condition: Orthogonal
Work diameter: 6¼ in O.D.
Wall thickness: 3/8 in.
Tool angle: 0° Back rake
Cutting: Dry
F_C: Cutting force, lb.
F_T: Thrust force, lb.
R: Resultant force, lb.
β : Direction of resultant force, deg.

Table 10. Summary of machining data.

Speed	Feed	F_C	F_T	R	β
450	.003	28	45.5	53.4	58.0
	.006	45.5	49	66.9	47.0
	.009	61	55.5	82.5	42.3
	.012	72	58.5	92.8	39.1
560	.003	31	42.5	52.6	54.0
	.006	44	47.0	64.4	47.0
	.009	56.5	53.5	77.8	43.5
	.012	72	53.5	89.7	36.7
705	.003	26	37.5	45.6	55.3
	.006	44	44.0	62.2	45.0
	.009	60	42.0	73.5	35.3
	.012	71	54.0	89.2	37.3
875	.003	26	29.0	39.3	48.6
	.006	41	36.0	54.5	41.3
	.009	56.5	42.5	70.7	37.0
	.012	69	42.5	81.0	31.6

Work material: Dilecto XX-79
Tool material: Rex-95 H.S.S.
Condition: Orthogonal
Work diameter: $6\frac{1}{4}$ in O.D.
Wall thickness: 3/8 in.
Tool angle: -5° Back rake
Cutting: Dry
F_C: Cutting force, lb.
F_T: Thrust force, lb.
R: Resultant force, lb.
β: Direction of resultant force, deg.

Table 11. Summary of machining data.

Speed	Feed	F_C	F_T	R	β
450	.003	24	32.5	40.4	53.6
	.006	44	37.5	57.8	40.5
	.009	61	52	80.2	40.5
	.012	72	56	91.2	38.0
560	.003	27	34.5	43.4	52.0
	.006	44	39	58.8	41.5
	.009	61	52	80.2	40.5
	.012	72	57	91.8	38.4
705	.003	27	36	45	53.2
	.006	64	42.5	61.2	44.0
	.009	60	56	82.1	43.0
	.012	72	58.5	92.8	39.1
875	.003	27	45.5	53.0	59.3
	.006	44	39	58.8	41.6
	.009	60	60	85.0	45.0
	.012	72	62	95.1	40.8

Work material: Dilecto XX-79
Tool material: Rex-95 H.S.S.
Condition: Orthogonal
Work diameter: $6\frac{1}{4}$ in O.D.
Wall thickness: 3/8 in.
Tool angle: -10° Back rake
Cutting: Dry
F_C: Cutting force, lb.
F_T: Thrust force, lb.
R: Resultant force, lb.
β: Direction of resultant force, deg.

istics of the machine tool. It is primarily responsible for the pressure exerted by the chip on the tool face, and hence, it is against this force that the tool will have to be supported.

2. It is the only force component which contributes, in a practical sense, to the total power consumption in machining.

3. It contributes to the heat generated at the tool-chip interface, to land wear, tool-cratering, and tool-edge chipping.

Feeding Force, F_T

It is of interest to know the feeding force, F_T, for the following reasons:

1. It plays a major role in the friction present between the tool and chip, and tool and work piece.

2. Although it represents a minor part of the energy required to shear the chip from the work material, it is the second major factor in the heat generated at the tool-chip interface after the cutting force, F_C.

3. Sometimes it is convenient to study the change in the feeding force for the tool-wear phenomena in case other methods are not suitable.

Resultant Force Vector, $\bar{R}$

It is important to know the magnitude and direction of the resultant cutting force, R, for the following simple reason: It being the force acting on the workpiece as well as on the tool, it helps in designing a suitable holding device for workpiece and tool.

Coefficient of Friction, μ.

The coefficient of friction is important for two reasons:

1. It determines the amount of heat generated on the tool-face, and thus helps to determine the tool-life.

2. It helps in the selection of a suitable cutting fluid.

The quantities mentioned above are discussed separately for each material under different conditions.

(1) PVC With Geon Vinyl.

a. Cutting Force, F_C:

The graphical representation of cutting force, F_C is shown on pp. 49-57. From the study of these tables and graphs the following important facts are derived:

(i) Effect of Speed:

There did not seem to be any influence of cutting speed on the force. For 10 deg. rake angle and at .018 i.p.r. feed, the increase was only 9% when the speed was increased from 325.0 f.p.m. to 631.0 f.p.m. The highest increase was approximately 19% when speed was increased from 325.0 f.p.m. to 631.0 f.p.m. at neg. 5 deg. rake angle. In one case the force was decreased by 15% when the speed was increased from 509.0 f.p.m. to 631.0 f.p.m. at .018 i.p.r. for 5 deg. rake angle. Except for these slight variations the cutting force, F_C was nearly constant.

(ii) Effect of Feed:

There seemed to be quite an increase in the

Fig. 13. Relations between the cutting force and feed.

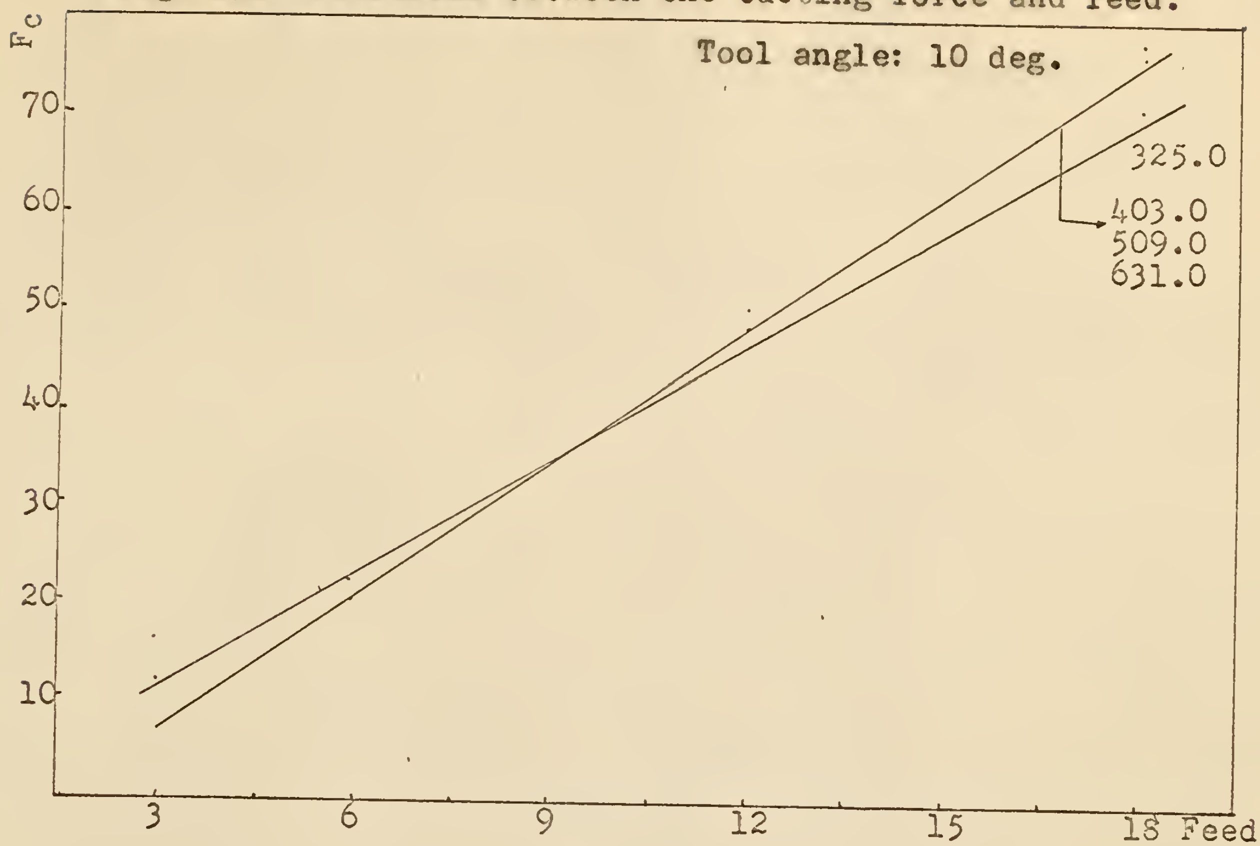


Fig. 14. Relations between the feeding force and feed.

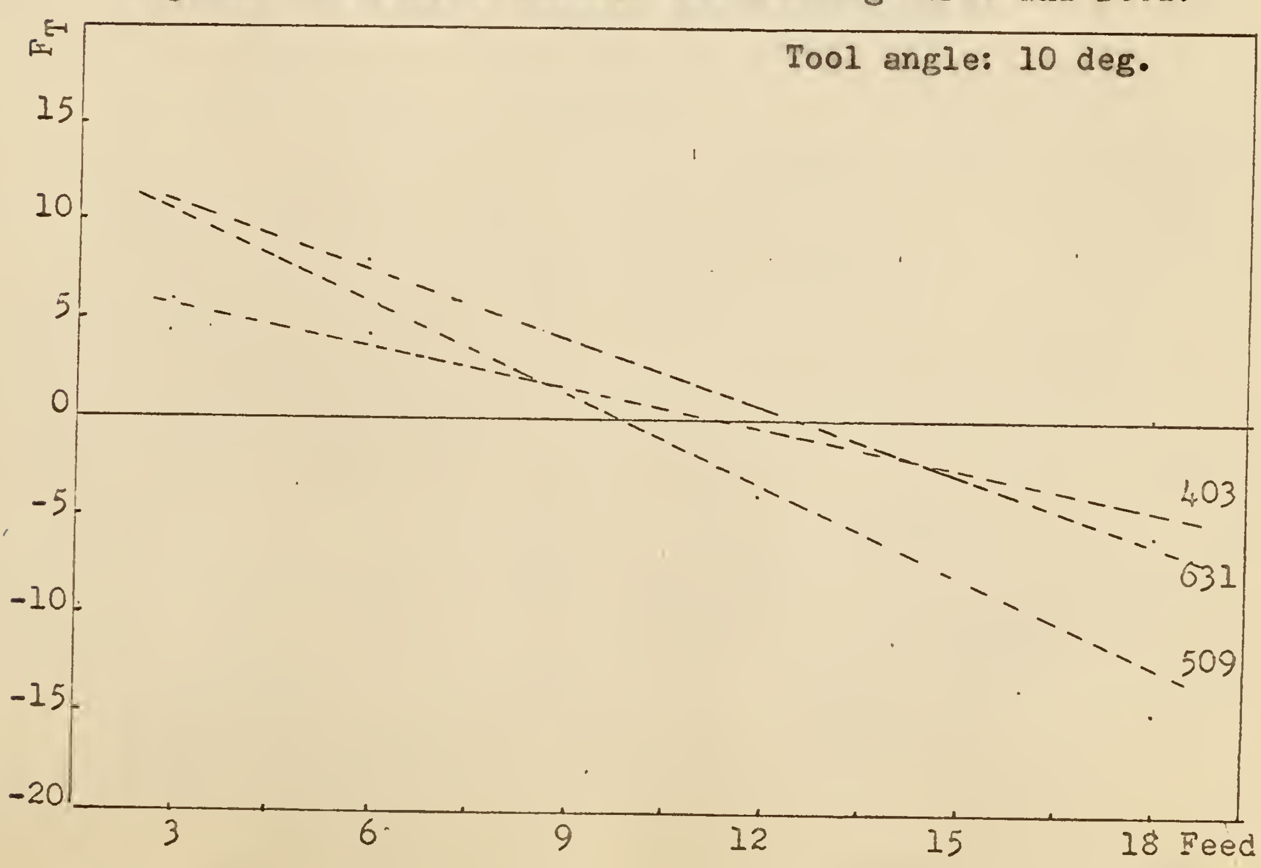


Fig. 15. Relations between the cutting force and feed.

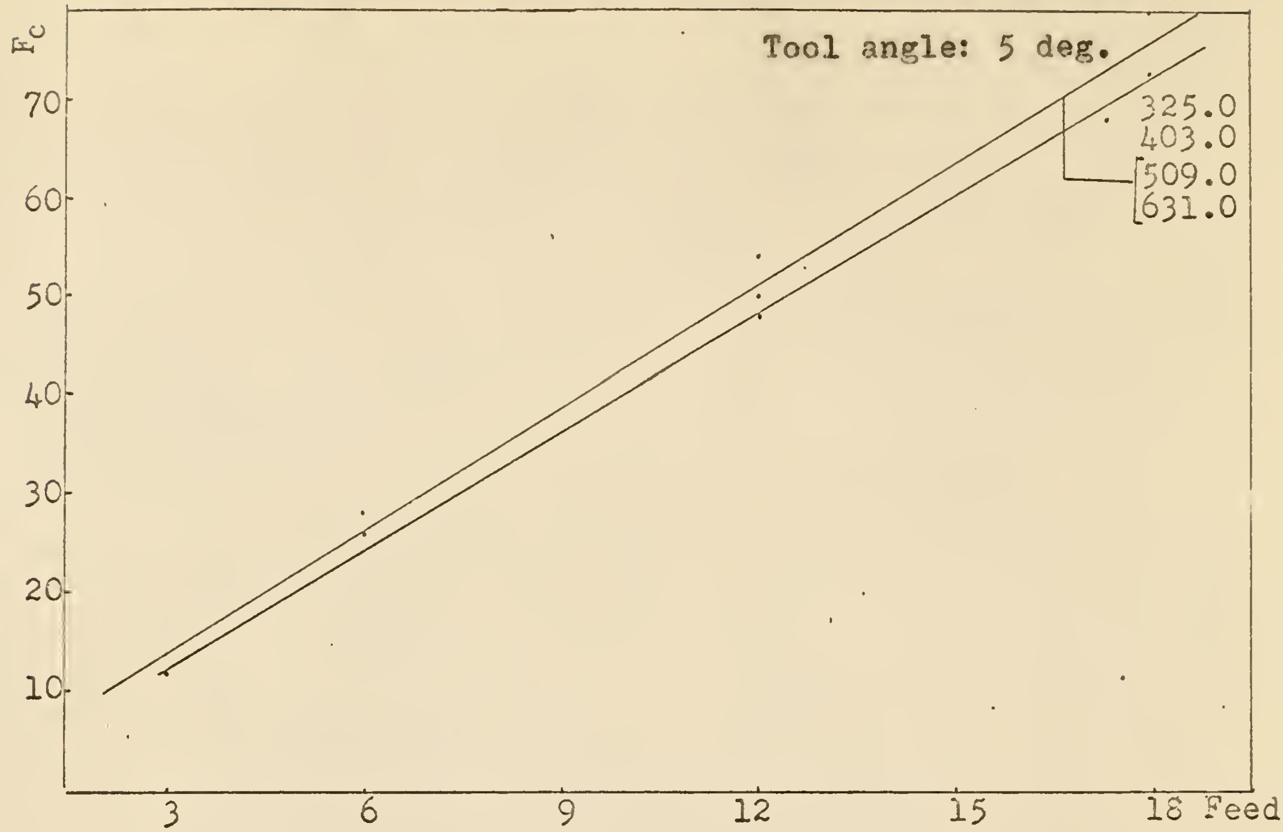


Fig. 16. Relations between the feeding force and feed.

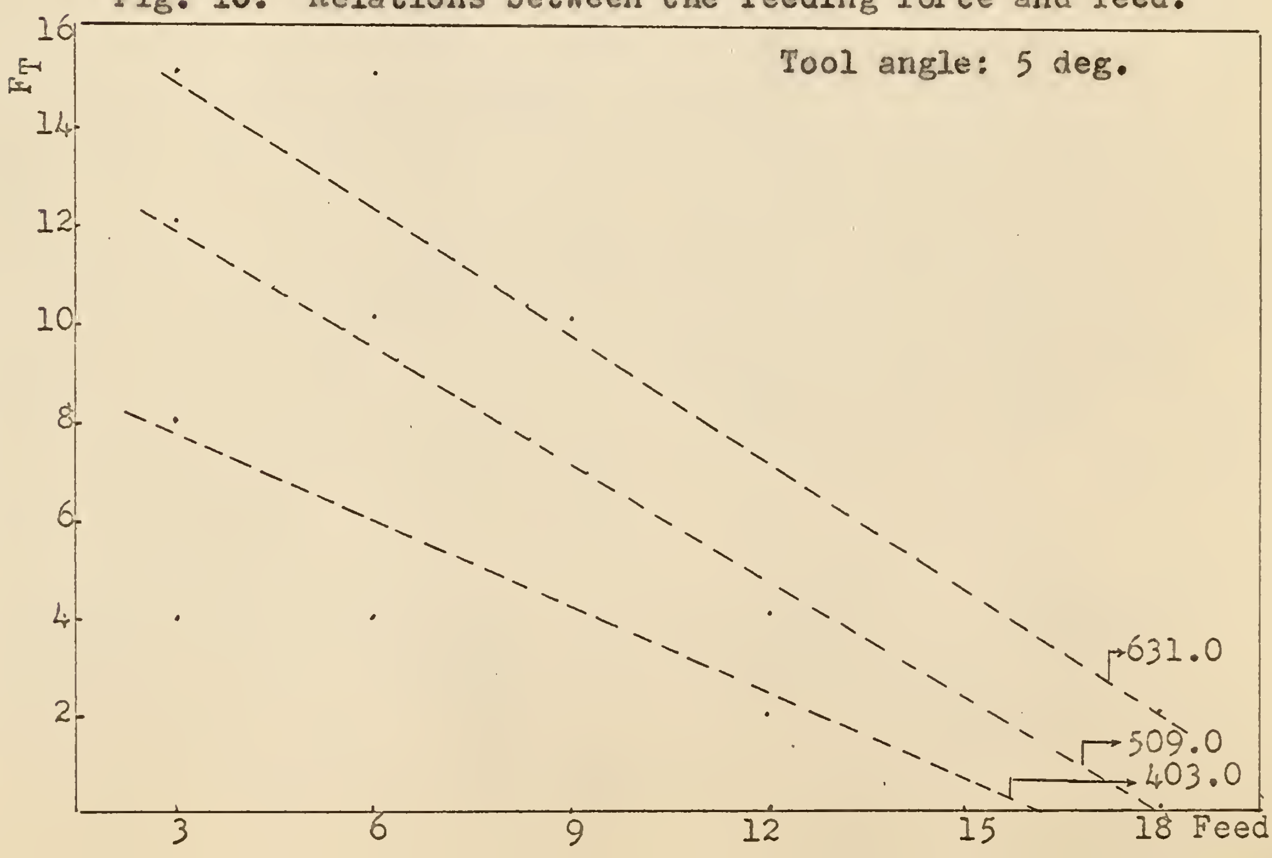


Fig. 17. Relations between the cutting force and feed.

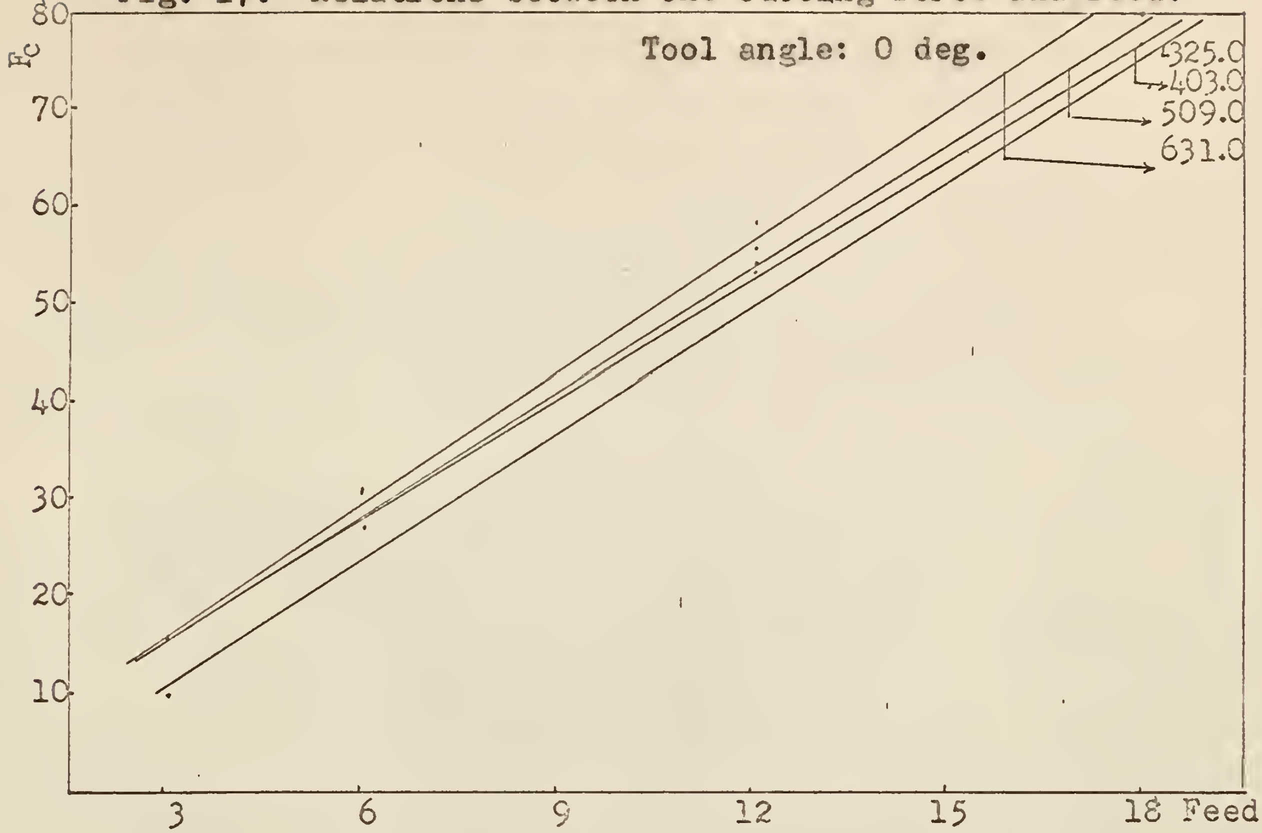


Fig. 18. Relations between the cutting force and feed.

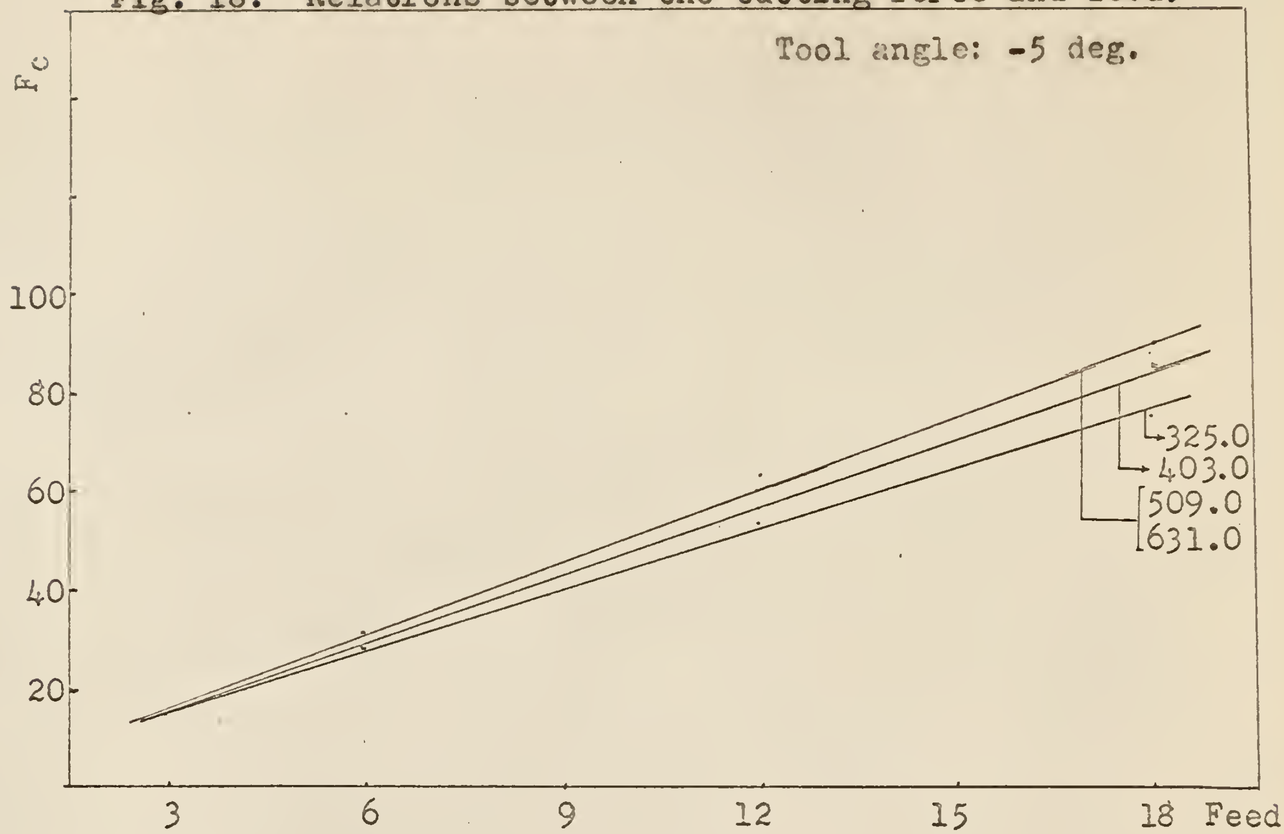


Fig. 19. Relations between the feeding force and feed.

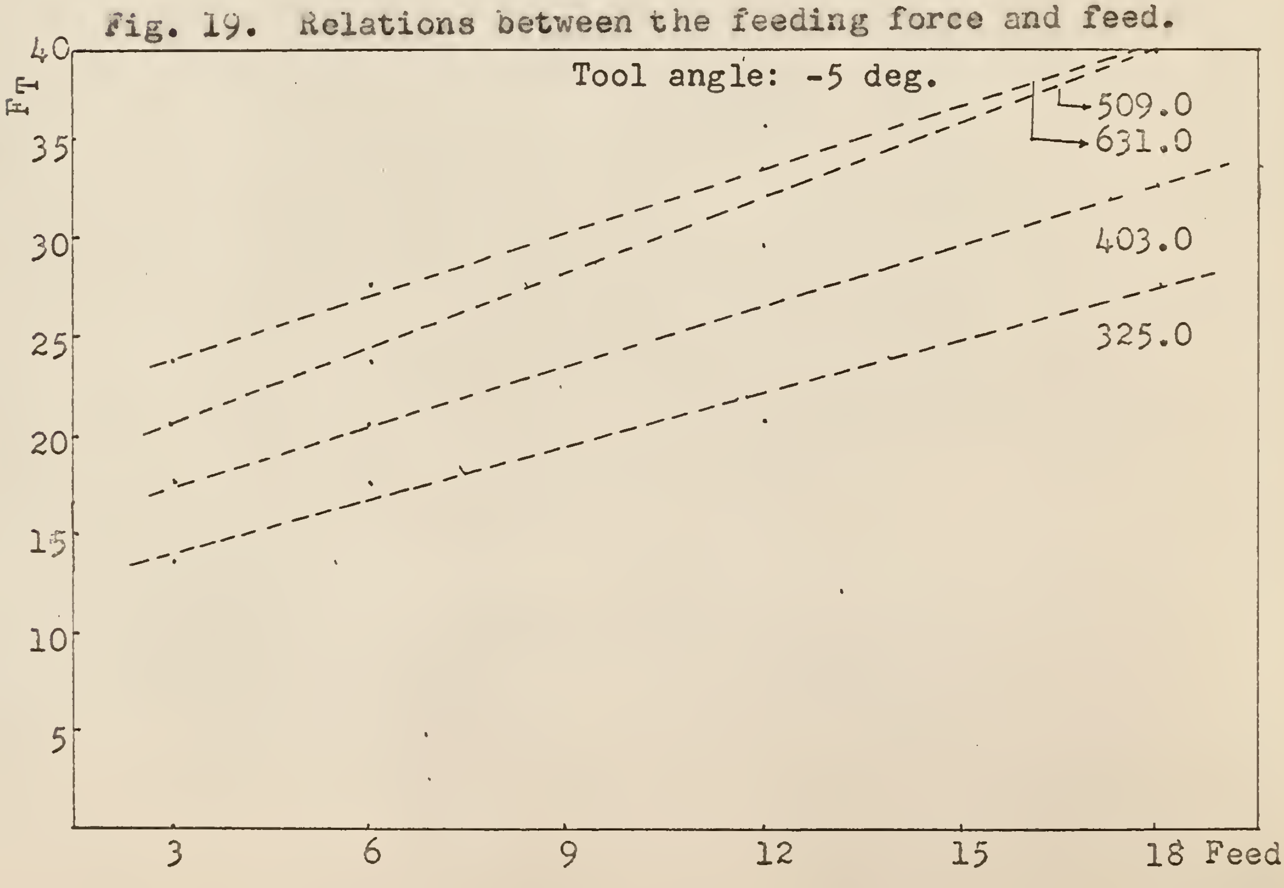


Fig. 20. Relations between the cutting force and feed.

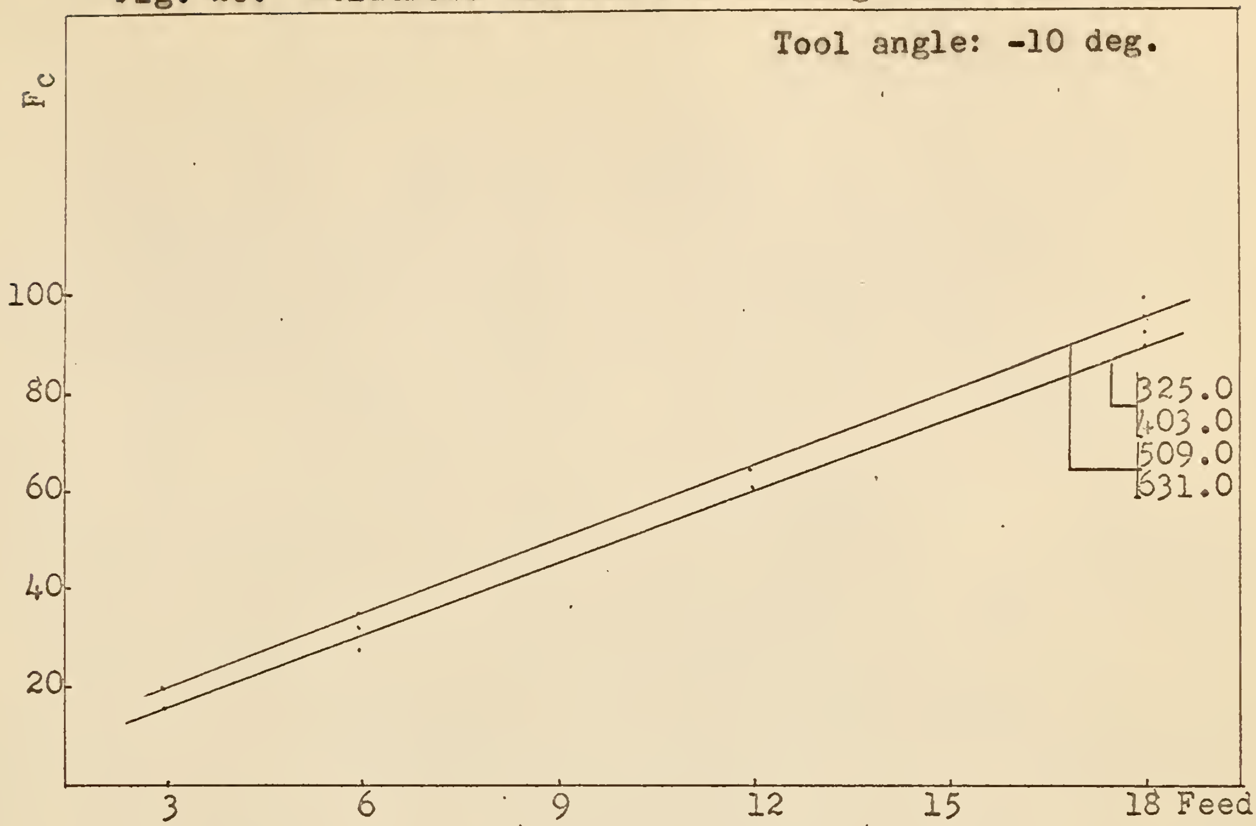


Fig. 21. Relations between the feeding force and feed.

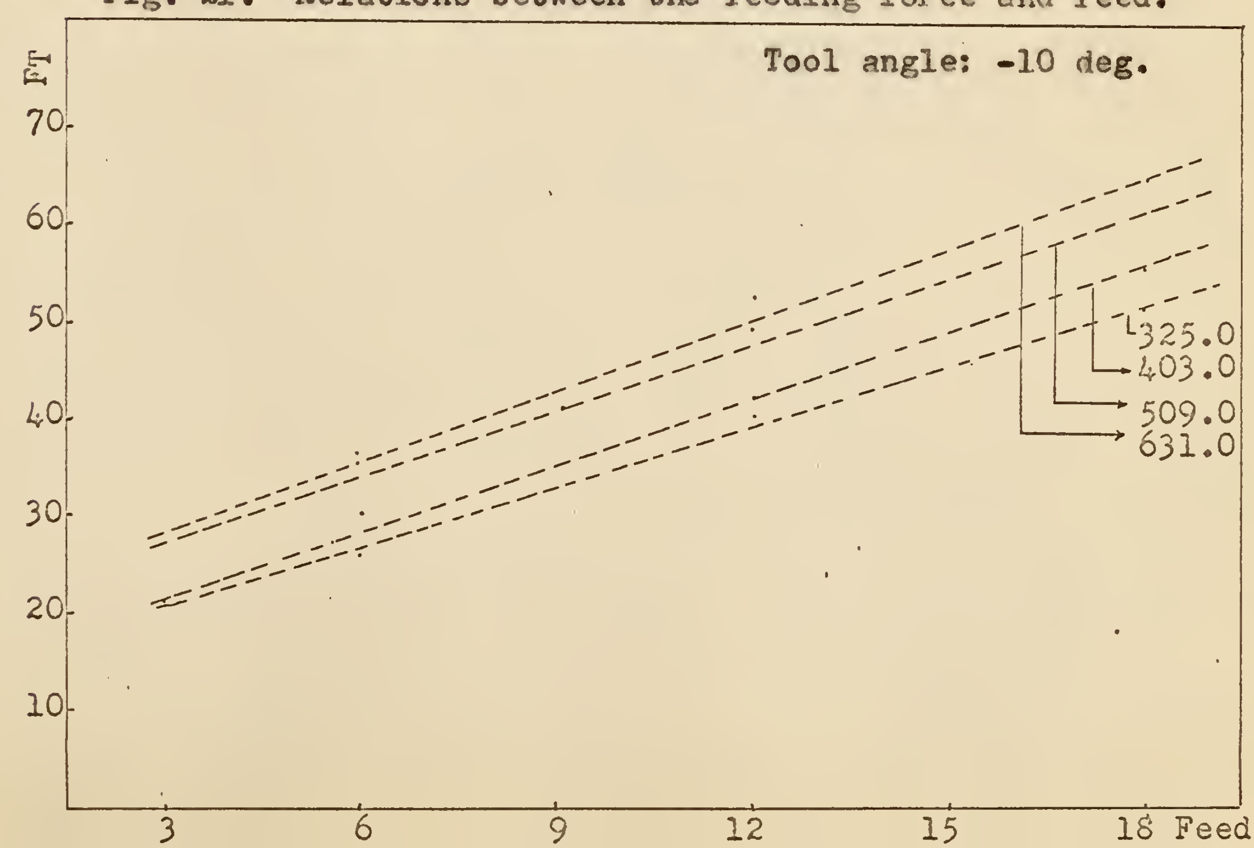


Fig. 22. Relations between the cutting force and the rake angle of a tool.

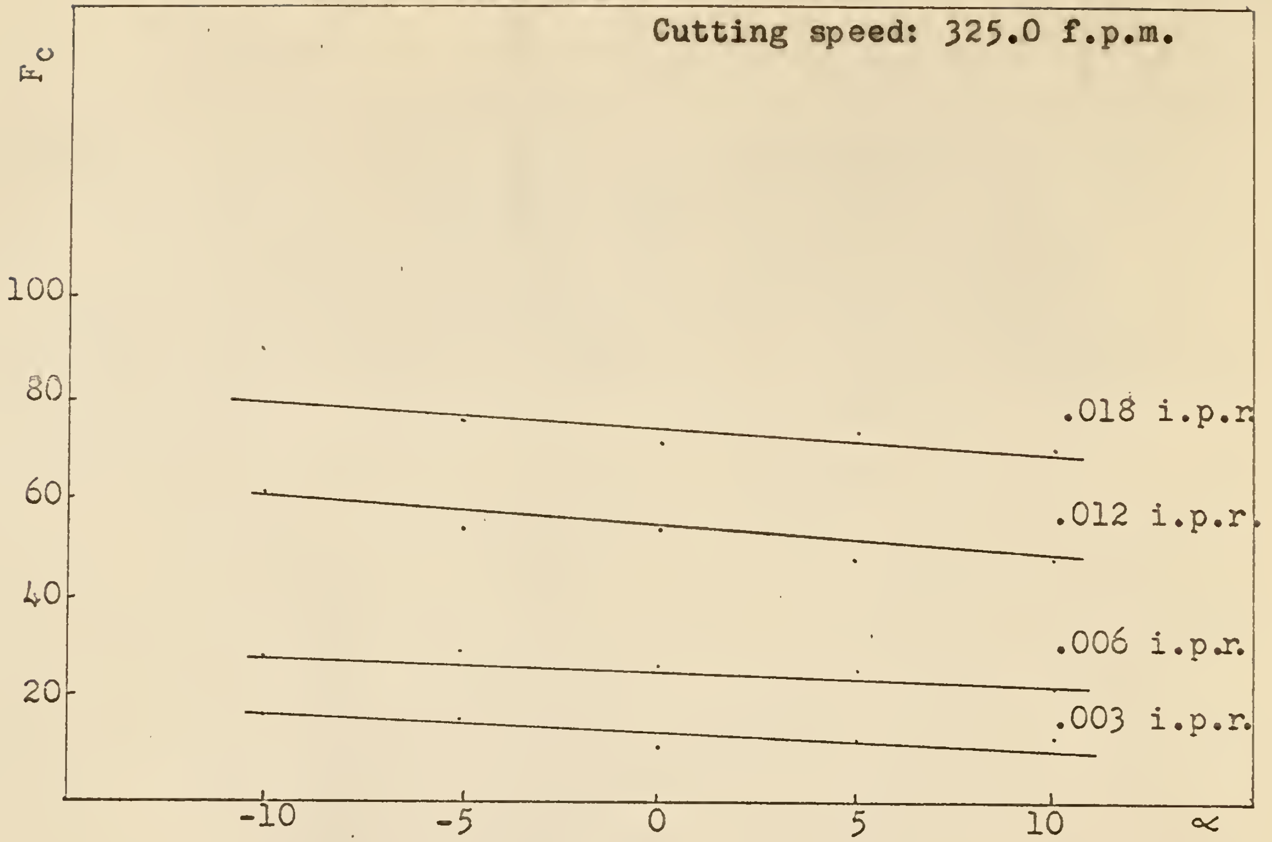


Fig. 23. Relations between the feeding force and the rake angle of a tool.

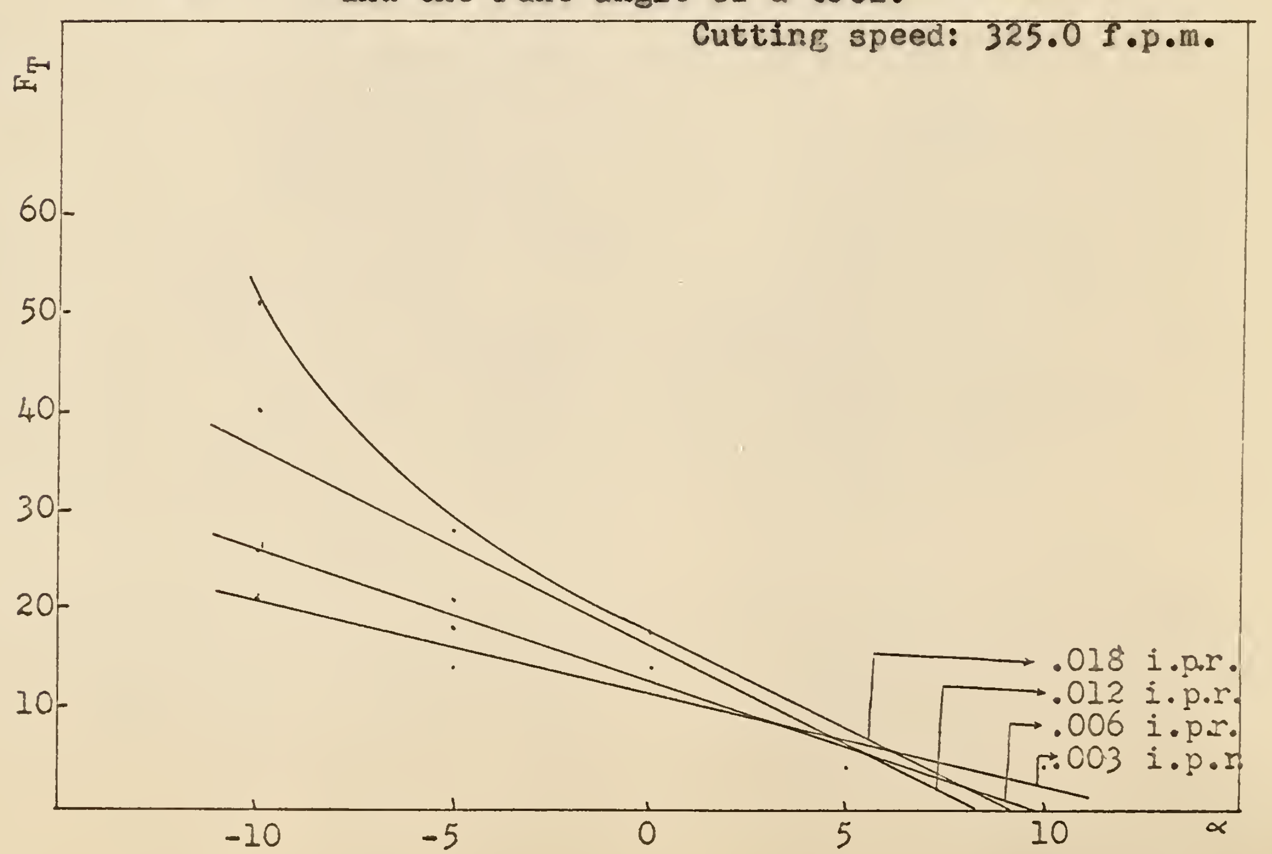


Fig. 24. Relations between the cutting force and the rake angle of a tool.

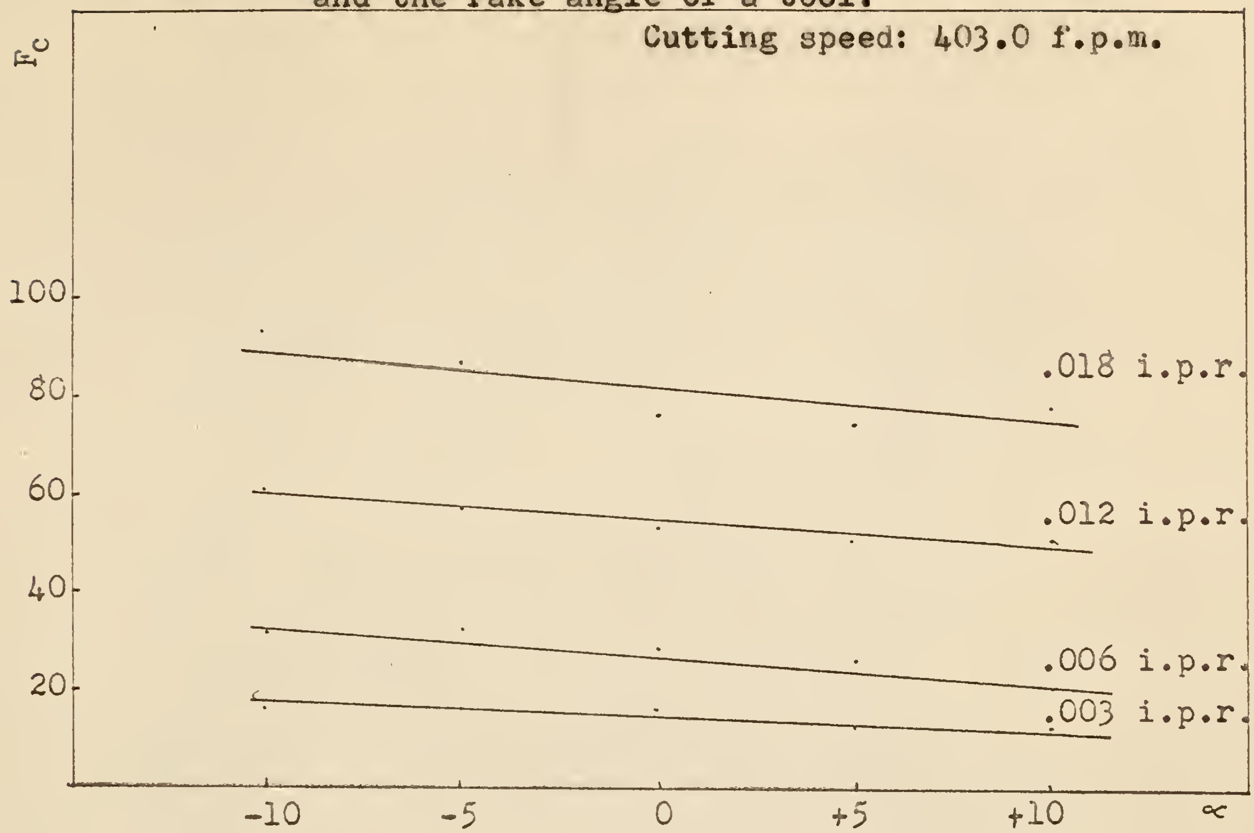


Fig. 25. Relations between the feeding force and the rake angle of a tool.

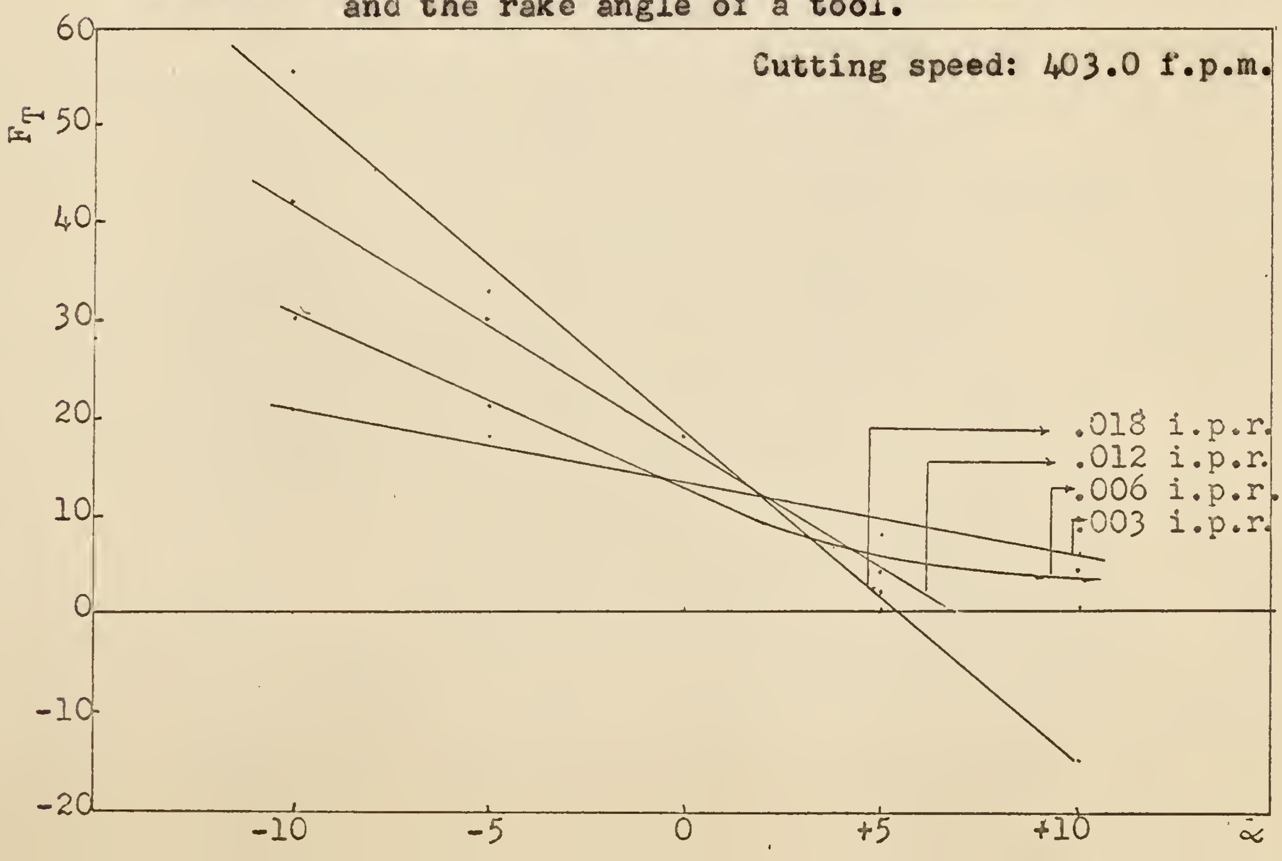


Fig. 26. Relations between the cutting force and the rake angle of a tool.

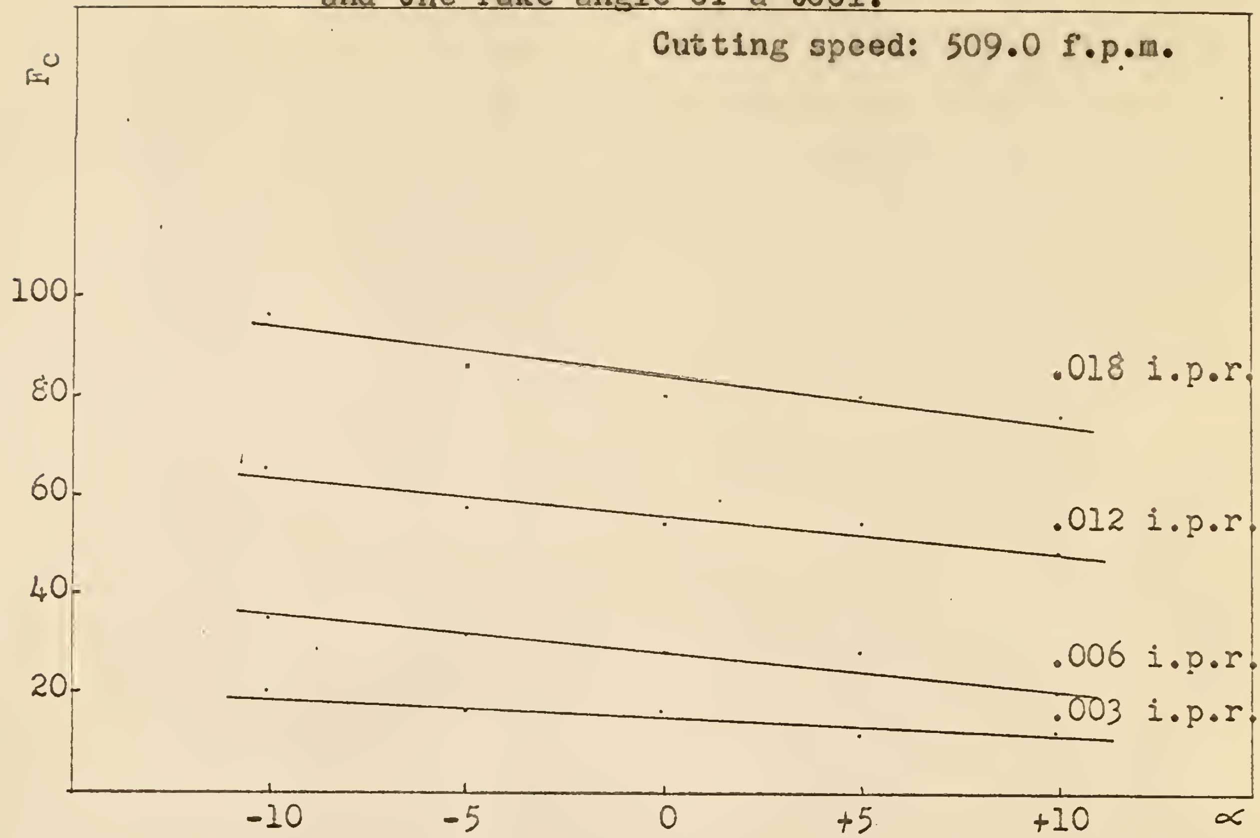


Fig. 27. Relations between the feeding force and the rake angle of a tool.

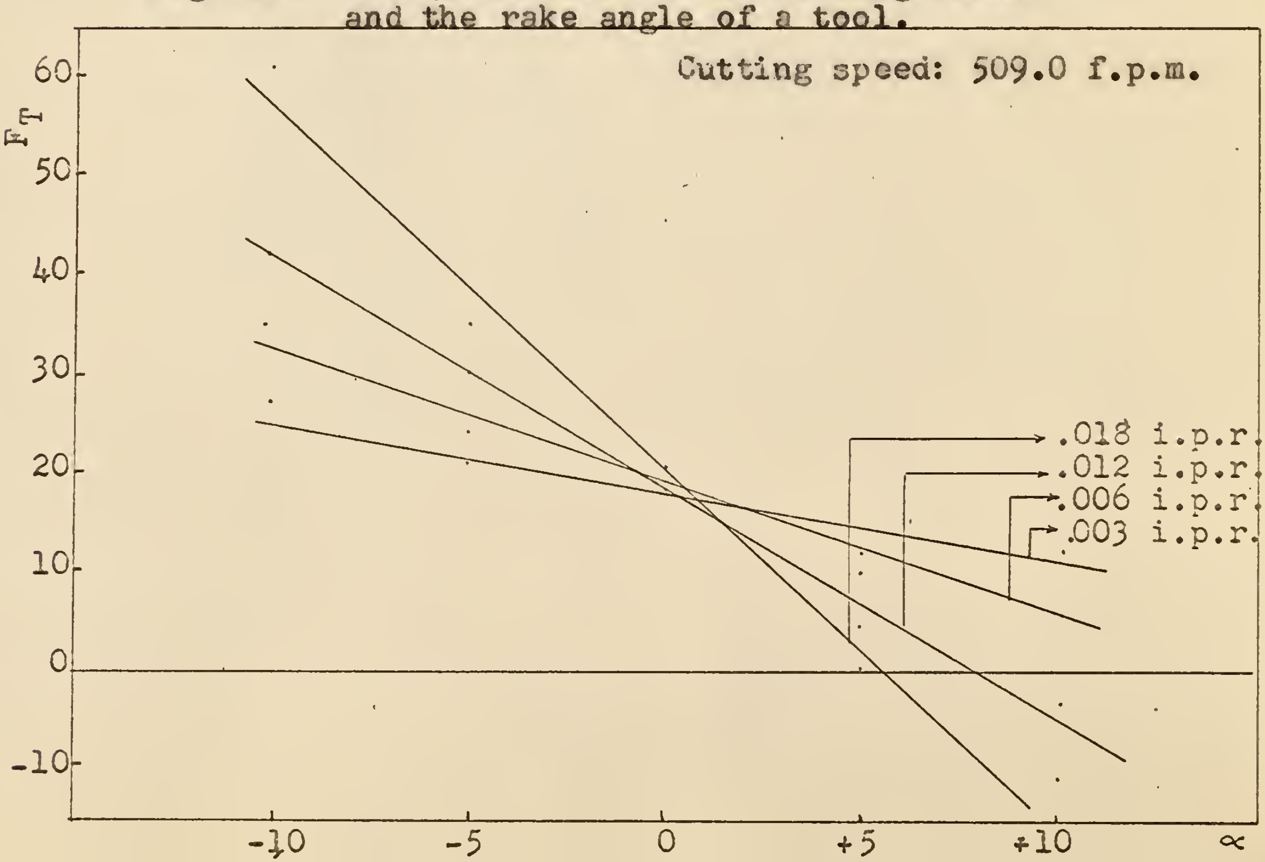


Fig. 28. Relations between the cutting force and the rake angle of a tool.

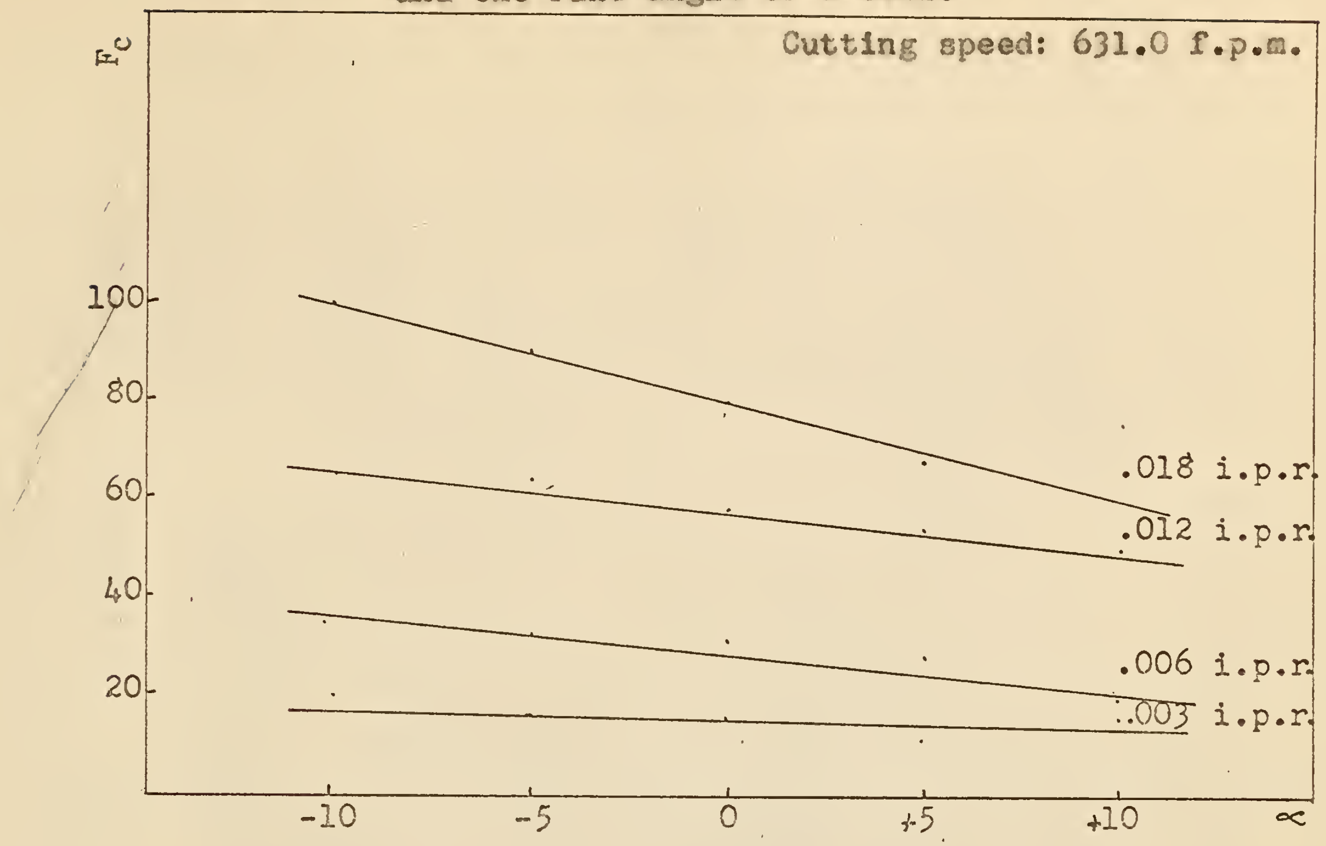
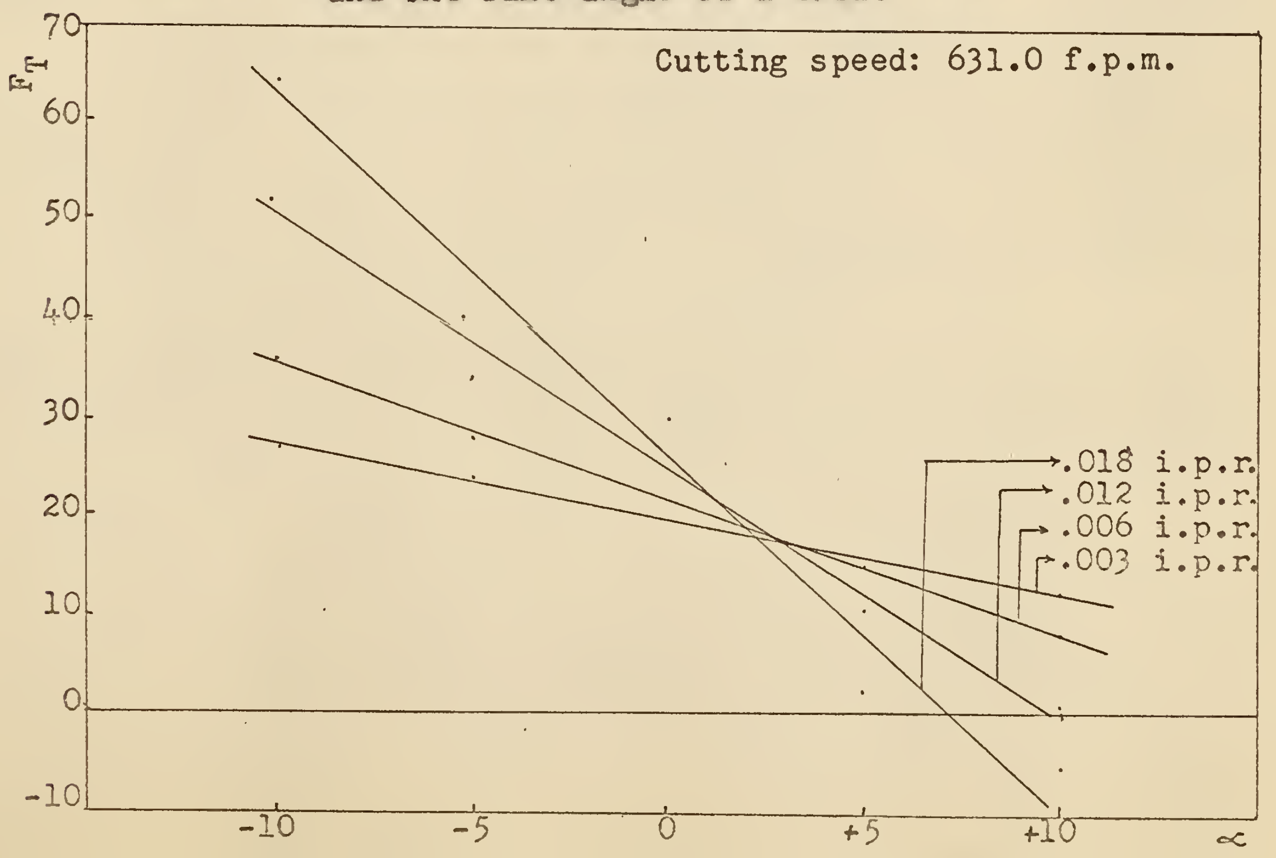


Fig. 29. Relations between the feeding force and the rake angle of a tool.



force, F_C when the feed was increased. This increase ranged from five to six times when the feed was increased from .003 i.p.r. to .018 i.p.r. This considerable increase could be attributed to higher rates of strain in the formation of chip and thus chip pressure.

(iii) Effect of Rake Angle:

It was noted that there was more influence of rake angle at higher feeds and speeds, although there was a decreasing trend in cutting force as the rake angle was increased.

Due to a decrease in rake angle, the shear plane is increased. With an increase in shear plane, the force is increased. Therefore, the cutting force, F_C has an increasing trend when the rake angle is decreased.

The highest increase in force was observed to be approximately 33% when the rake angle was decreased from 10 deg. to neg. 10 deg. at 631.0 f.p.m. and .018 i.p.r. feed.

b. Feeding Force, F_T:

(i) Effect of Speed:

Unlike the cutting force, F_C, speed has some effect on feeding force. But there was no significant trend to indicate a continuous increase in force while increasing speed. Negative feeding forces were recorded for 10 deg. rake angle. The highest negative force recorded was 15 pounds for 403.0 sfpm and .018 i.p.r. feed.

For positive 5 and 10 deg. rake angle the feeding force was found to be decreasing with the increase in speed. But with 0 deg., neg. 5 and neg. 10 deg., the situation was reversed. The feeding force increases with the increase in the speed. The increase in force was nearly doubled when the speed was increased from 325.0 sfpm to 631.0 fpm for 0 deg. rake angle and at .018 i.p.r. feed; while with neg. 5 deg. and neg. 10 deg. rake angles, the increases in force were 43% and 25%, respectively, for the same situation.

(ii) Effect of Feed:

For positive rake angles, the feeding force was found to decrease when the feed was increased. The feeding force remained almost constant at 0 deg. angle, and for negative rake angles, the force was increased with the increase in the feed. The highest increase recorded was from 27 lbs. to 64 lbs. when cutting at 631.0 fpm with neg. 10 deg., and increasing the feed from .003 i.p.r. to .018 i.p.r.

A very unusual situation was observed in that the feeding force was greater than the cutting force, F_C, at lower feeds when the rake angle was decreased. The higher values of feeding force could be attributed to the compressive strains existing both perpendicular to and along the cutting direction. The strains perpendicular to the cutting direction exist beneath a tool and on the cut surface. Therefore, the cut surface is rubbed against the relief surface of a tool. This pressure on the relief surface of a tool is found more in the case of negative tool due to higher values of compressive strains.

(iii) Effect of Tool Angle:

There is a very significant decreasing trend found when increasing the rake angles. The highest increase was found to be from -12 lbs. to 61 lbs. or 73 lbs., when decreasing the tool rake angle at 509 f.p.m. and .012 i.p.r. This increasing trend seems to be very significant at higher speeds and feeds.

c. Resultant Cutting Force, R.

Magnitude and direction of cutting forces, R, are shown on pp. 61-68 for different speeds, feeds, and tool angles. The direction of the force is pointed away from the tool point. This is the direction of resultant force acting on the workpiece.

The following important facts were noted:

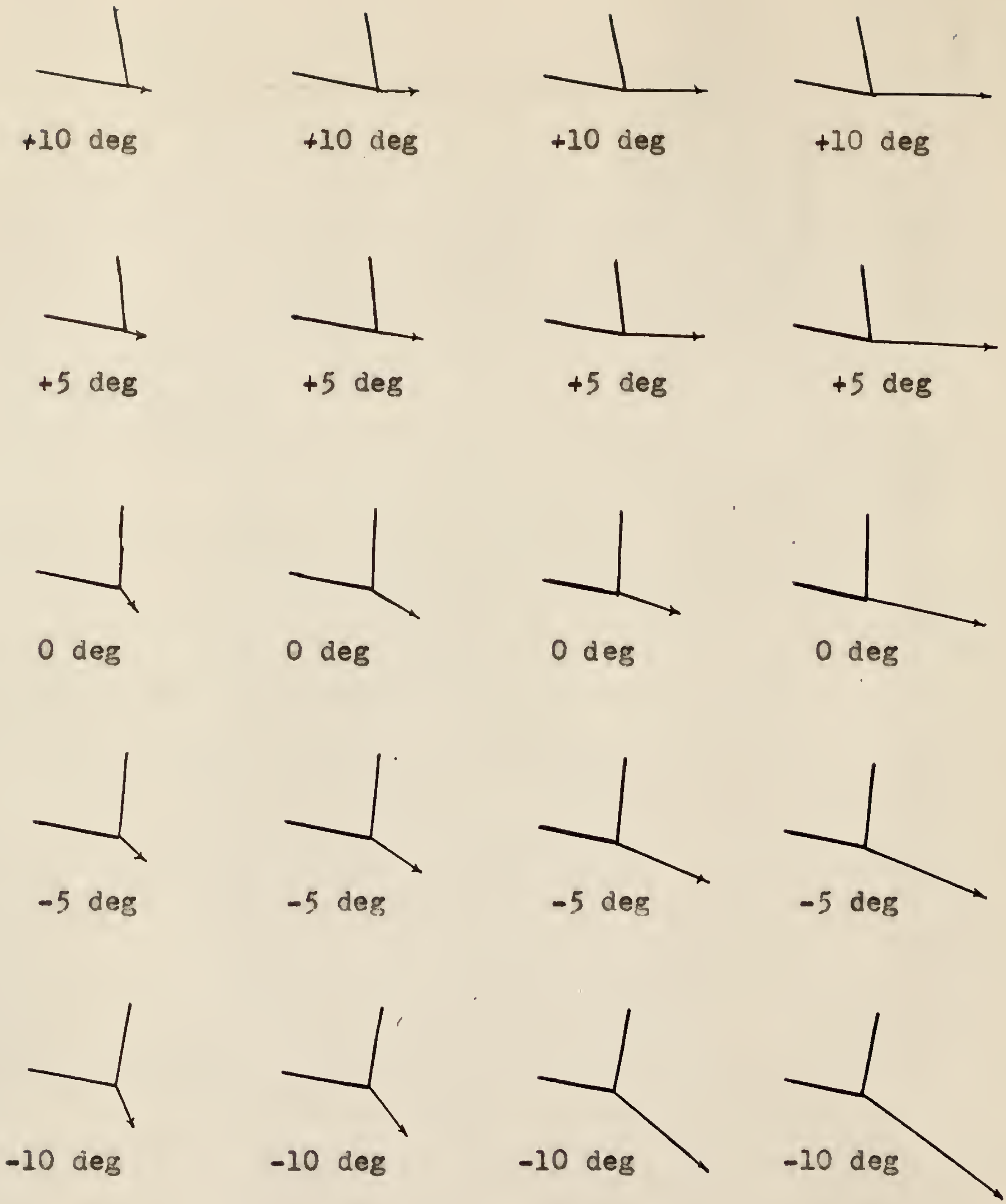
1. There seemed to be no influence of cutting speed on the resultant force. There was

Fig. 30. Magnitude and direction of Resultant cutting force, R.

Work material: PVC with Geon Vinyl

Tool material: Rex-95 H.S.S.

Speed: 325.0 f.p.m.



Feed: .003 i.p.r. .006 i.p.r. .012 i.p.r. .018 i.p.r.

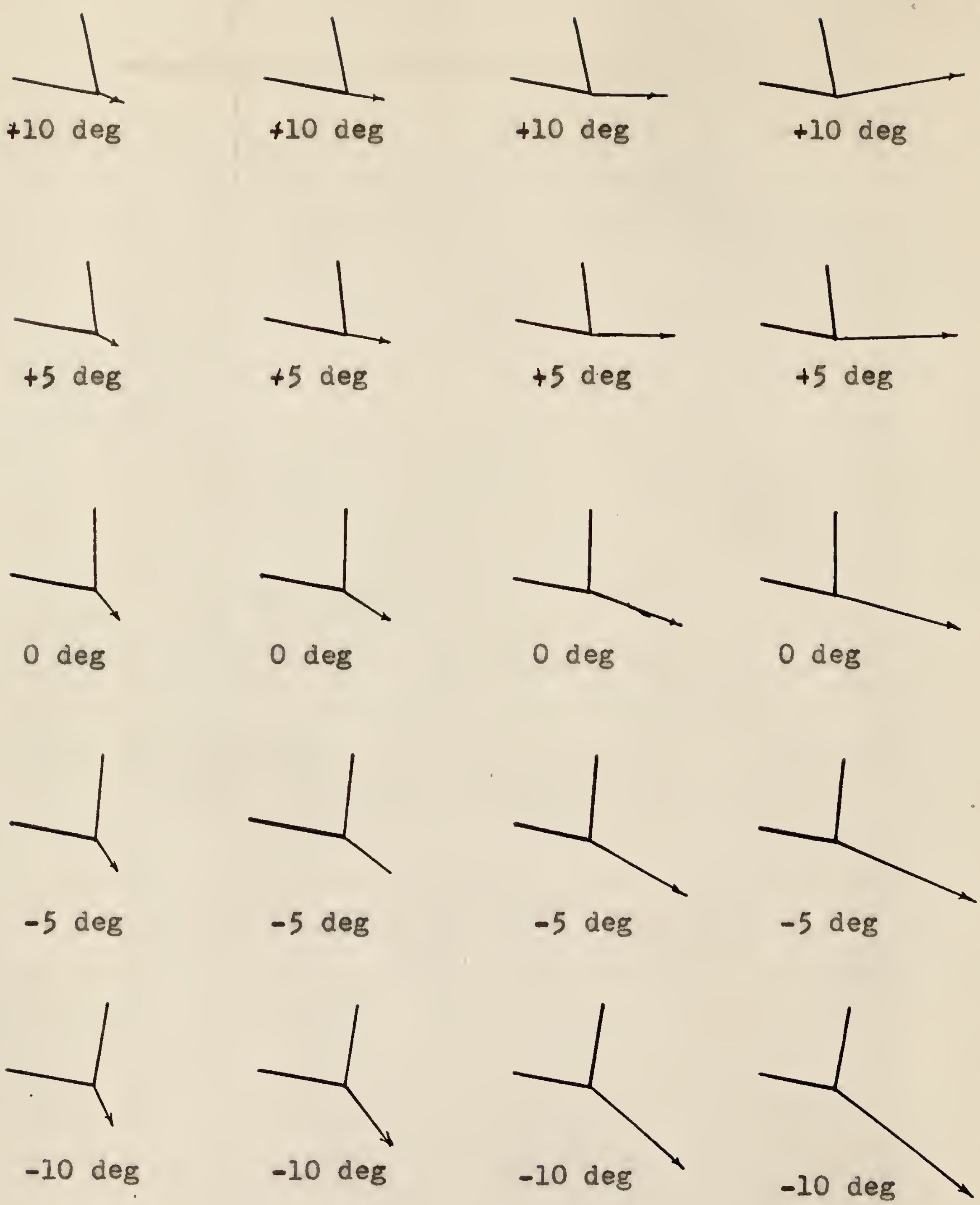
Scale: 1 in. = 50 lbs.

Fig. 31. Magnitude and direction of Resultant cutting force, R.

Work material: PVC with Geon Vinyl.

Tool material: Rex - 95 H.S.S.

Speed: 403.0 f.p.m.



Feed: .003 i.p.r. .006 i.p.r. .012 i.p.r. .018 i.p.r.

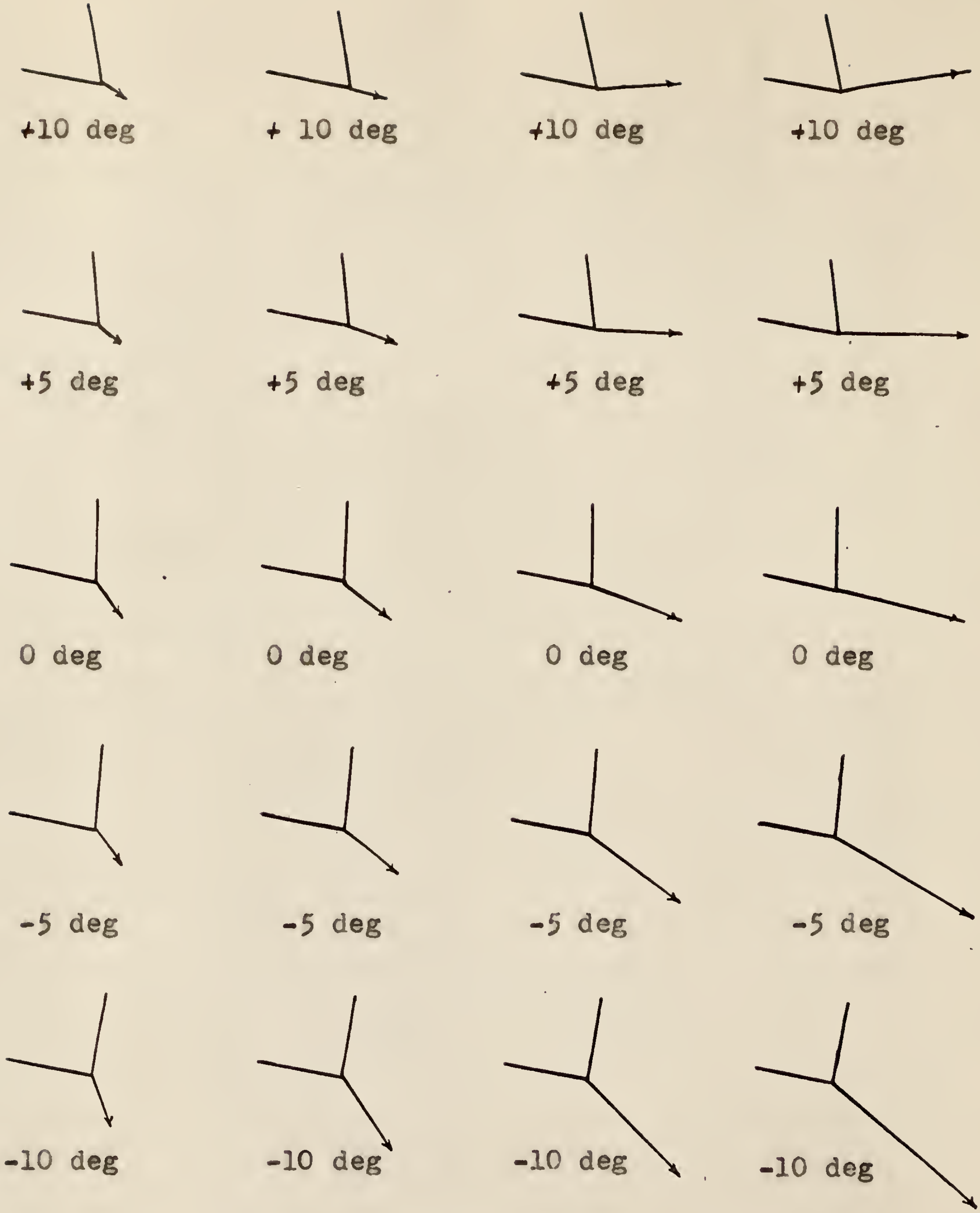
Scale: 1 in. = 50 lbs.

Fig. 32. Magnitude and direction of Resultant cutting force, R.

Work material: PVC with Geon Vinyl.

Tool material: Rex - 95 H.S.S.

Speed: 509.0 f.p.m.



Feed: .003 i.p.r. .006 i.p.r. .012 i.p.r. .018 i.p.r.

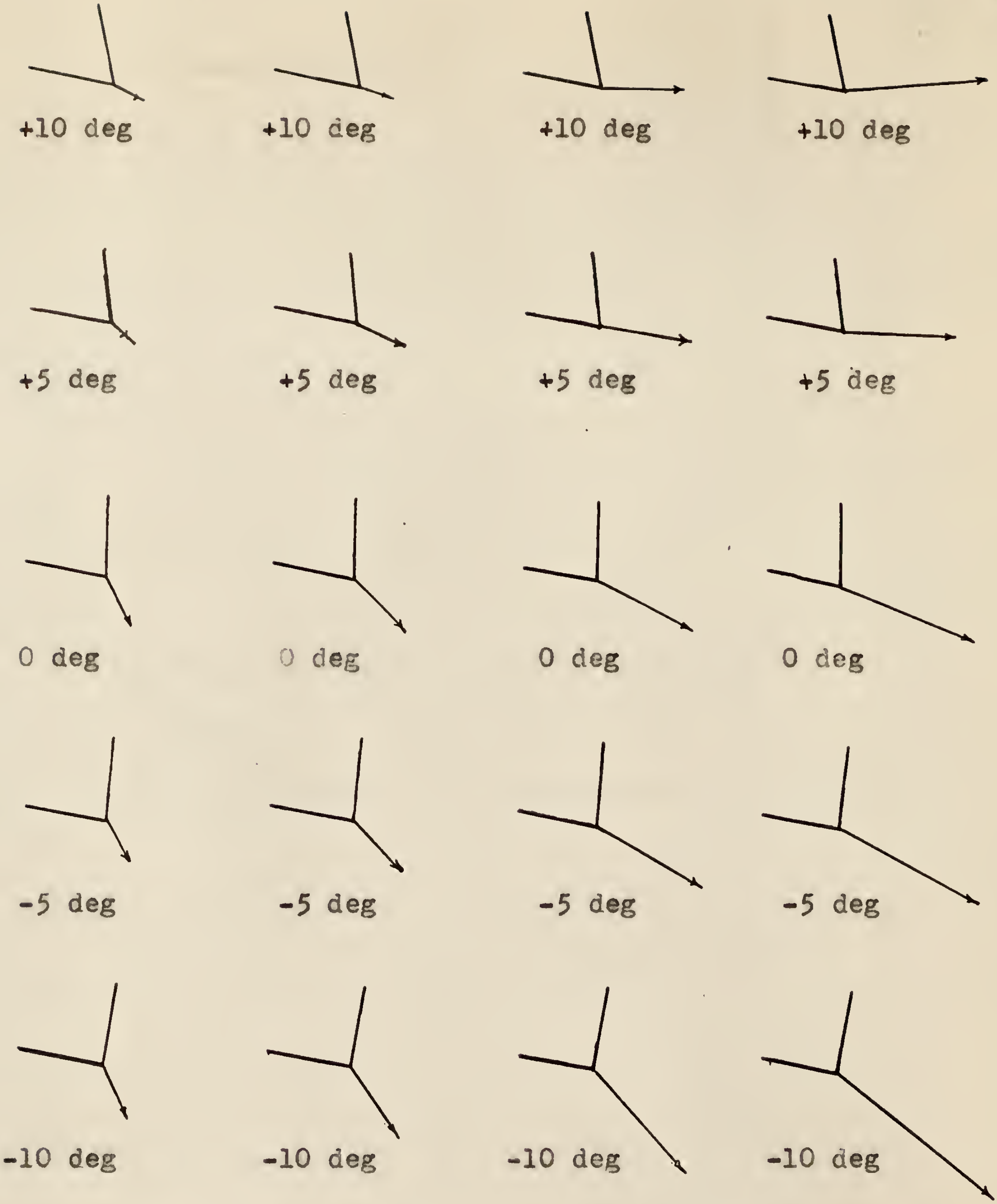
Scale: 1 in. = 50 lbs.

Fig. 33. Magnitude and direction of Resultant cutting force, R.

Work material: PVC with Geon Vinyl

Tool material: Rex - 95 H.S.S.

Speed: 631.0 f.p.m.



Feed: .003 i.p.r. .006 i.p.r. .012 i.p.r. .018 i.p.r.

Scale: 1 in. = 50 lbs.

some change in the direction of the force. Except for positive 10 deg. angle this direction is increased (the direction being measured with respect to horizontal)

2. The resultant cutting force was increased with the increase in feed. This increase was more as the rake angle was decreased at higher speeds. The highest increase recorded was, for -10 deg., a little over 2.5 times at 631.0 f.p.m. The direction of the force was found to decrease with an increase in feed.

3. The magnitude and direction increased as the rake angle decreased. Approximately 50% increase was found when going from 10 deg. to -10 deg. at .018 i.p.r. and 631.0 f.p.m.

d. Friction in Tool Face, μ.

The graphical representations of coefficient of friction for various conditions are shown on pp. 70-72.

A very good trend was noticed for the coefficient of friction versus feed. In all cases the trend was a decreasing one with an increasing feed. At higher feeds, it seems to become horizontal. This decreasing trend was more significant when the tool angle was increased.

e. Critical Rake Angle:

Kobayashi (2), in his work, defined this quantity, angle, "as the rake angle of a tool which makes F_T equal to zero. Since the direction of the resultant

Fig. 34. Relations between coefficient of friction and feed.

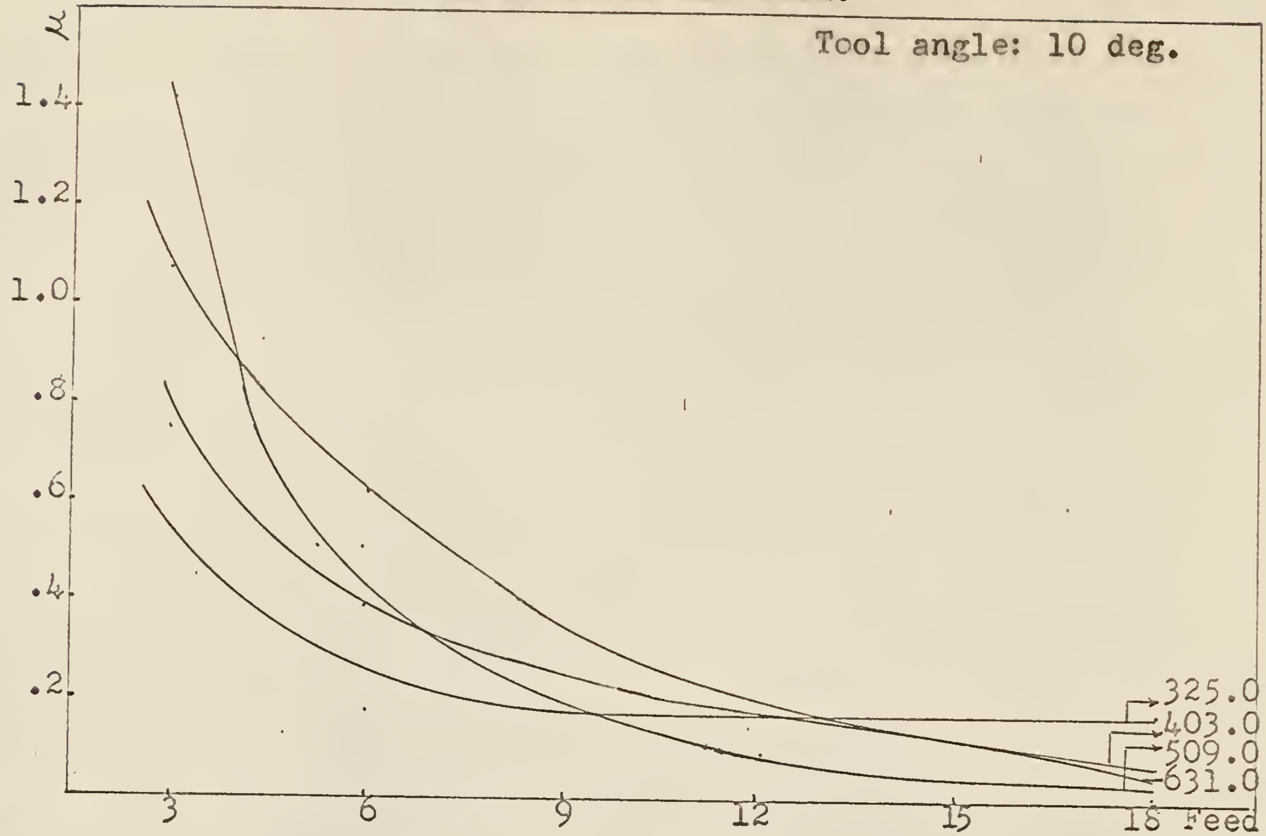


Fig. 35. Relations between coefficient of friction and feed.

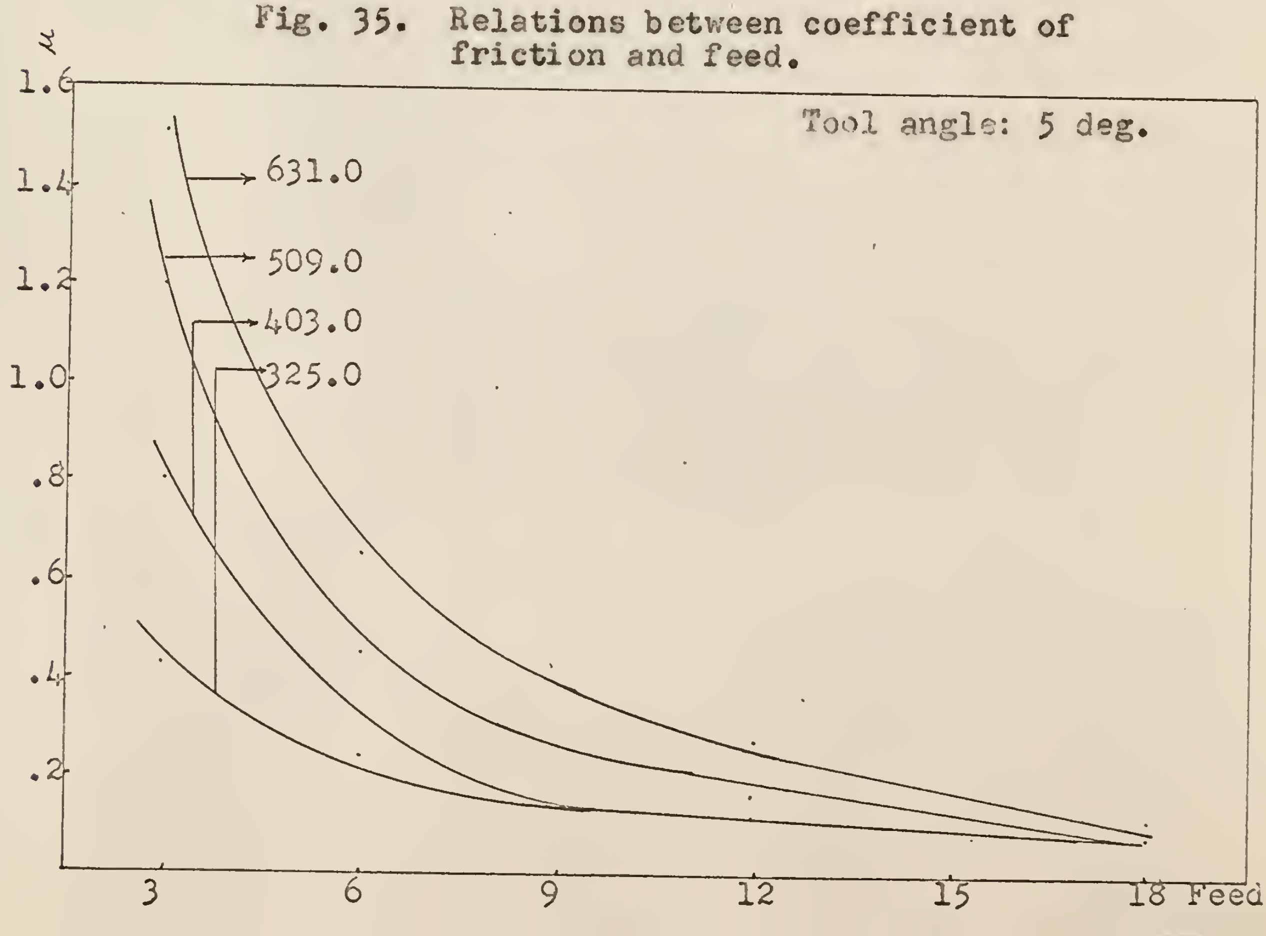


Fig. 36. Relations between coefficient of friction and feed.

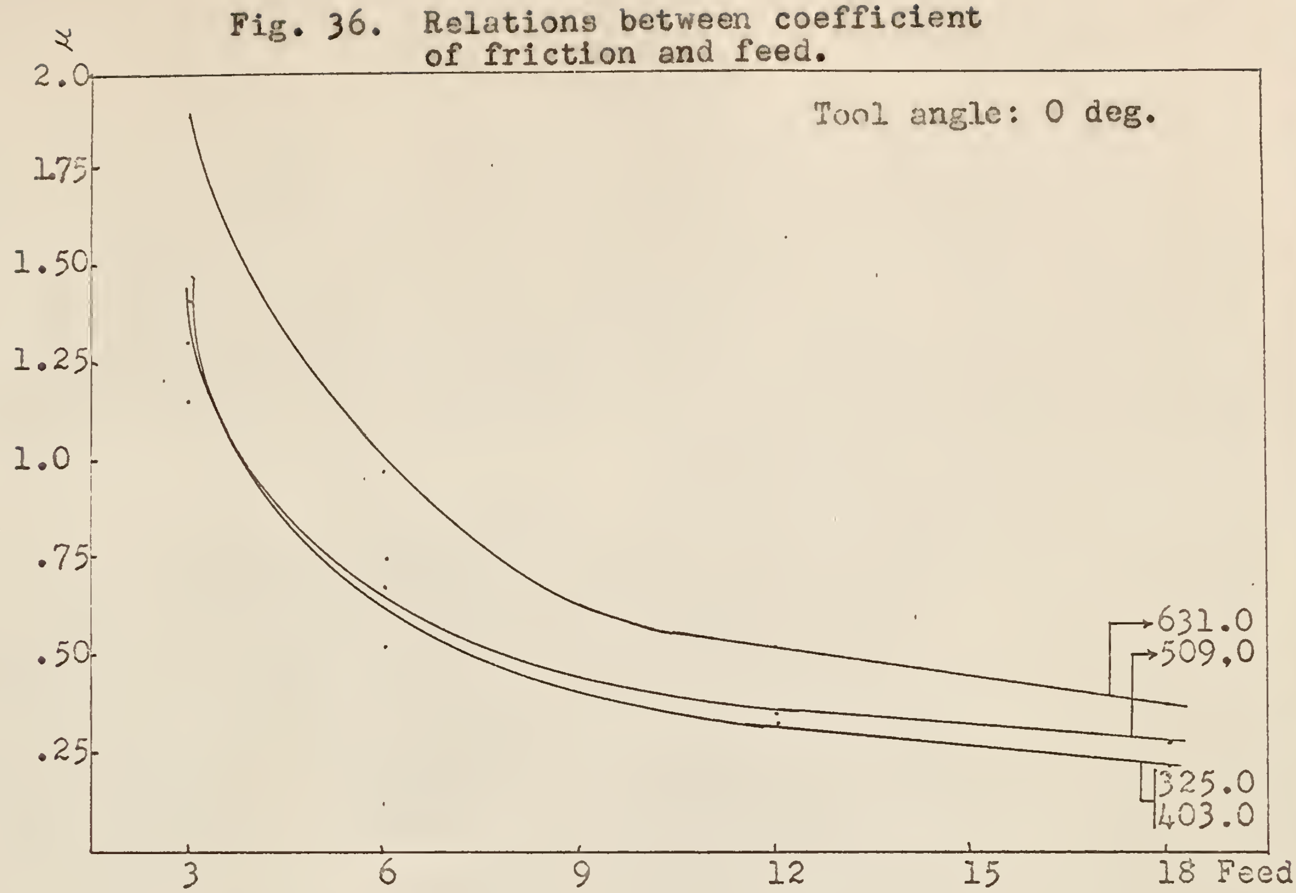


Fig. 37. Relations between coefficient of friction and feed.

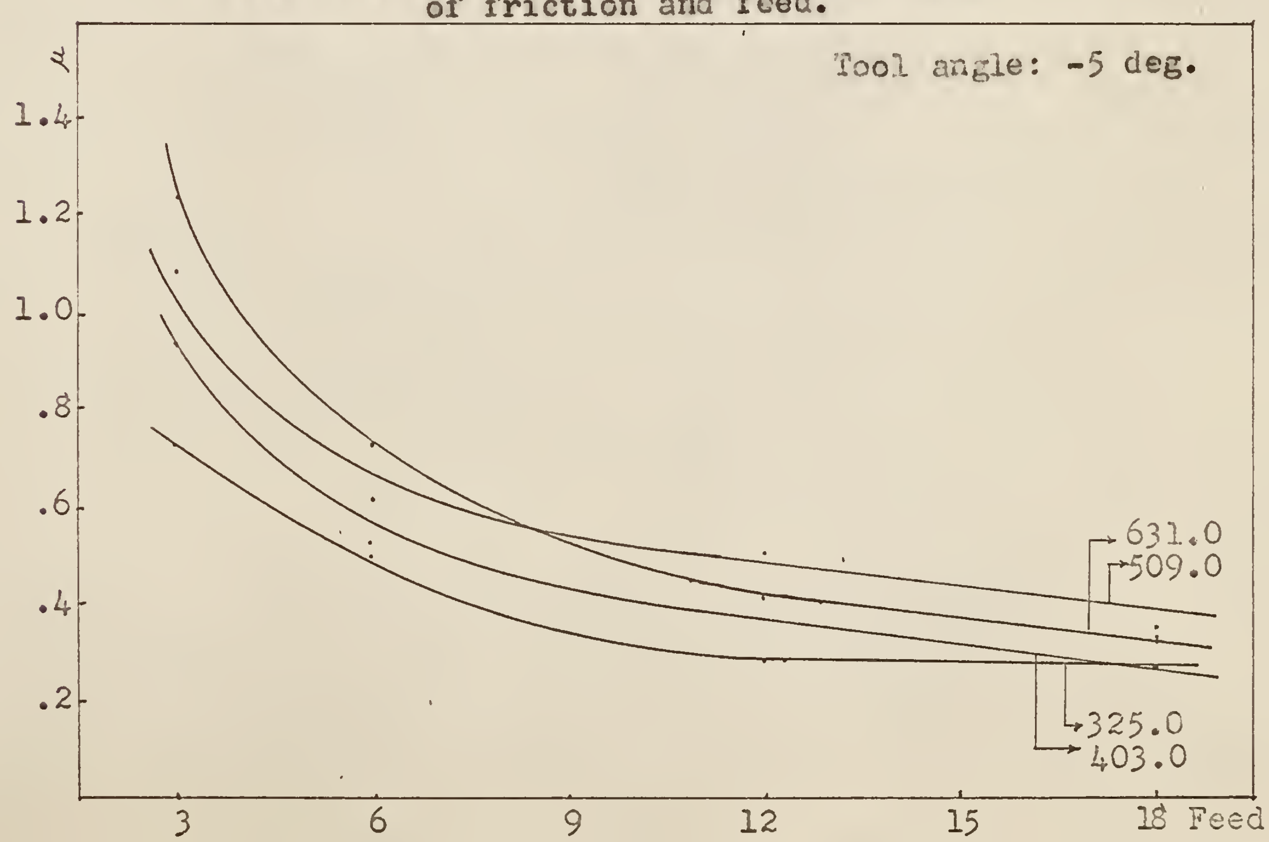
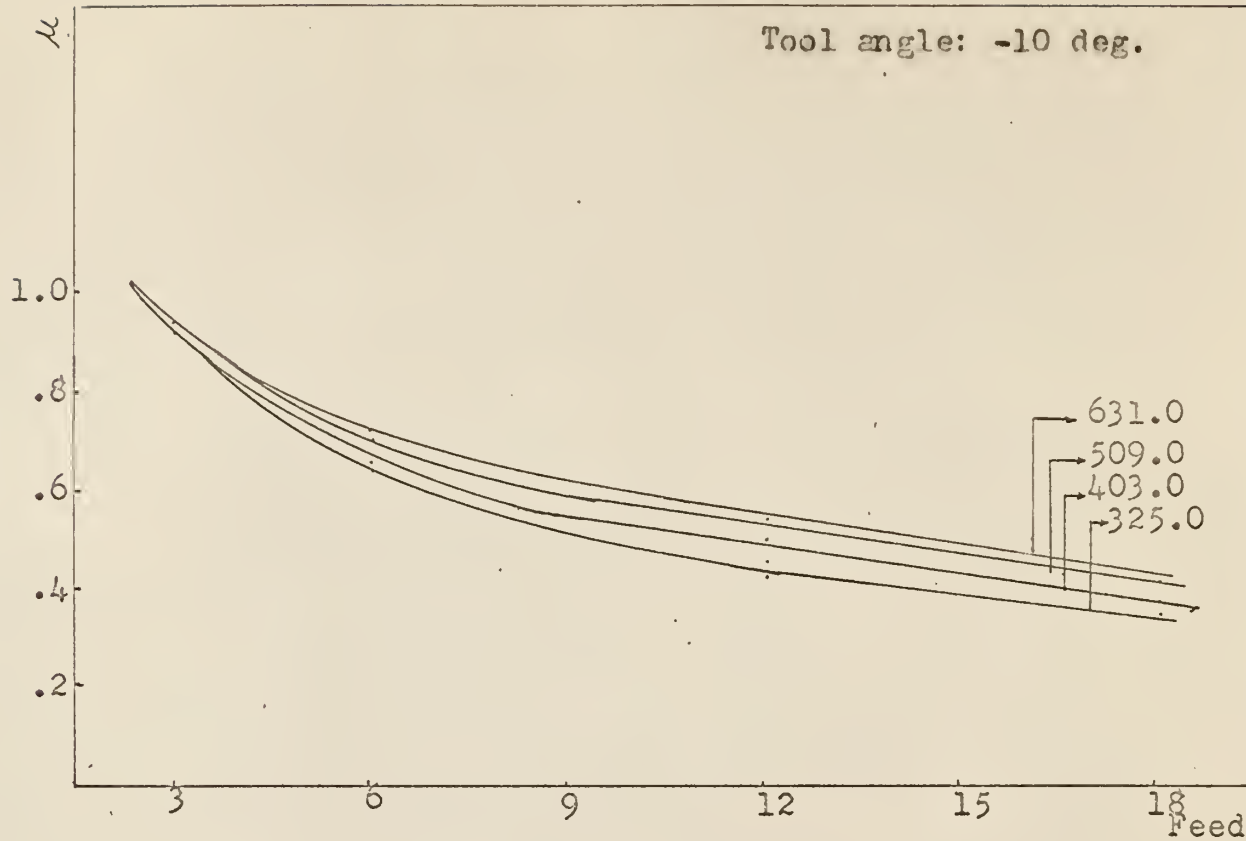


Fig. 38. Relations between coefficient of friction and feed.



cutting force exactly coincides with the direction of the cutting, the work material does not deform upwards or downwards during cutting. This may be the optimum rake angle for plastics to obtain the most accurate parts. The value of the critical rake angle is influenced by the frictional behavior of chips on the rake surface of a tool."

In the present case, for PVC Plastics, this critical rake angle was found to lie between 5 and 10 deg. positive. This approached 10 deg. as the speed was increased.

(2) Formica Grade CN (Fabric Base).

The forces were measured for different speeds and rake angles. The feed was constant, .012 i.p.r. From Table VI, the following are some interesting points:

a. Cutting Force, F_C:

(i) There was not any appreciable effect of speed on the cutting force.

(ii) A constant increase in cutting force was found when the rake angle was decreased. For all speeds, this increase was nearly twice when decreasing the tool angle from 10 deg. positive to 10 deg. negative.

b. Feeding Force, F_T:

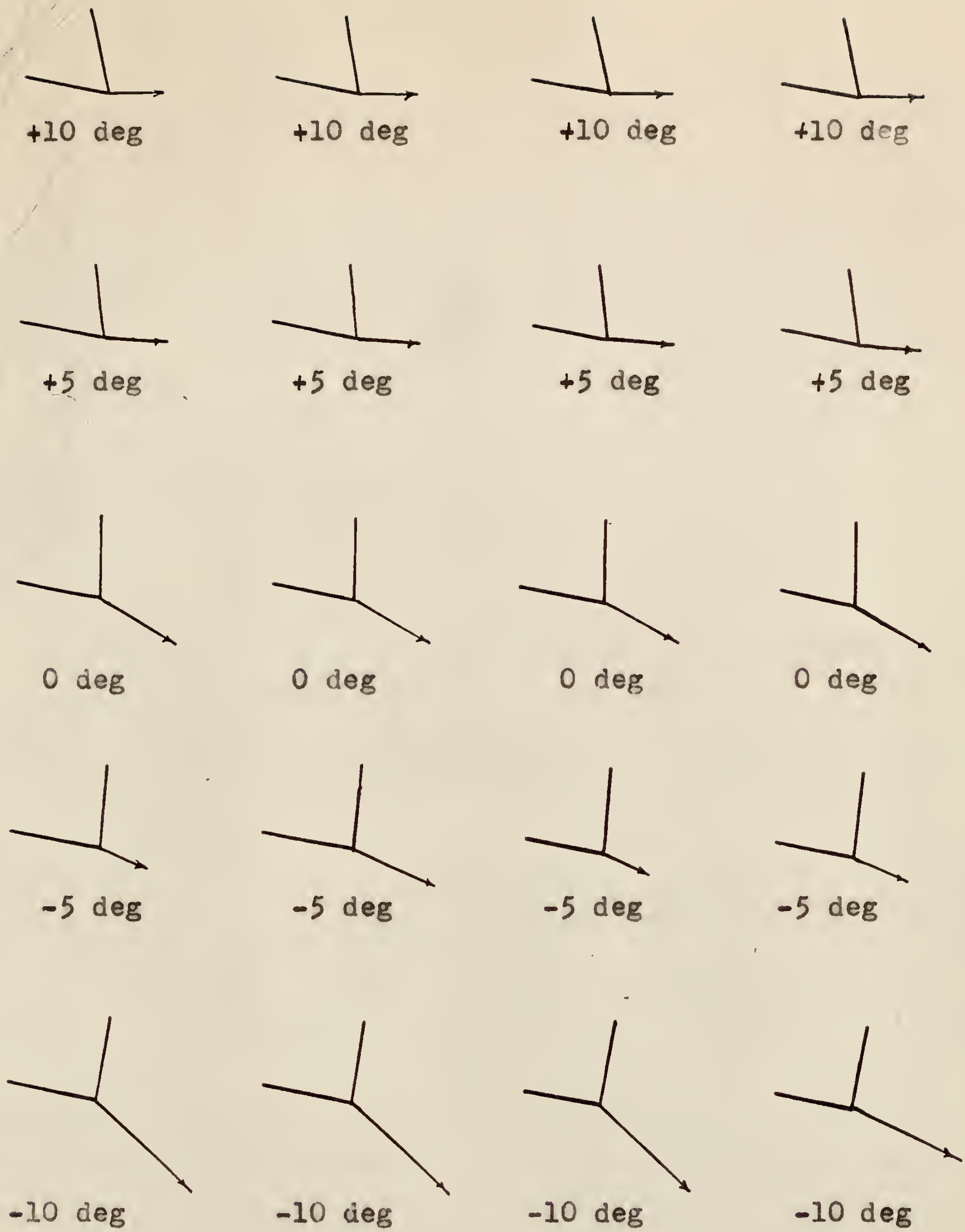
The feeding force seemed to be constant at increasing speeds, except at one place, where the force was surprisingly dropped from 45.5 lbs. to 27 lbs. when

Fig. 39. Magnitude and direction of Resultant cutting force, R.

Work material: Formica Grade CN.

Tool material: Rex - 95 H.S.S.

Feed: .012 i.p.r.



Speed: 740.0 f.p.m. 914.0 f.p.m. 1125.0 f.p.m. 1415.0 f.p.m.

Scale: 1 in. = 50 lbs.

cutting with -10 deg., and speed increased from 1125.0 f.p.m. to 1415.0 f.p.m. This could be an experimental error.

Here, too, a zero feeding force was observed at all speeds for positive 10 deg. angle. A positive tool rake angle and higher speeds seemed to be very advantageous.

c. Resultant Cutting Force, R:

From the Fig. 39 it was noticed that the tool angle significantly changed the magnitude as well as direction of the force. With the decrease in the rake angle, the magnitude and direction both were increased. The increase in the magnitude was almost twice at all speeds. There was no effect of speed on the magnitude as well as direction of the resultant cutting force, R.

(3) Dilecto XX-79.

This material was machined for different angles, feeds, and speeds.

a. Cutting Force, F_C:

From the graphs shown on pp. 77-81 the following important points were derived:

(i) In this case, too, there was no effect of speed on cutting force.

(ii) A very significant effect of feed was found on cutting force, F_C. Nearly a 150% increase was recorded for 10 deg. tool when the feed was increased from .003 to .012 i.p.r. The force was

Fig. 40. Relations between the cutting force and feed.

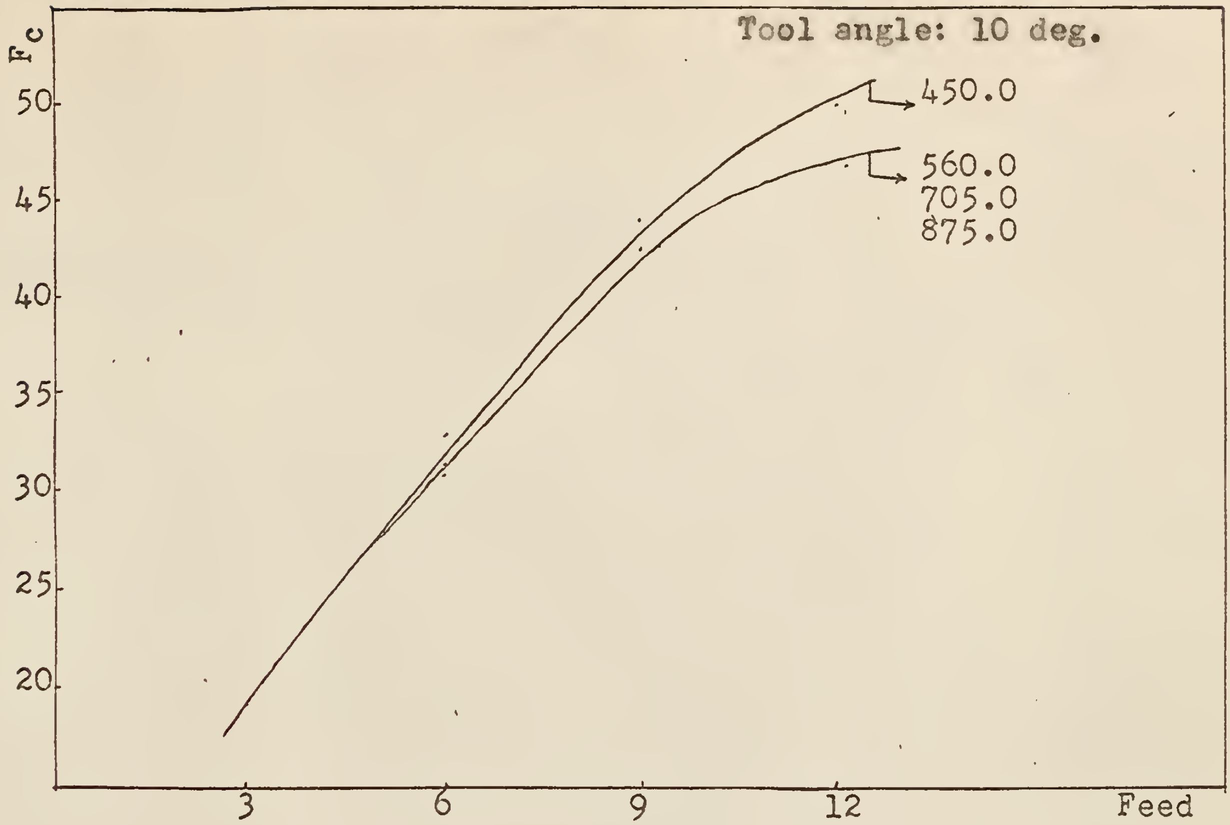


Fig. 41. Relations between the feeding force and feed.

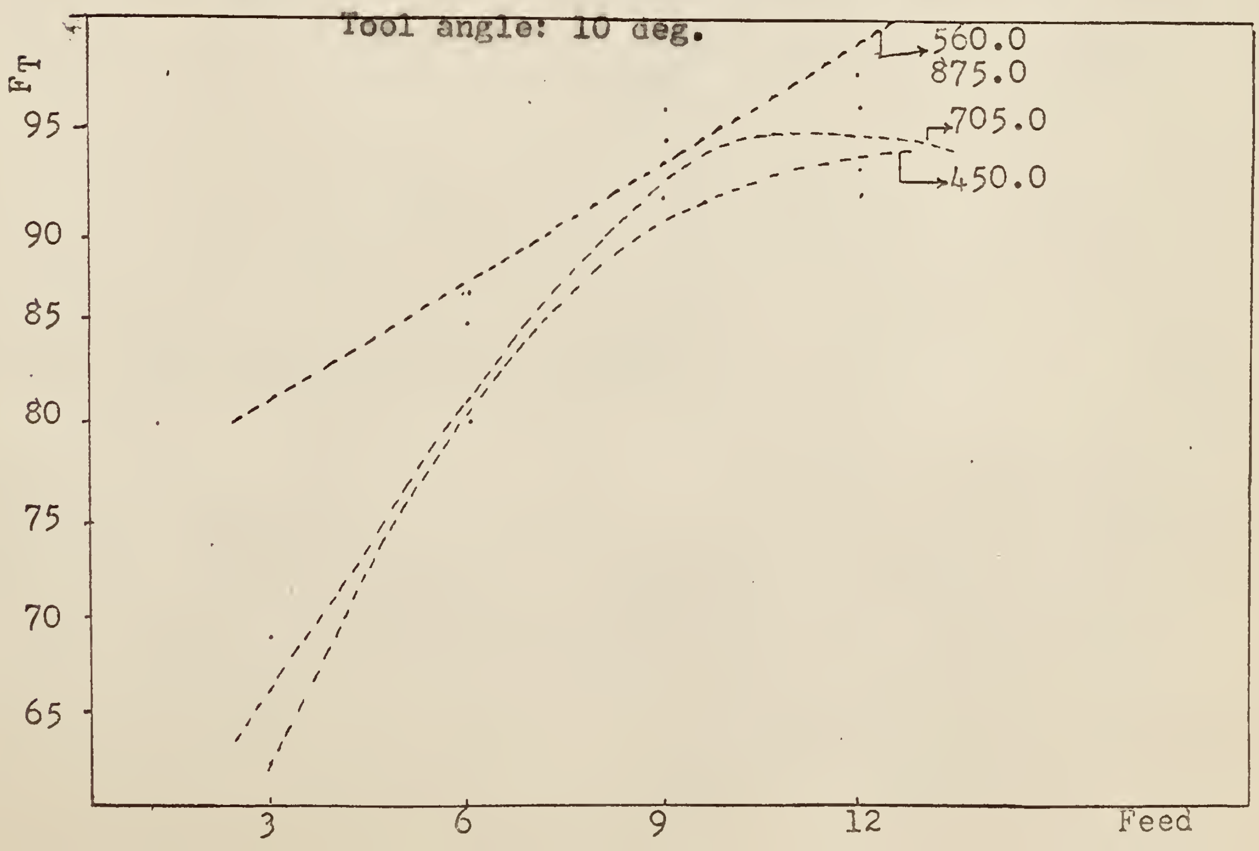


Fig. 42. Relations between the cutting force and feed.

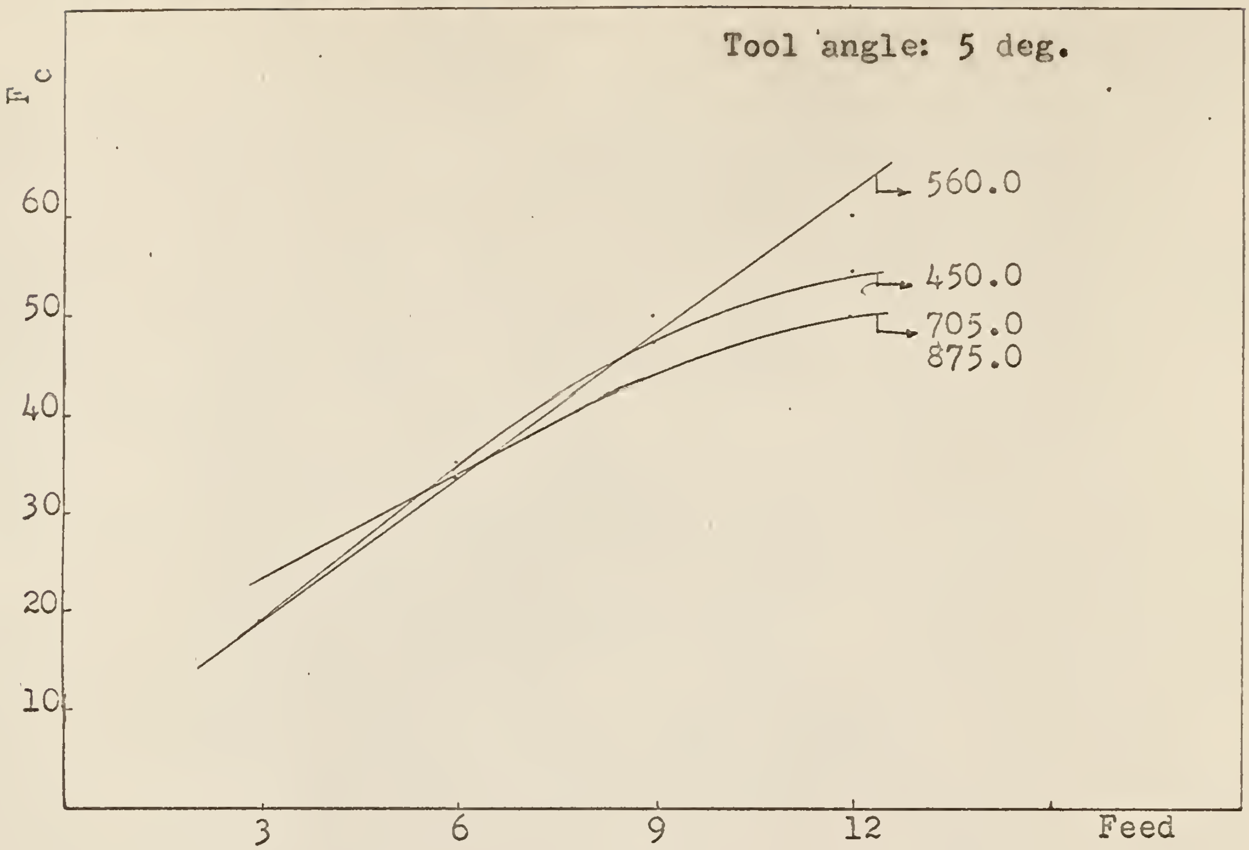


Fig. 43. Relations between the feeding force and feed.

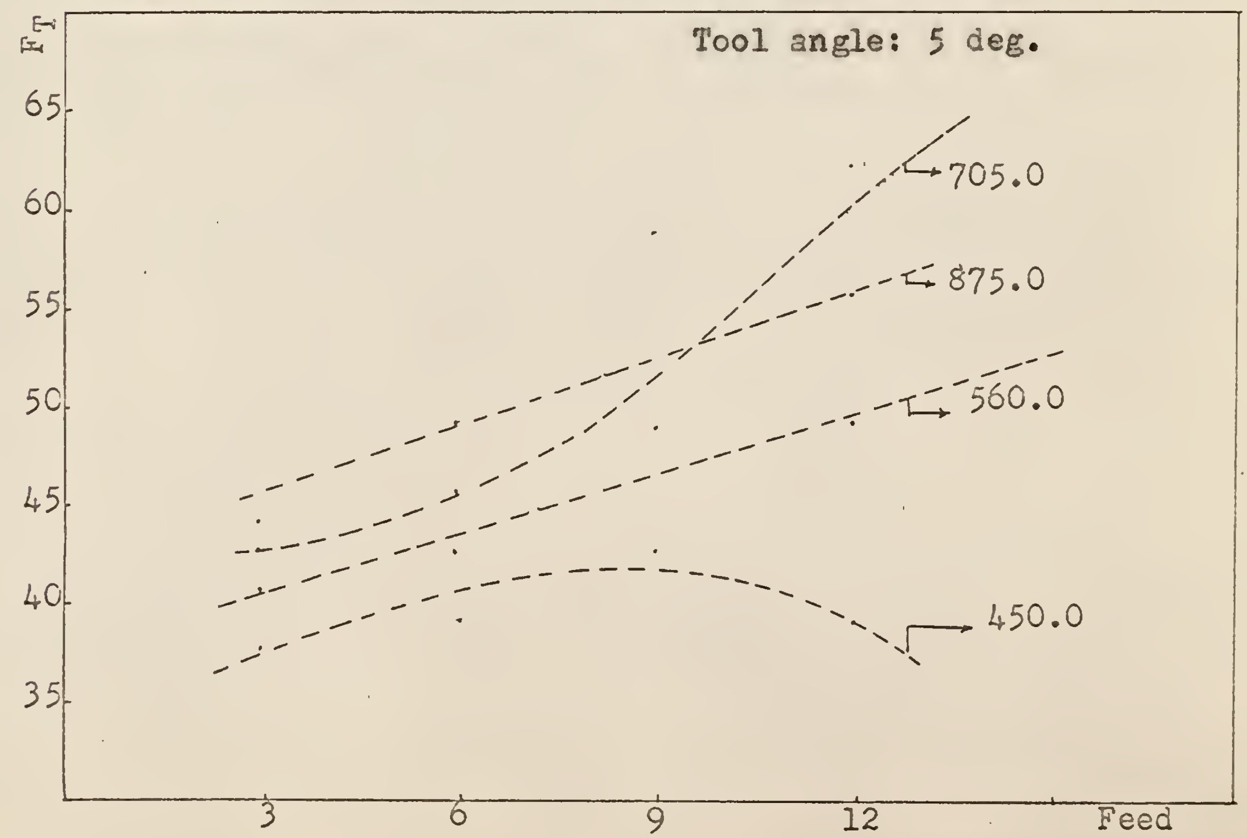


Fig. 44. Relations between the cutting force and feed.

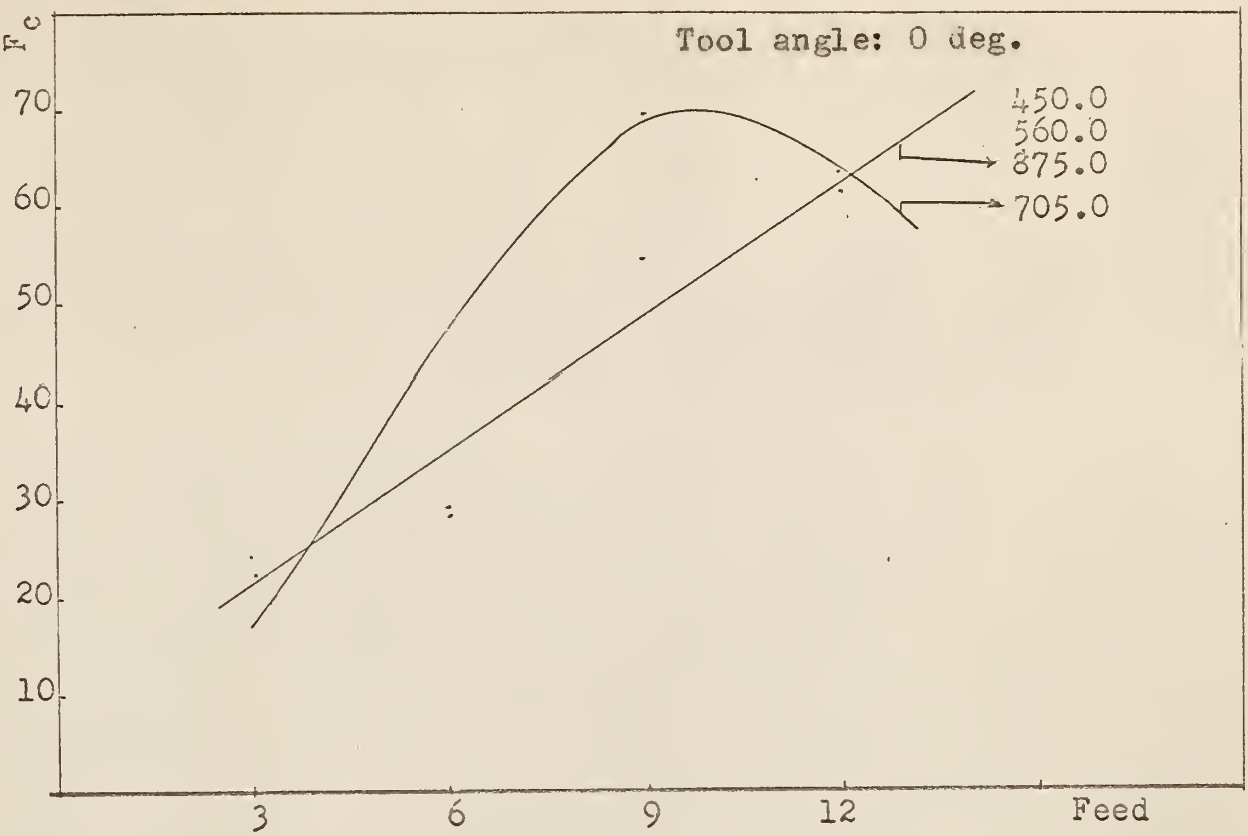


Fig. 45. Relations between the feeding force and feed.

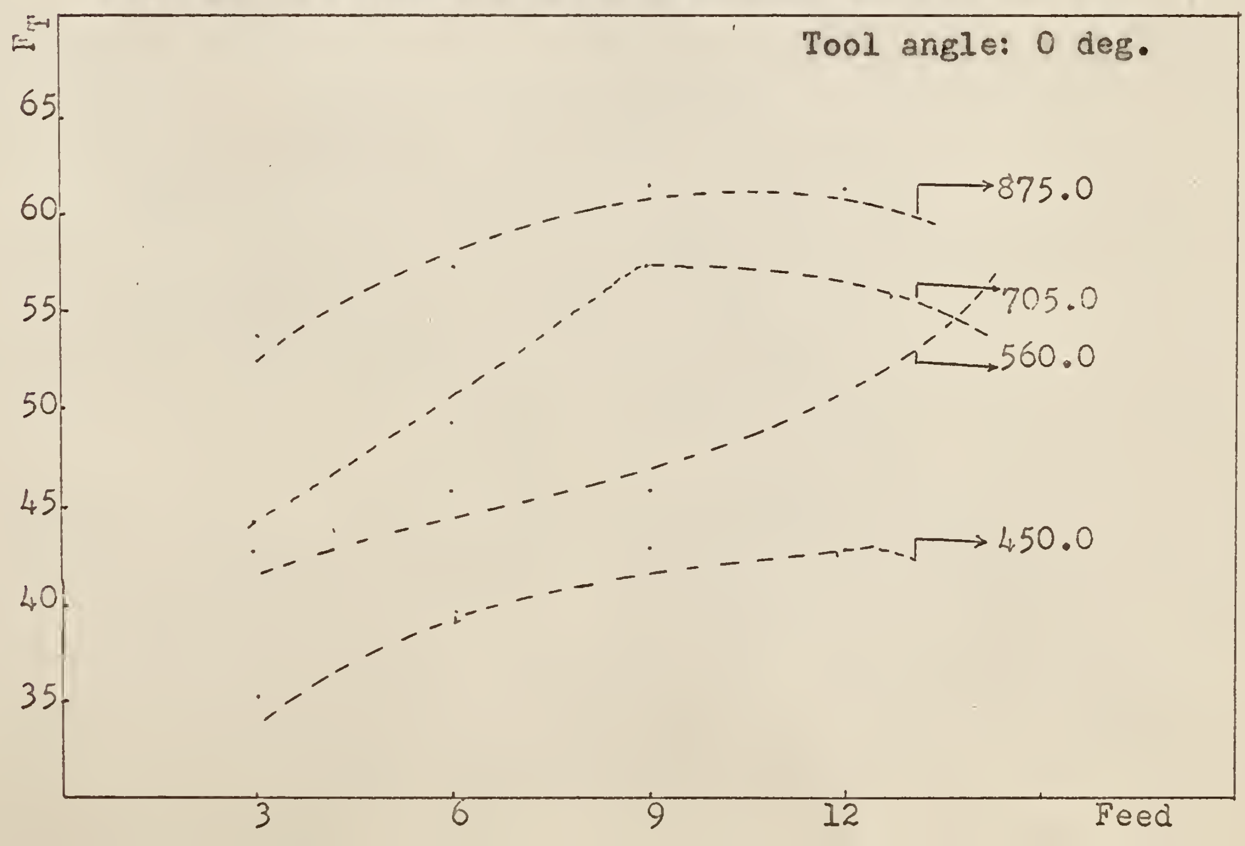


Fig. 46. Relations between the cutting force and feed.

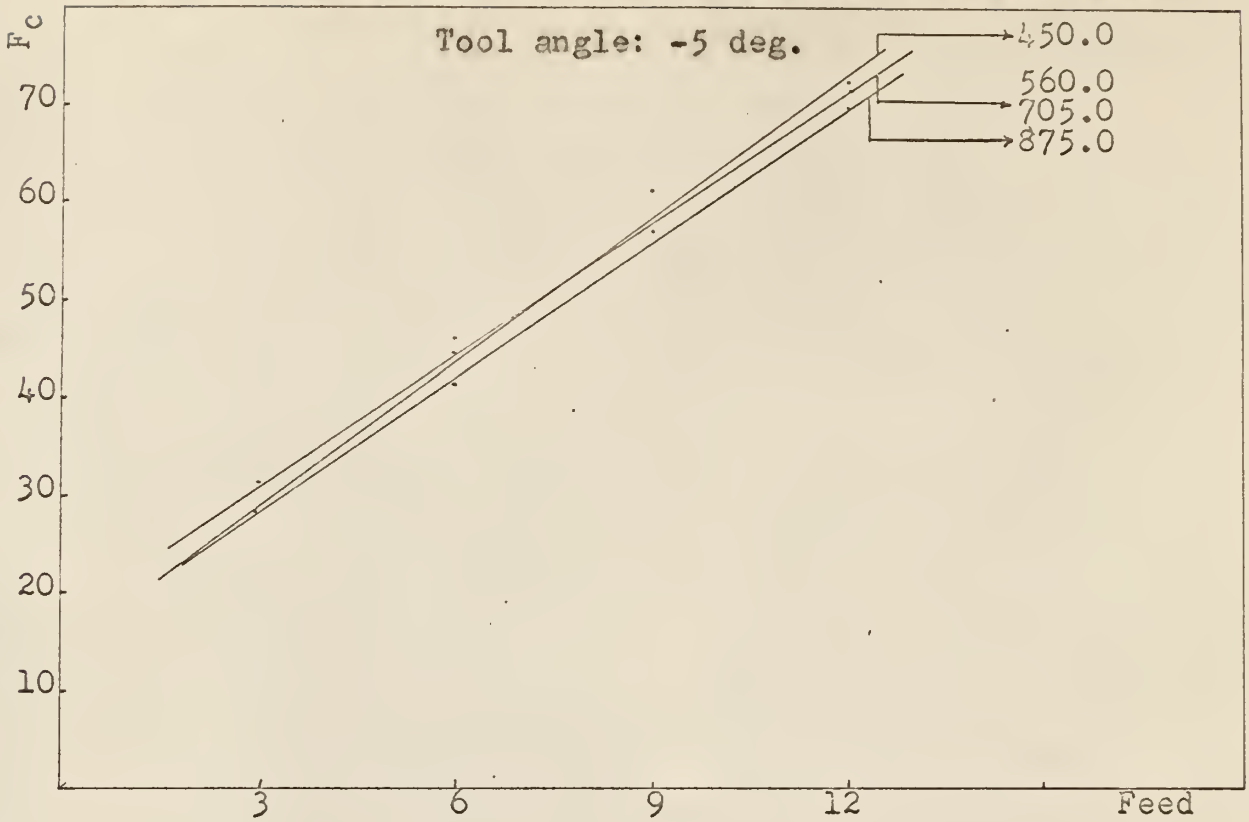


Fig. 47. Relations between the feeding force and feed.

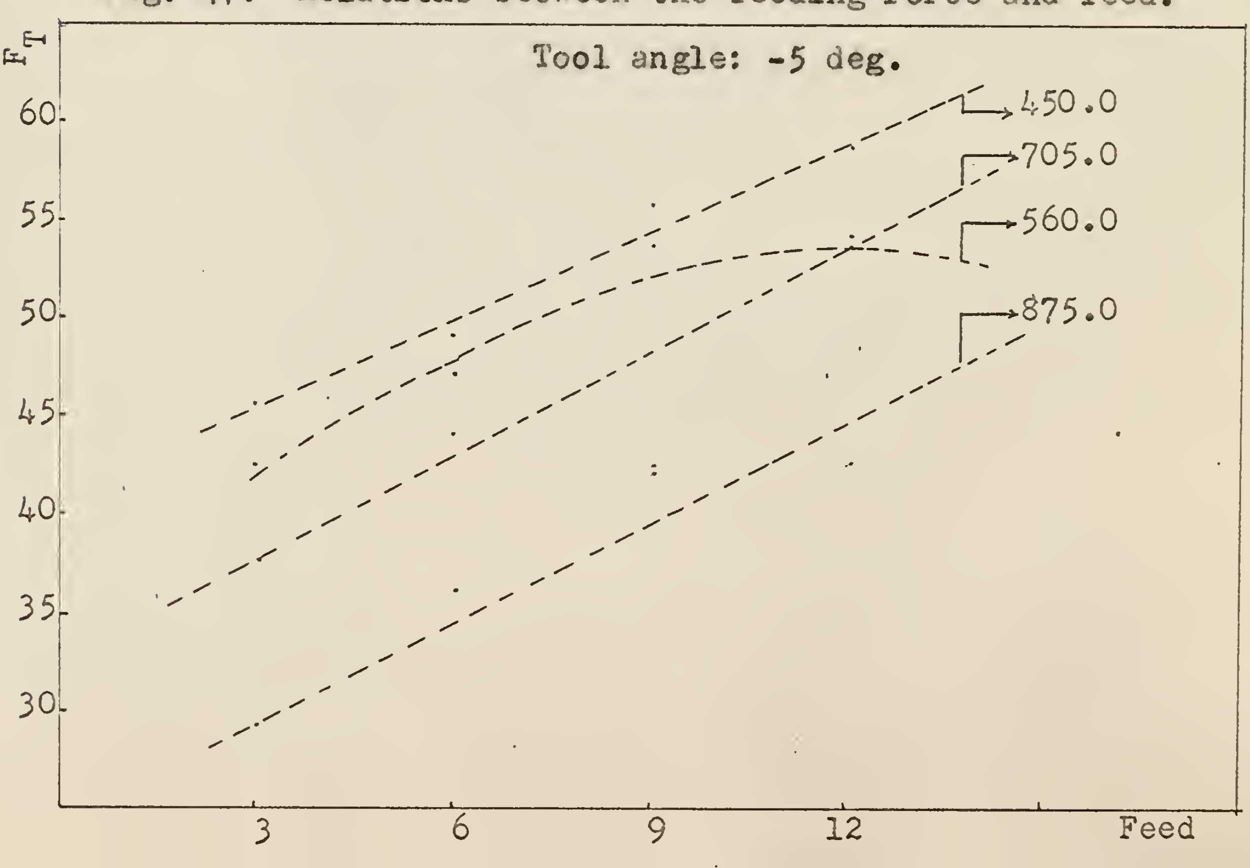


Fig. 48. Relations between the cutting force and feed.

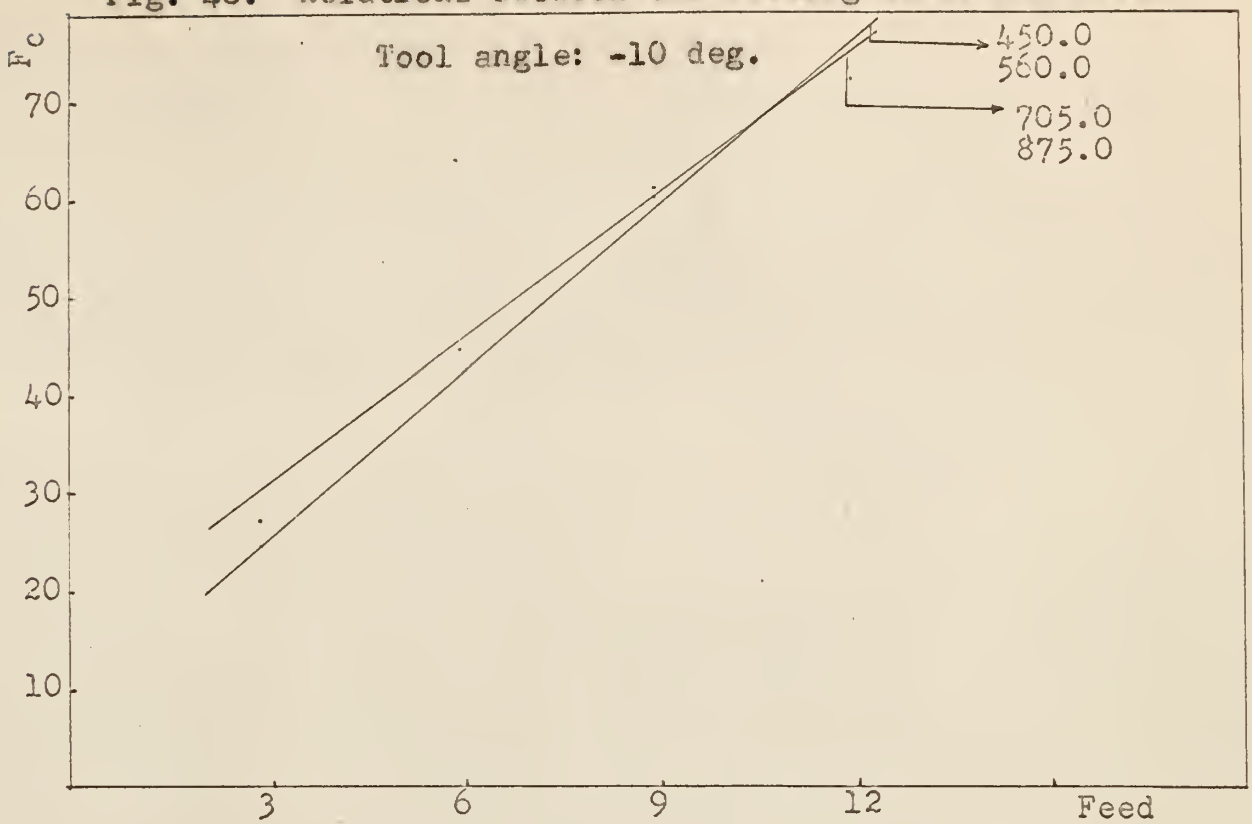
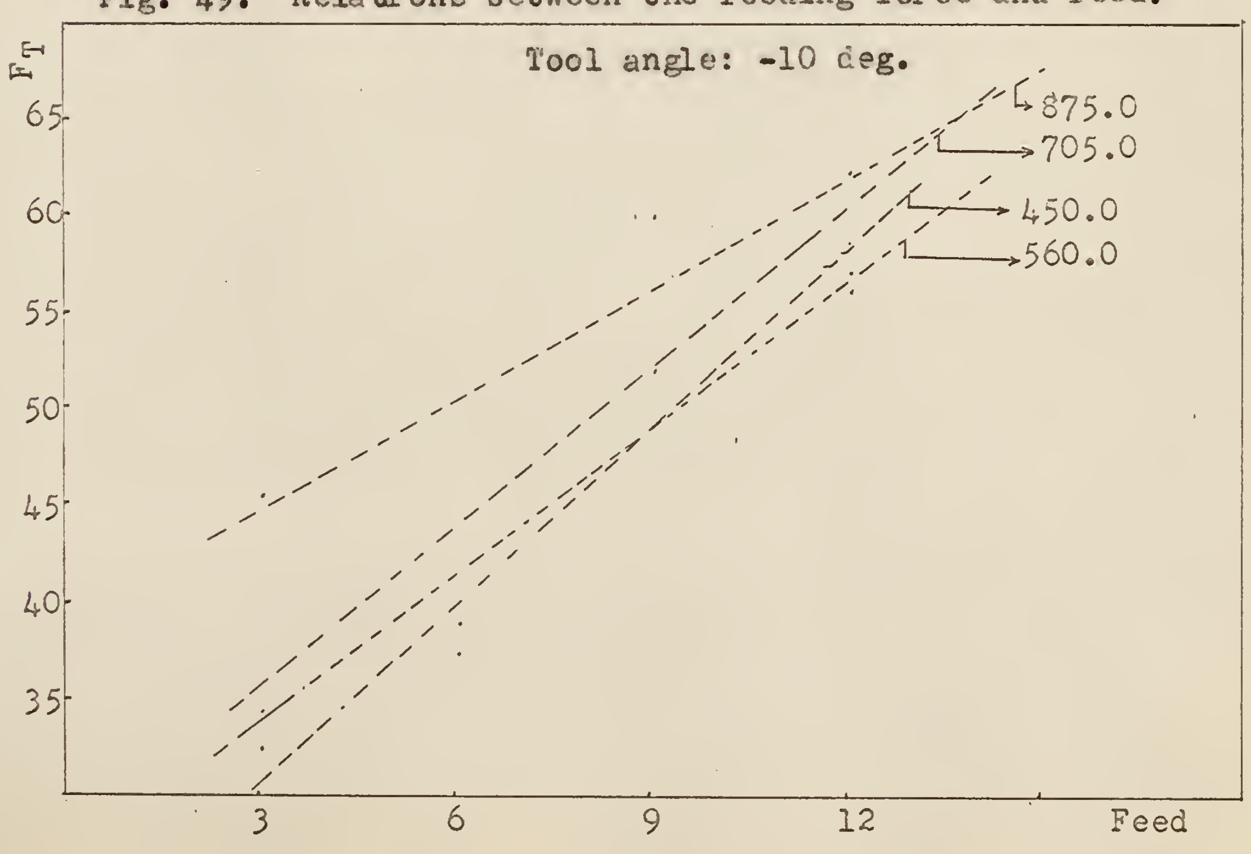


Fig. 49. Relations between the feeding force and feed.



a little over twice in case of 5 deg. tool, while 1.5 increase was found in case of 0, -5, and -10 deg. tool.

(iii) The second major factor, after feed affecting the cutting force, was tool rake angle. Decreasing the tool rake angle caused an increase in the cutting force. This increase was more profound at higher speeds and feeds. Nearly a 50% increase was noted when decreasing the rake angle from 10 to -10 deg. at 875.0 f.p.m. and .012 i.p.r. There seemed to be a linear relationship with the rake angle.

b. Feeding Force, F_T:

From the tables and graphs some very important points were noticed:

(i) There was some change in feeding force when the cutting speed was changed. The trend was not the same in all cases. The following small table shows this change at various conditions:

Table 14. Variations in feeding force.

Rake angle	Speed change	Feed	Change in force
10 deg.	450.0 to 875.0	.003	30%
5 "	"	.012	40%
0 "	"	.003	50%
0 "	"	.012	50%
- 5 "	"	all	-25 to -30%
-10 "	"	all	increasing

Fig. 50. Relations between the cutting force and the rake angle of a tool.

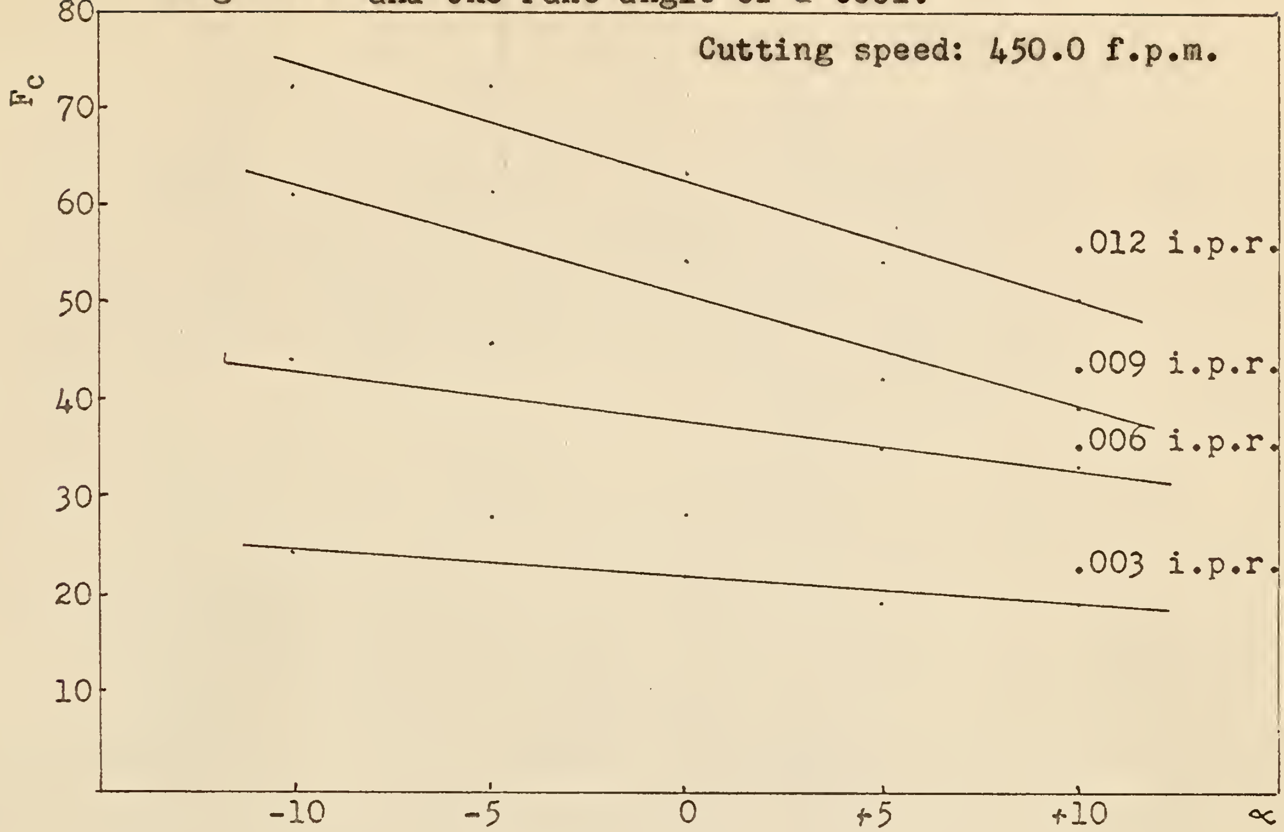


Fig. 51. Relations between the cutting force and the rake angle of a tool.

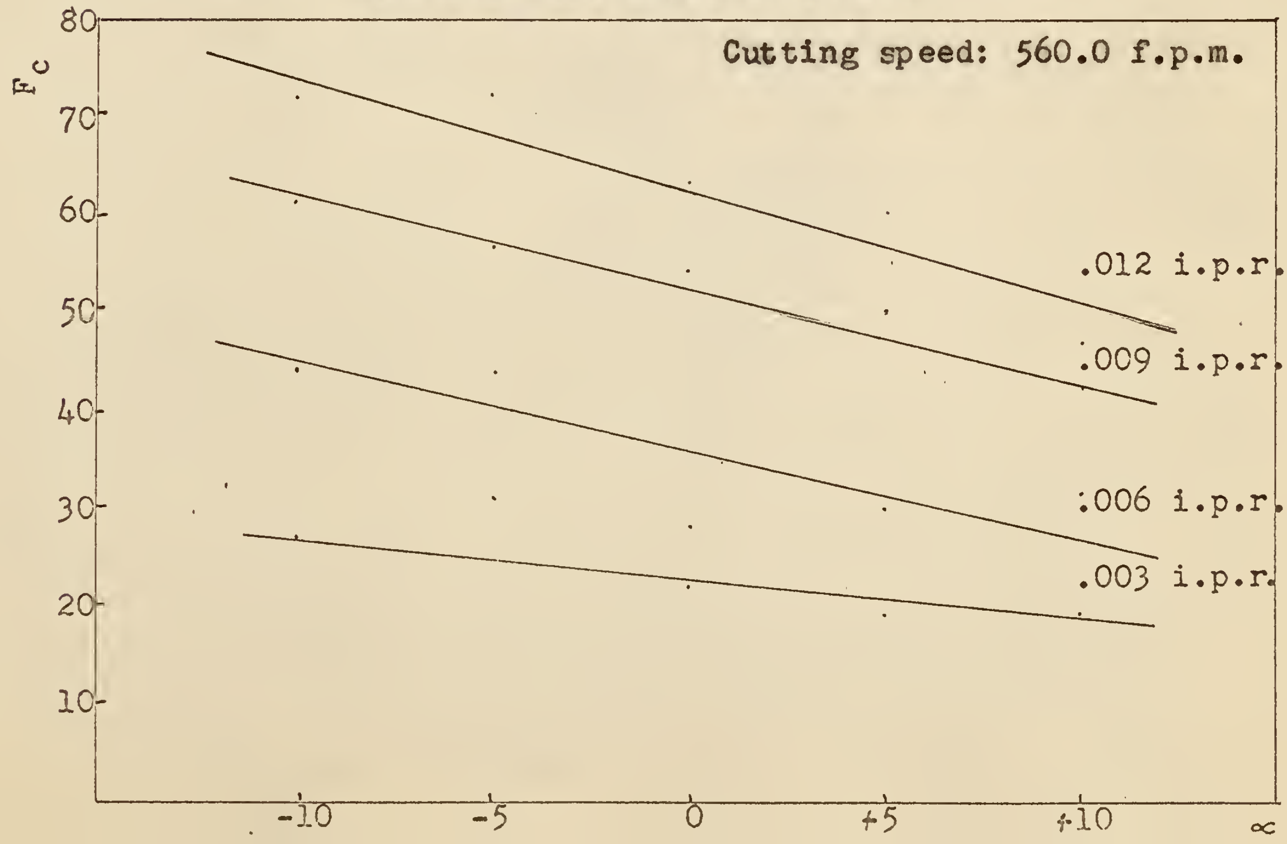


Fig. 52. Relations between the cutting force and the rake angle of a tool.

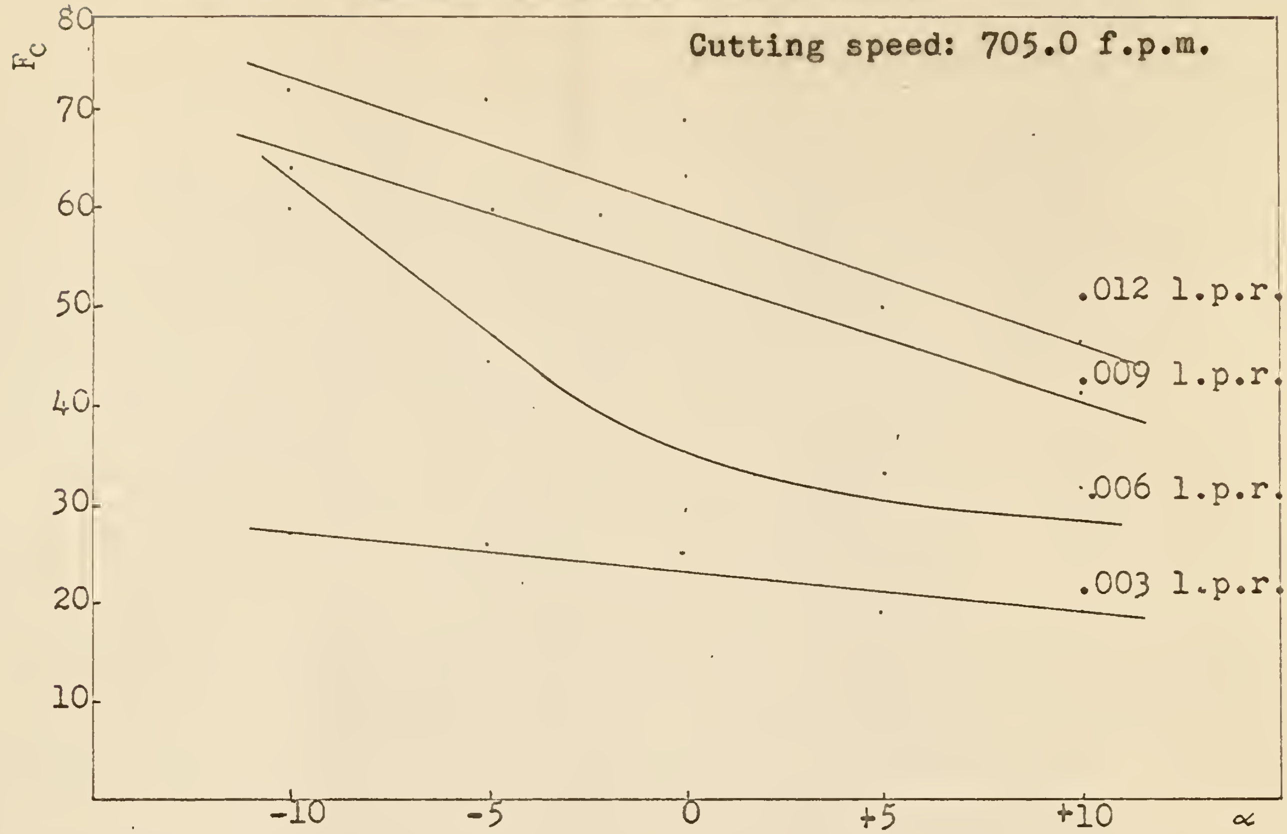


Fig. 53. Relations between the cutting force and the rake angle of a tool.

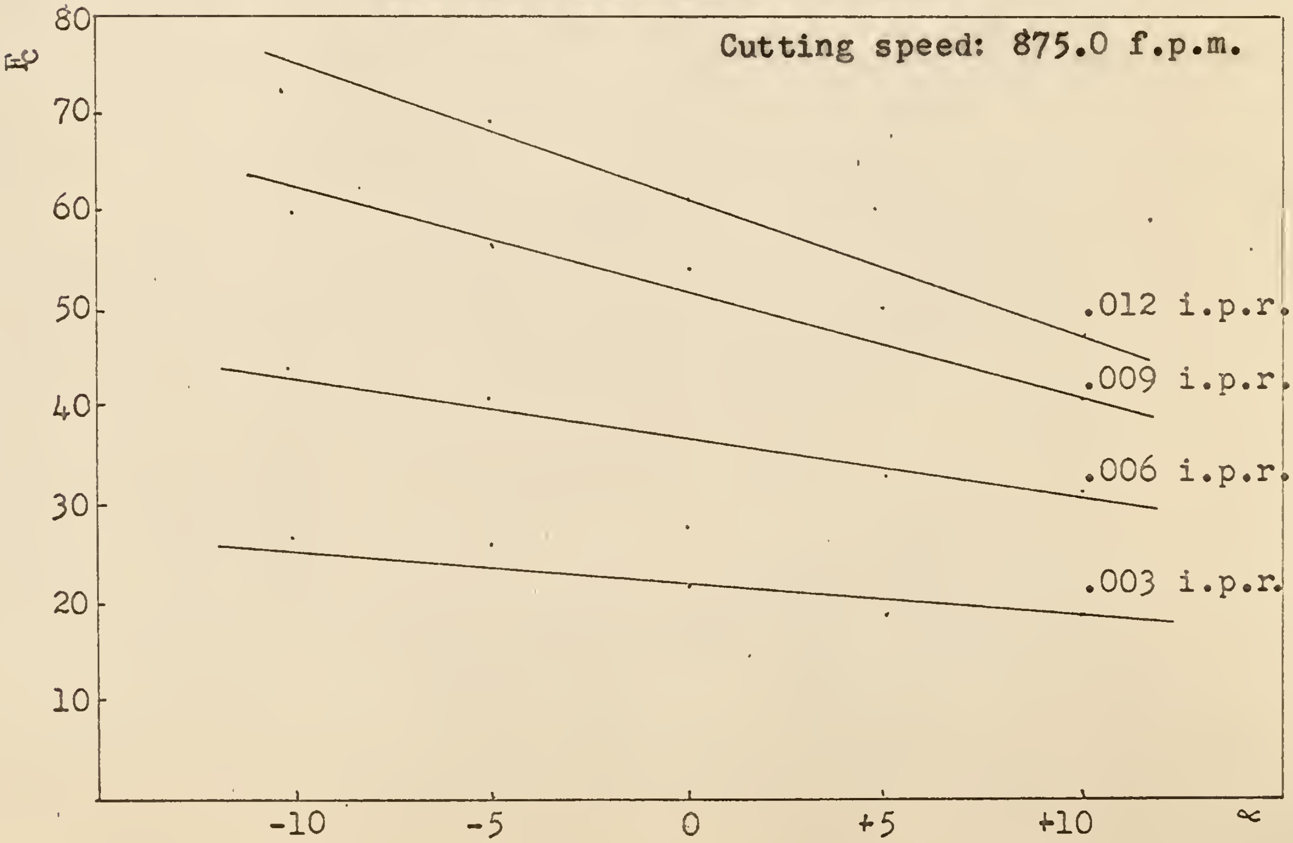


Table 13. Effect of tool angle on feeding force.

Speed	Angle	Feed .003 F_T	.006 F_T	.009 F_T	.012 F_T
450.0	+10	62	81.0	91.0	91.0
	+ 5	37.5	39.0	42.5	39.0
	0	35	39.0	42.5	42.5
	- 5	45.5	49.0	55.5	58.5
	-10	32.5	37.5	52.0	56.0
560.0	+10	81	86.0	95.5	97.5
	+ 5	40.5	42.5	49.0	49.0
	0	42.5	45.5	45.5	52.0
	- 5	42.5	47.0	53.5	53.5
	-10	34.5	39.0	52.0	57.0
705.0	+10	68.5	79.5	94.0	92.5
	+ 5	42.5	45.5	49.0	62.0
	0	44.0	49.0	57.0	55.5
	- 5	37.5	44.0	42.0	54.0
	-10	36.0	42.5	56.0	58.5
875.0	+10	81.0	84.5	95.5	95.5
	+ 5	44.0	49.0	58.5	55.5
	0	53.5	57.0	61.0	66.0
	- 5	29.0	36.0	42.5	42.5
	-10	45.5	37.0	60.0	62.5

Work material: Dilecto XX-79
Tool material: Rex-95 H.S.S.
Condition: Orthogonal
Work diameter: 6¼ in O.D.
Wall thickness: 3/8 in.
Cutting: Dry

From the above table it was seen that there was an increase in the force at all tool rake angles except neg. 5 deg.

(ii) The feed seemed to have a very significant effect on feeding forces. Higher values of the forces for positive angles were supported by the tool temperature.

(iii) The effect of tool angles was noticed to be random. To make simple, a special table was constructed (Table 13) on page 85. There was no particular trend which could define clearly the effect of tool rake angle on feeding force. In general, there was a decrease in the force with decreasing tool rake. This was not the situation with the other two materials.

c. Resultant Cutting Force, R:

The direction and magnitude of the resultant cutting forces are shown on pp. 87-94.

(i) Very high values of resultant forces were recorded at higher speeds and feeds for -10 deg. tool rake angle.

(ii) There was quite a variation in the magnitude of forces with an increase in speed. A clearer picture can be seen from the following table:

Fig. 54. Magnitude and direction of Resultant cutting force, R.

Work material: Dilecto xx-79

Tool material: Rex-95 H.S.S.

Speed: 450.0 f.p.m.

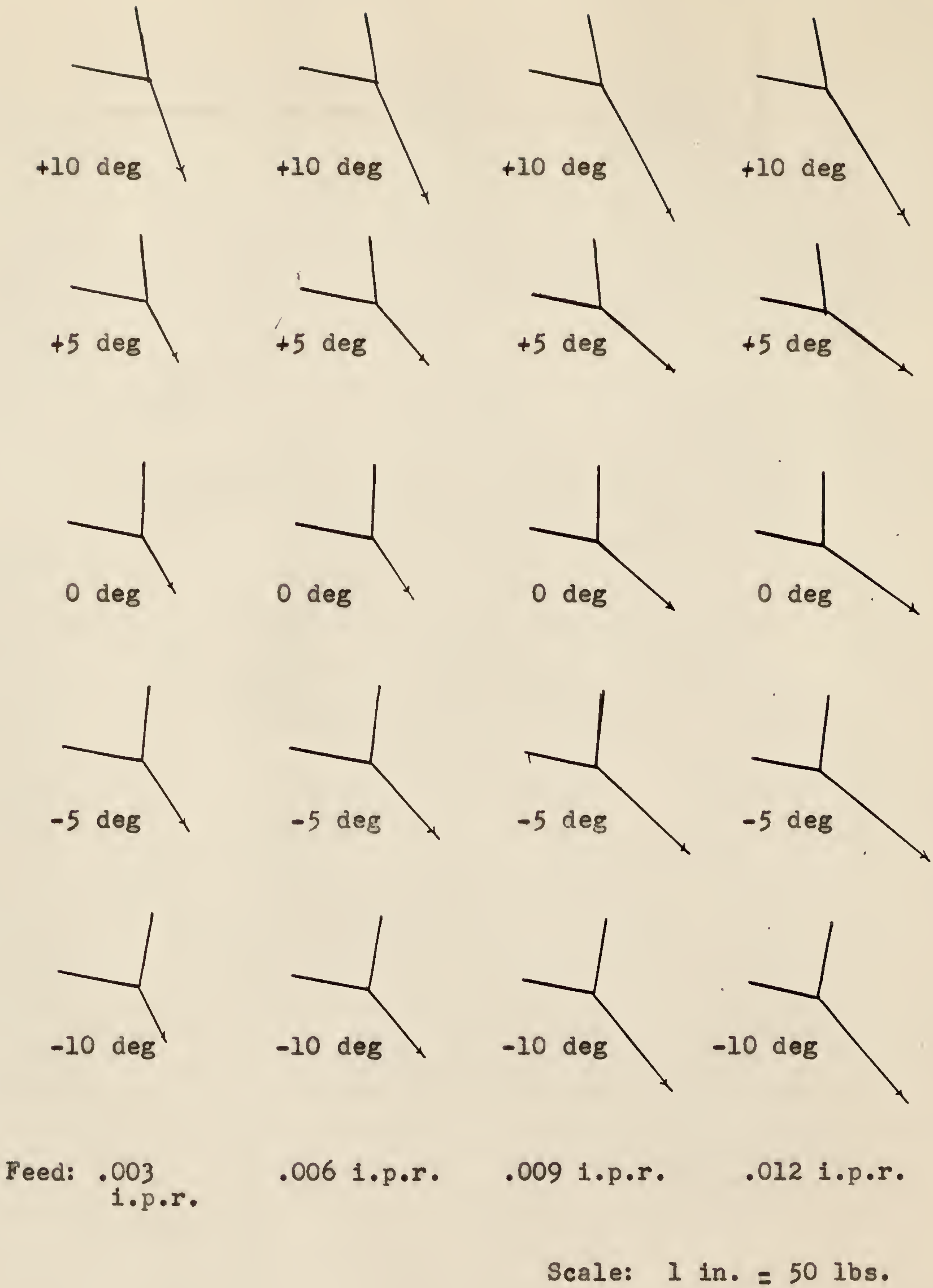
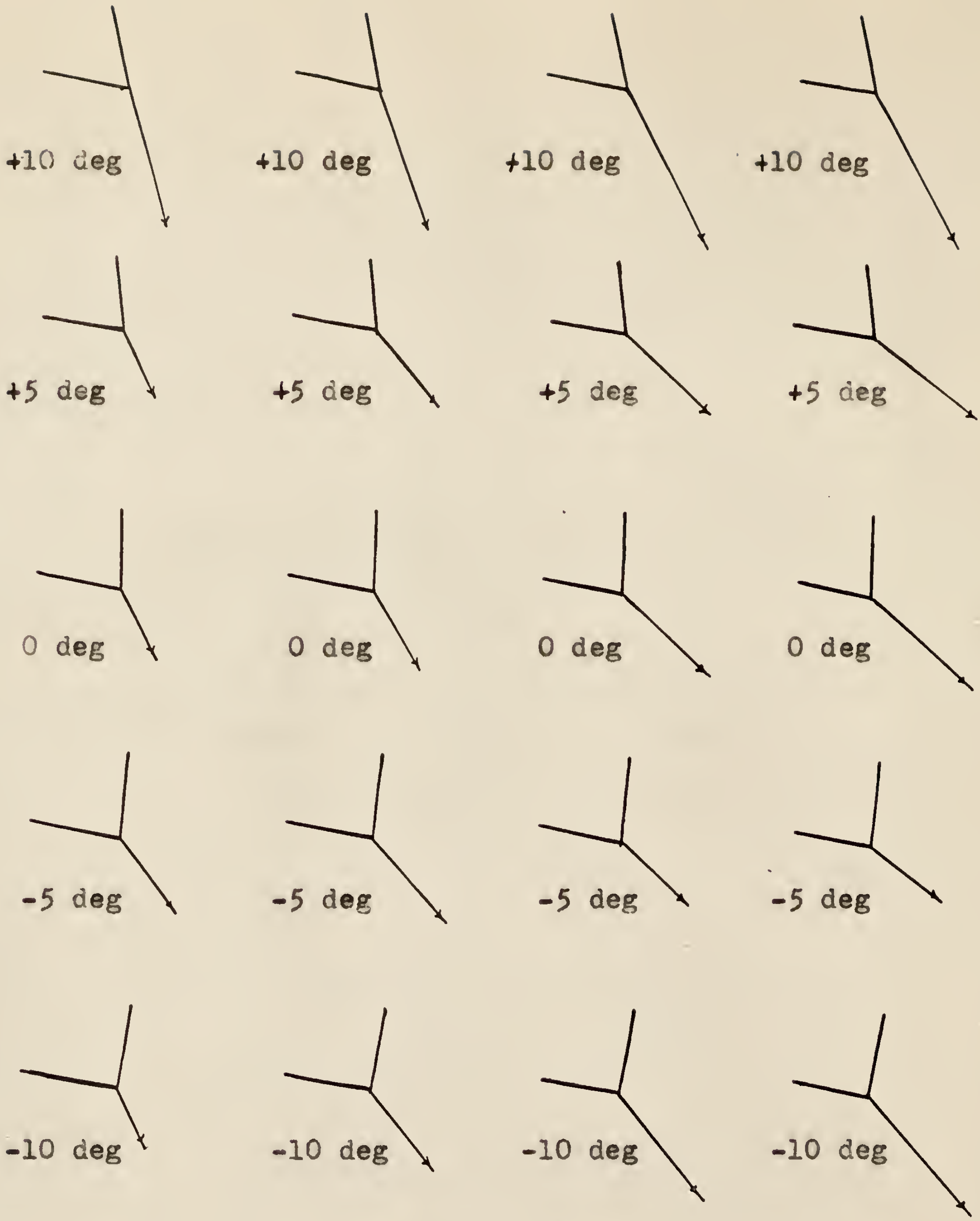

+10 deg
+10 deg
+10 deg
+10 deg
+5 deg
+5 deg
+5 deg
+5 deg
0 deg
0 deg
0 deg
0 deg
-5 deg
-5 deg
-5 deg
-5 deg
-10 deg
-10 deg
-10 deg
-10 deg
Feed: .003 i.p.r.
.006 i.p.r.
.009 i.p.r.
.012 i.p.r.
Scale: 1 in. = 50 lbs.

Fig. 55. Magnitude and direction of Resultant cutting force, R.

Work material: Dilecto xx-79

Tool material: Rex-95 H.S.S.

Speed: 560.0 f.p.m.

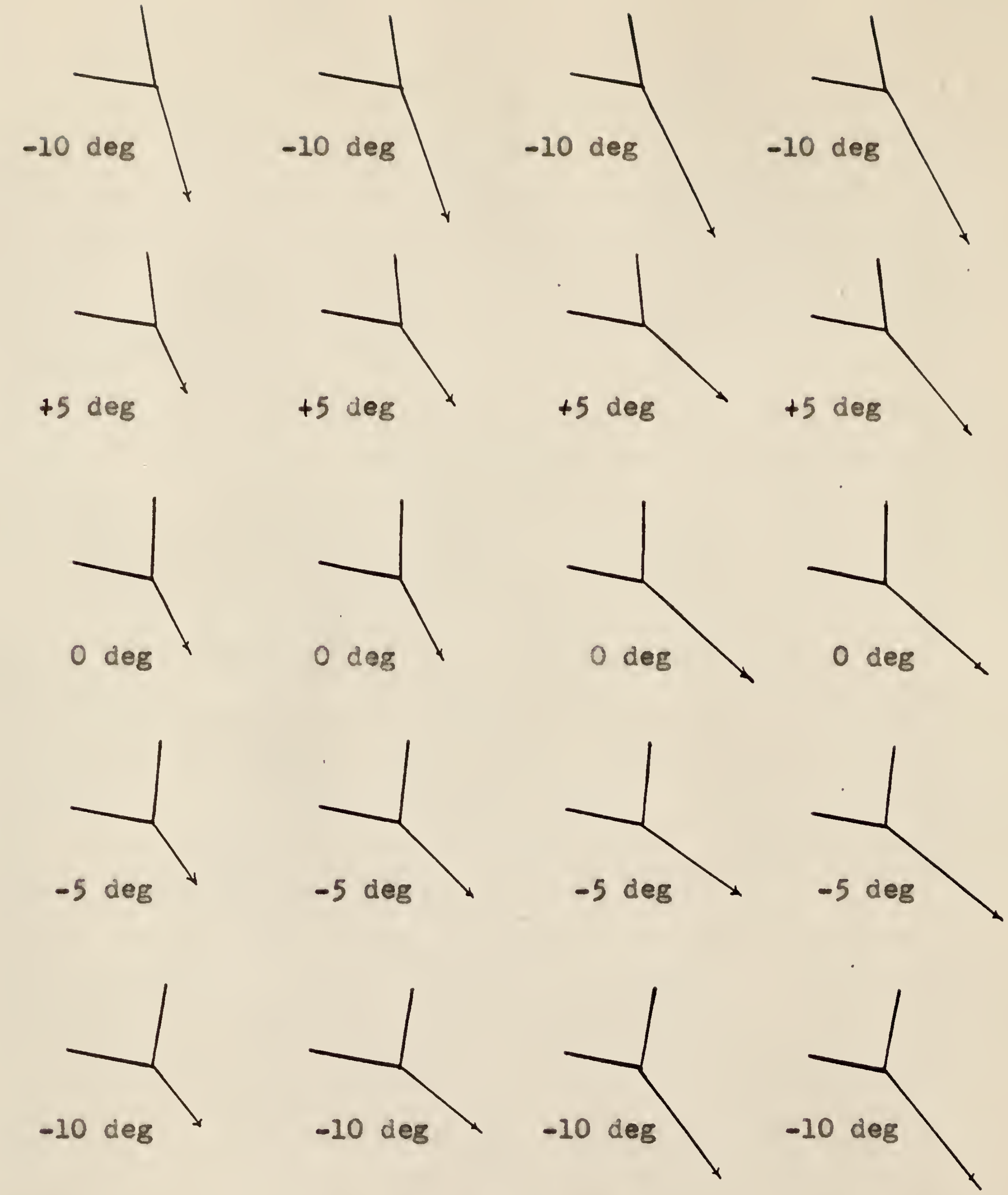


Feed: .003 i.p.r. .006 i.p.r. .009 i.p.r. .012 i.p.r.

Scale: 1 in. = 50 lbs.

Fig. 56. Magnitude and direction of Resultant cutting force, R.

Work material:	Dilecto XX - 79
Tool material:	Rex - 95 H.S.S.
Speed:	705.0 f.p.m.



Feed: .003 i.p.r. .006 i.p.r. .009 i.p.r. .012 i.p.r.

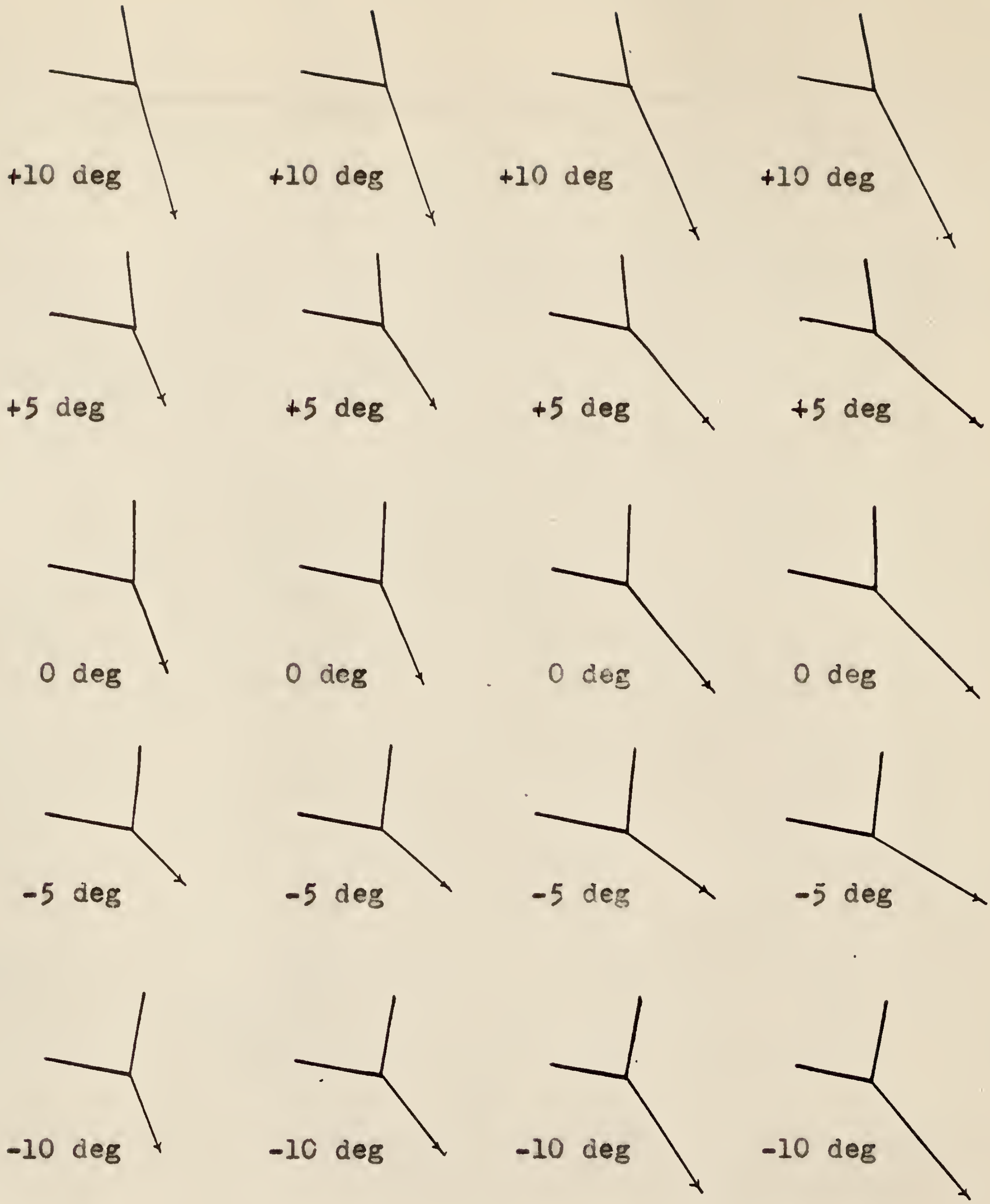
Scale: 1 in. = 50 lbs.

Fig. 57. Magnitude and direction of Resultant cutting force, R.

Work material: Dilecto xx-79

Tool material: Rex-95 H.S.S.

Speed: 875.0 f.p.m.



Feed: .003 i.p.r. .006 i.p.r. .009 i.p.r. .012 i.p.r.

Scale: 1 in. = 50 lbs.

Table 15. Variations in resultant force.

Tool angle	Speed change	Feed	Change in force
10	450.0 to 875.0	.003	28%
5	"	.012	23%
0	"	.003	40%
- 5	"	.003	-26%
-10	"	.003	32%

The increase was most noticeable at lower feeds. The direction remained almost constant with a change in speed.

(iii) The feed rate affected the magnitude and the direction of the force. With an increase in feed the magnitude was increased and the direction was decreased. This increase in magnitude was greater at lower speeds.

(iv) The tool rake angles have more effect on the magnitude of the resultant cutting force, R. With the decrease in the tool angle there was a decrease in the force. This decrease was more at lower speeds. There was not much change in the direction of the force.

Tool-Wear Study

In machining, the tool life is a very important factor in determining economy of production. Certain plastics have more abrasive characteristics. For example, with TFE resins tool wear becomes a necessary criterion in deciding the optimum conditions. From the preliminary study it was found necessary to carry out a brief tool-wear study. The usual method to study tool-wear is to measure the wear under the microscope. The microscopic procedure was tried but was not feasible for several reasons.

On a worn tool, the cutting force is increased. So it was decided to machine the material with the same tool, speed, and feed, and note the forces at each 30-second interval. There were some difficulties in machining continuously. One was the straightness of the pipe which caused chatter at higher speeds. This was eliminated partially by machining at lower feeds and speeds. The second major problem was chip removal. The chip formed was soft and ribbon type and interfered with continuous machining. However, with some outside help this was almost eliminated. The speed and feed were 254 sfpm and .003 i.p.r. The tool was first ground to 5 deg. rake angle and then was honed to give a more accurate and sharp cutting edge.

The results are given in Table 12. The total time for machining was 40 minutes. The total material removed was 83.7 cu. in. From the table it can be seen that there was little change in the cutting force, F_C. It remained practically constant throughout the machining period, while there was a continuous increase in the feeding force. Nearly 6.75 increase in the force was found during the entire period. This showed a considerable increase in the resultant cutting force.

This study gives a clear picture for further study in a more scientific way for the tool-wear study in machining some plastics, particularly a filler type.

Table 12. Tool-wear Study.

Time T min.	F_C	F_T	Time T min.	F_C	F_T	Time T min.	F_C	F_T
0.5	15	2	14.0	14	8.0	27.0	14.5	12.5
1.0	16	2.75	14.5	14	9.25	27.5	14.5	13.0
1.5	16	3.5	15.0	14	10.0	28.0	14.5	13.0
2.0	16	3.5	15.5	15	9.25	28.5	14.5	13.0
2.5	16	3.5	16.0	15	9.25	29.0	15.0	13.0
3.0	16	3.5	16.5	15	10.0	29.5	15.0	13.0
3.5	17	5.0	17.0	15	10.0	30.0	16.0	11.5
4.0	17	5.0	17.5	15	10.0	30.5	16.0	11.5
4.5	17	5.0	18.0	15	10.0	31.0	16.0	12.5
5.0	16	7.0	18.5	15	10.0	31.5	15.0	13.0
5.5	17.5	7.0	19.0	15	10.0	32.0	15.0	13.0
6.0	17.5	7.0	19.5	15	10.0	32.5	15.0	13.0
6.5	17.5	7.0	20.0	14.5	10.0	33.0	15.0	13.0
7.0	17.5	7.0	20.5	14.5	7.5	33.5	16.0	13.0
7.5	16	7.0	21.0	14.5	7.5	34.0	16.0	13.0
8.0	16	7.0	21.5	14.5	7.5	34.5	16.0	13.0
8.5	16	7.0	22.0	14.5	8.0	35.0	16.0	13.0
9.0	16	7.0	22.5	15	8.0	35.5	16.0	13.0
9.5	13	7.0	23.0	15	10.0	36.0	16.0	14.0
10.0	13	7.0	23.5	16	10.0	36.5	16.0	14.5
10.5	13	7.0	24.0	16	10.0	37.0	16.0	14.5
11.0	13	7.0	24.5	16	10.0	37.5	16.0	14.5
11.5	13	7.0	25.0	16	10.0	38.0	16.0	14.5
12.0	13	7.5	25.5	14.5	11.5	38.5	16.0	15.0
12.5	13	7.5	26.0	14.5	11.5	39.0	16.0	15.5
13.0	14	8.0	26.5	14.5	12.5	39.5	16.0	15.5
13.5	14	8.0				40.0	16.0	15.5

Work material: Cycolac LL
Tool material: Rex-95 H.S.S.
Tool angle: +5° B.R.
Work diameter: 3½ in OD
Wall thickness: ¼ in.
Cutting speed: 254.0 f.p.m.
Feed: .003 i.p.r.
Condition: Orthogonal
Cutting: Dry
F_C: Cutting force, lb.
F_T: Thrust force, lb.

CONCLUSIONS

The machining of plastics was studied in order to find optimum machining conditions. An orthogonal cutting condition was adopted to measure tool-bit forces at various speeds, feeds, and tool rake angles. A brief tool wear study was carried out. The materials used were PVC with GEON VINYL, CYCOLAC LL ABS PLASTIC, FORMICA Grade CN (Fabric Base), and DILECTO XX - 79.

The conclusions drawn from the study are:

(1) Due to wide varieties and great usage of plastics, there seems to be a need to study the basic mechanics of machining plastics. Study of chip formation, strain phenomena during cutting, and various factors affecting the tool forces such as speed, feed, tool geometry, and depth of cut, will help to work with plastics.

(2) In all three materials used for tool-bit force measurements, feed and tool rake angle were the main factors. Increasing feed and decreasing tool rake angle gave higher values of cutting forces.

(3) Cutting speed did not have an appreciable effect on forces. Lower feeds, higher tool rake angles, and higher cutting speeds would give an optimum condition.

(4) There is an appreciable amount of tool wear when machining plastics. Microscopic tool wear studies were made, but more study should be made to find a better method for determining tool wear.

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STUDY OF EFFECT OF SPEED, FEED, AND TOOL RAKE ANGLE IN MACHINING PLASTICS

by

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The purpose of this thesis was to study the effect of some machining variables on tool-bit forces while machining plastics, and thereby establish optimum machining conditions. A need to machine plastic is found in industries due to its wide usage. They are found in all kinds of mechanical, electrical, and chemical applications, from microminiature bearings and insulators to structural parts of rockets and missiles. Since the cutting conditions are mainly based on the shop worker's past experience, these are not necessarily economical and reasonable. For cutting plastics under optimum conditions the characteristics and peculiarities of cutting phenomena in plastics needed to be investigated.

The machining variables were cutting speed, feed, and tool rake angle. Tool-bit forces were measured with the help of a lathe dynamometer. The dynamometer was designed to measure three forces acting on the tool, but an amplifier had the facility to record only two forces. Due to this an orthogonal cutting condition was adopted, and only the cutting force, F_C, and the feeding force, F_T, were recorded. For tool-bit force measurements, three different kinds of plastic materials were used: (1) PVC with GEON VINYL, (2) FORMICA Grade CN, and (3) DILECTO XX-79. A brief tool-wear study was also carried out while machining CYCOLAC, LL - ABS plastic.

By comparing and combining the experimental conclusions of the project, certain general conclusions were drawn as follows:

1. Cutting speed did not have much effect on tool-bit forces. Very high speeds could be used without affecting the forces on the

tool. Frictional conditions were also unaffected by the cutting speeds.

2. Feeds and tool rake angles were the main variables affecting the tool forces. Forces were found to have a linear relationship with feeds and tool rake angles.

The increase in cutting force, F_C, ranged from five to six times for PVC with GEON VINYL plastic, when feed was increased from .003 to .018 ipr. While in case of DILECTO XX-79 plastic, the increase in F_C was about 150% when the feed was increased from .003 to .012 ipr. Negative feeding forces were observed when machining PVC with GEON VINYL plastic. Critical rake angle seemed to lie between 5 and 10 degrees. The coefficient of friction measured for PVC with GEON VINYL plastic decreased with increasing feeds and finally approached a constant at higher feeds.

By decreasing tool rake angles, the cutting forces were increased. The effect was more evident at higher speeds and feeds. In all cases tool rake angle was the second major factor to affect the tool forces.

In a more generalized statement it could be said that plastics are machined more efficiently at higher speeds, lower feeds, and high positive tool rake angles (back rake angle in practice). The writer feels that studies should be carried out to study the effect of tool rake angles more than 10 deg. positive and going up to 40 deg. positive.

3. There seemed to be an appreciable amount of tool-wear when machining plastics. When ABS plastic was machined at 254

fpm speed and .003 ipr feed, the feeding force increased nearly seven times after machining 83.7 cu. in. of material (or 40 min.). There were some difficulties in machining continuously and thus measuring the forces continuously. The writer feels that more tool-wear studies on other plastics should be carried out in order to establish tool-life equations.