THE UNIVERSITY OF MICHIGAN

COLLEGE OF ENGINEERING
Department of Mechanical Engineering

Final Report

GENERAL MACHINABILITY STUDIES ON THREE GRADES OF STAINLESS STEEL

Part I

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ABSTRACT

The comparative tests conducted in this program indicated that differences in the level of cutting forces were influenced by the work material. Regardless of the type of cut, the standard grade of stainless steel (18-8) required the highest cutting forces; in most cases this difference was substantial.

There appears to be a rational correlation between tool life, tool wear, and cutting forces. The poorest tool life and highest forces were exhibited by the same material, whereas the material that required lowest forces also led to superior tool life.

OBJECTIVE

The purpose of this program was to analyze the machining behavior of three grades of stainless steel, one straight 18-8 grade and two modified grades. Comparisons were made of tool-wear characteristics and cutting force and energy requirements.

I. INTRODUCTION AND GENERAL CONCLUSIONS

Relative machinability of two or more materials can be determined by several methods. For the purposes of this study the magnitude of forces required to tap, drill, mill, and turn the work materials served as one basis of comparison. In addition, tool-life tests when turning with high-speed steel and sintered carbide tools provided a second basis of comparison. The general conclusions reached were:

1. Superior tool life resulted when turning the 18-8M material with either high-speed steel or sintered carbide tools.

2. Regardless of the type of cut, the 18-8M material required the lowest machining forces.

3. In most instances, the 18-8 material required the highest machining forces.

4. With few exceptions, the 18-8MA material was intermediate between the other materials regardless of the type of test conducted up to this point in the over-all program.

II. THE MATERIALS INVESTIGATED

The three grades of stainless steel were coded by the sponsor as 18-8, 18-8M, and 18-8MA. These symbols have been used throughout the entire program.

All turning tests were conducted on bars originally supplied in the form of rounds approximately two inches in diameter. Tapping specimens were made from stock supplied in the form of one-inch rounds while milling and drilling tests were performed on materials rolled into the form of one-inch squares.

III. DETAILED DESCRIPTION OF TEST PROGRAM

A. TOOL LIFE AND TOOL WEAR WHEN TURNING

A series of tool-life tests, using high-speed steel cutting tools, was conducted on each of the three work materials. In addition, tool-wear tests were run on each material using sintered carbide cutting tools.

1. Tool Life With High-Speed Steel Tools

Procedure.—Test bars were in the approximate form of two-inch rounds by two feet long. After completing a cleanup cut to remove the outside scale and to true the bar, an individual tool-life test was conducted. Such a test involves the operation of a cutting tool at a given size of cut and cutting velocity until complete tool failure results. The elapsed time from start of cut to the failure point is considered as the tool life. This procedure was continued at varying speed levels until enough data points were obtained to establish the relationship between cutting velocity and tool life.

At the conclusion of each test and prior to the use of a freshly ground tool for the subsequent test, a cleanup cut was taken at the shoulder of the bar where the previous failure had resulted. This eliminated any possible effects of work-hardening.

Test Conditions.—These tests were conducted without a cutting fluid on a 14-inch swing Monarch Engine Lathe equipped with a variable speed drive source. "Mo-Max" high-speed steel tools ground to an ASA signature of 0, 8, 6, 6, 6, 15, 1/32 were used for these tests. A depth of cut of 0.050 inch and feed rate of 0.0153 inches per revolution comprised the constant size of cut that was utilized.

Test Results.—Figure 1 shows the results plotted on log-log graph paper where the trend of tool life versus cutting velocity has been drawn as a straight line. The three lines constitute a comparison of the three work materials and each may be expressed by an equation of the general form $VT^n = C$ where:

V = cutting velocity (measured at OD) in feet per minute
T = tool life in minutes
C = a proportionality constant
n = arithmetic slope of the tool-life line.

Table I includes the equations of each line and a calculated velocity for a 20-minute tool life (V_{20}) for comparative purposes. Both actual and relative values for V_{20} are shown with the lowest value (material 18-8) being used as a

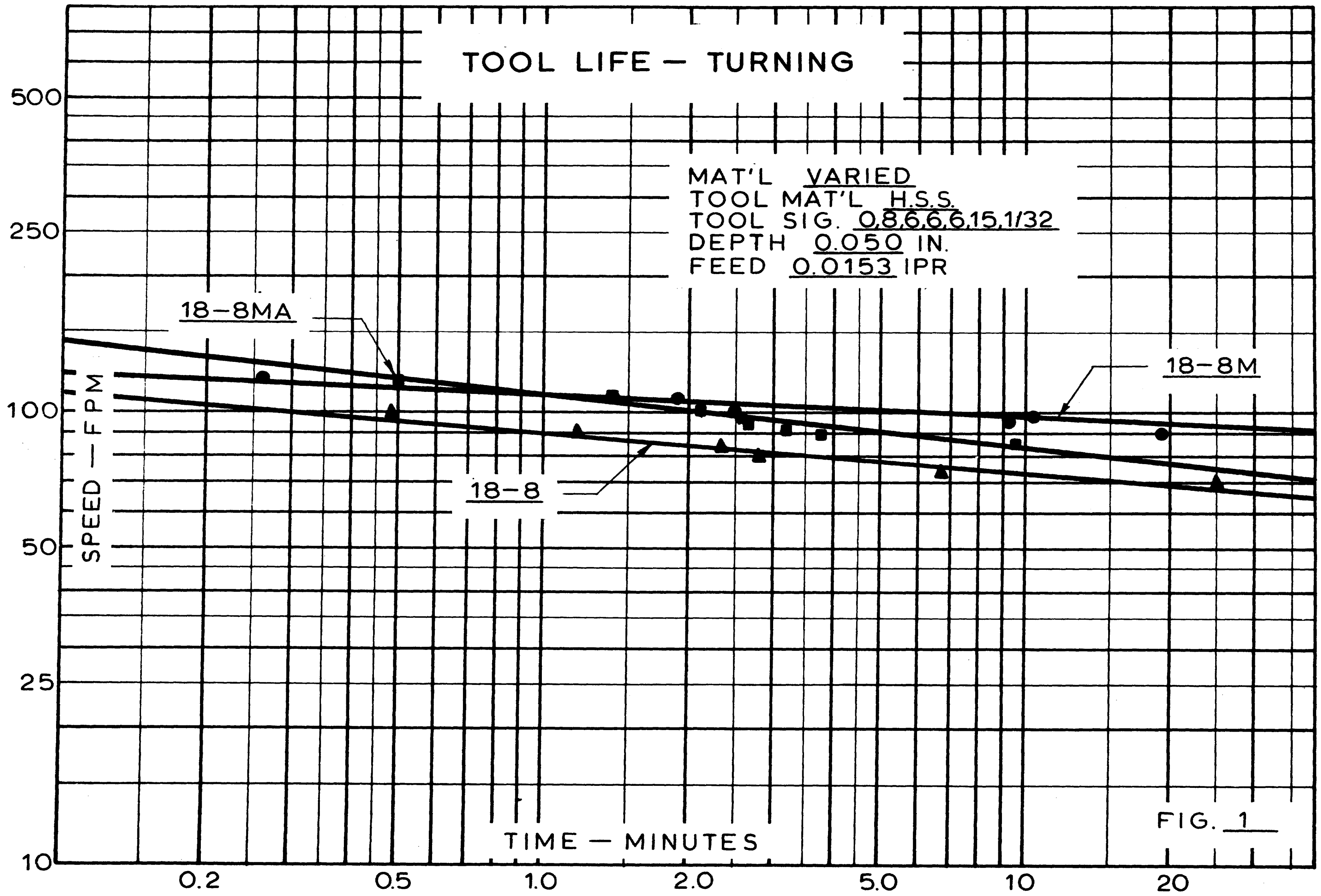

Fig. 1. Tool life-turning (high-speed steel).

base reference of 100%. Because the slopes of the three lines differ, relative ratings based upon a tool life other than 20 minutes will differ from those shown in Table I.

TABLE I

TOOL LIFE VS. CUTTING VELOCITY*

Test Material	Tool-life Equation	V_{20} Actual-fpm	V_{20} Relative-%
18-8	$VT^{.089} = 92$	71	100
18-8MA	$VT^{.115} = 108$	76	107
18-8M	$VT^{.055} = 109$	93	131

*Using the conditions stated under "TEST CONDITIONS."

2. Tool Wear Using Sintered Carbide Tools

Procedure.—Test bars similar to those used for the tool-life phase of this study were turned with sintered carbide tools at a constant velocity and size of cut. Periodically the cut was stopped, the tool removed, and a measurement of flank wear was obtained. This procedure was continued until a definite pattern of flank wear versus time was procured for each of the three work materials.

In addition, two of the materials were subjected to similar tests at different speed levels. Because the use of carbides required large amounts of work material, these tests were not always carried to complete failure of the cutting tool; however, the trends that were found do provide added analytical material.

Test Conditions.—Those tests that permitted a comparison of the three work materials were run on a 14-inch Monarch Engine Lathe with "Carboloy 350" type tools having an ASA signature of -5, -5, 5, 5, 45, 45, 1/32. All cutting was done dry and the constant size of cut consisted of a feed rate of 0.0105 inches per revolution and depth of cut of 0.050 inches. The cutting velocity was maintained at 400 feet per minute throughout.

Additional tests were conducted on the 18-8 and 18-8MA materials at different speed levels. Except for speed variations and a tool signature of -5, -5, 5, 5, 15, 15, 1/32, test conditions were identical to those listed in the preceeding paragraph. The reason for omitting the 18-8M material from this sequence of tests was a lack of material.

Test Results.—Figure 2 shows the comparative results of flank wear versus total operating time for the three materials. The abrupt vertical change in the wear curves for the 18-8 and 18-8MA materials indicates the probable start of tool failure. It will be noted that such a trend for the 18-8M material was not evident after 50 minutes of elapsed cutting time; consequently, that test was concluded short of failure. Each of the three curves consists of point-to-point connections for the sake of clarity; however, the general trend of these curves rather than any point-to-point slope provides the basis of analysis.

Figures 3 and 4 show the results obtained for different levels of cutting velocity using the 18-8MA and 18-8 materials, respectively. In addition to the average flank wear, measured values of the maximum notch that occurred on the side flank of the tool are also plotted.

3. Conclusions

(1) For the test conditions used, the 18-8M type material provides superior tool life. Of the remaining two materials, the 18-8 type leads to the poorest tool life although the difference between the 18-8 and 18-8MA is not greatly significant.

(2) The slope of the tool-life line for the 18-8M materials is much flatter than that found for the other two materials. This would indicate that the abrasive effect on tool wear is less pronounced for the 18-8M material.

(3) From the tool-wear tests using carbides, the 18-8M material creates much less tool wear than does either of the other materials. There is no significant difference between the 18-8 and 18-8MA materials.

(4) Taken together, conclusions (3) and (4) seem to show complete agreement.

(5) Within the limited scope of tests conducted, the difference in flank wear caused by the 18-8 and 18-8MA materials in speed ranges from 200 to 500 feet per minute does not appear to be substantial.

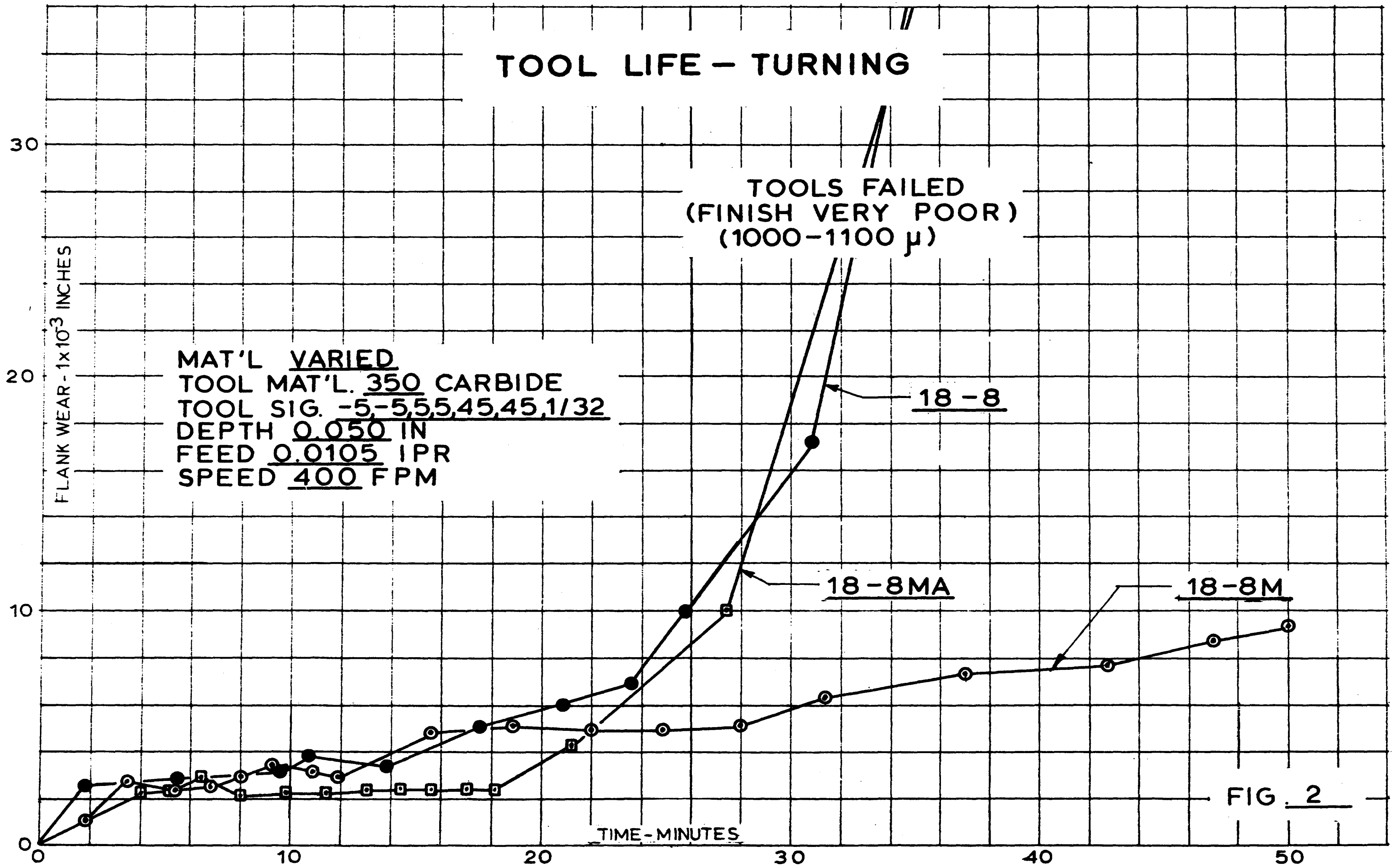

FIG. 2

Fig. 2. Tool life-turning (sintered carbides).

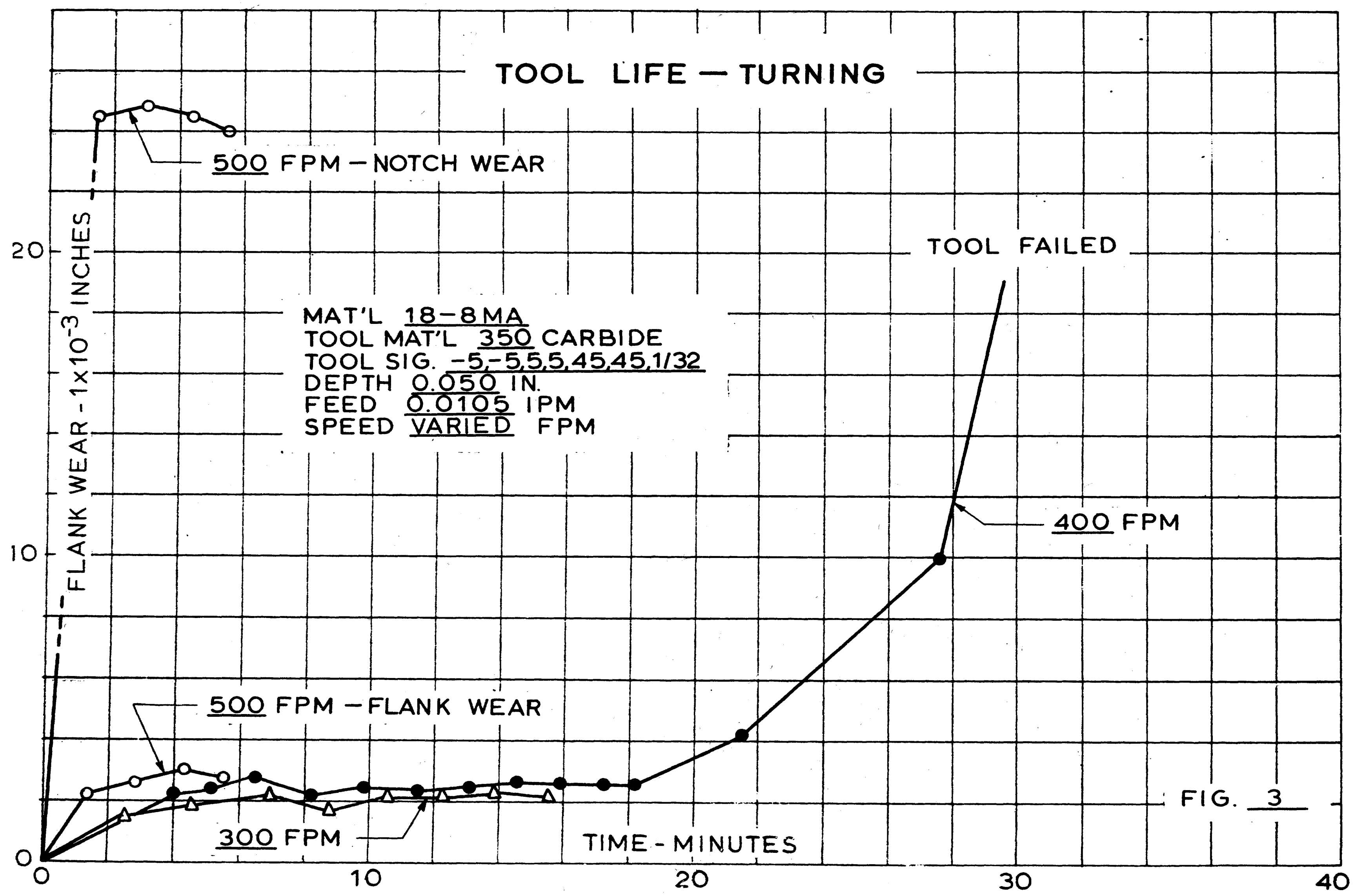

FIG. 3

Fig. 3. Tool life-turning (sintered carbides).

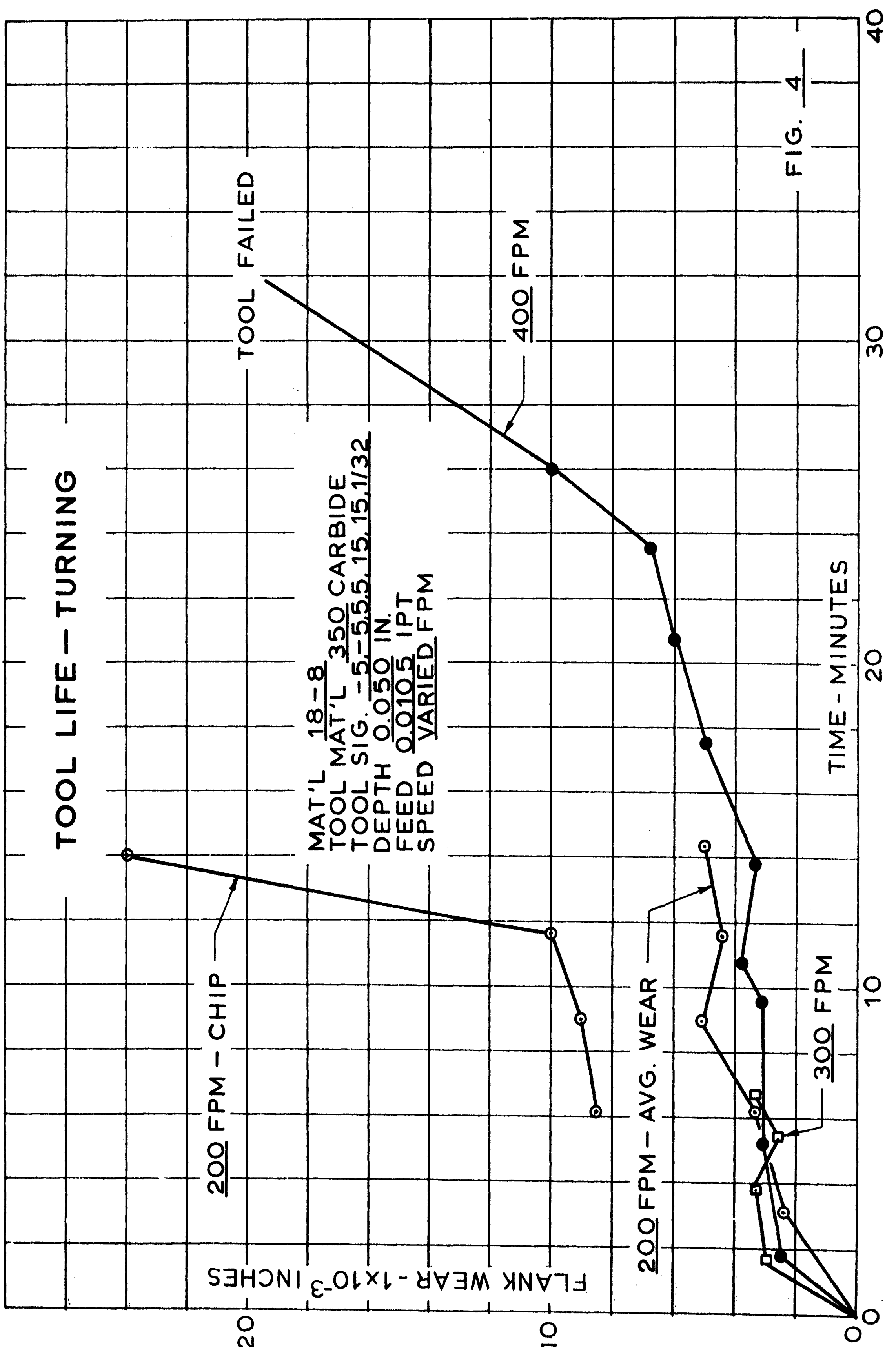

Fig. 4. Tool life-turning (sintered carbides).

B. TURNING FORCES

The three work materials were subjected to a number of turning tests to find the effects of feed rate and depth of cut on the magnitude of the feeding and cutting forces.

Procedure.—One of the materials was chucked in position and given a clean-up cut. After setting a particular feed rate and depth of cut, a turning operation was started. Once the levels of feeding force (parallel to axis of work rotation) and cutting force (perpendicular to the plane of tool motion) reached a stabilized condition, the test was concluded.

This technique was continued for various feed rates and depths of cut on each of the three work materials. Since the test intervals were short, the amount of tool wear did not require a fresh tool for each test. However, spot checks were made in the form of repeat tests to be certain that the measured force values were representative and repetitive.

Test Conditions.—All tests were performed on a 14-inch Monarch Engine Lathe using "Carboloy 883" grade of sintered carbide tools. The tool signature was constant at -5, -5, 5, 5, 60, 30, 1/32. These tests were run without a cutting fluid and the cutting velocity was constant at 400 feet per minute.

One group of tests consisted of a constant depth of cut of 0.050 inches and individual feed rates of 0.0028, 0.0052, 0.0105, and 0.0153 inches per revolution, respectively. For the second set of tests the feed rate was maintained at 0.0105 inches per revolution while the depth of cut was adjusted in values of 0.025, 0.050, 0.075, and 0.100 inches, respectively.

A two-component wire-resistance strain-gage type of dynamometer was used to obtain measurements of both forces.

Test Results.—Figures 5 and 6 contain the test points plotted on log-log graph paper. Whenever tests were repeated, average values have been utilized. Figure 5 indicates the influence of feed rate and depth of cut upon the magnitude of the cutting force while Fig. 6 presents the effects of these variables upon the feeding force. As may be noted, the trends can be represented by straight lines which lead to equations of the general form $F = Kf^a d^b$, where:

F = force (cutting or feeding)
K = a proportionality constant
f = feed rate in inches per revolution
d = depth of cut in inches
a and b = magnitude of the slopes of the lines that show the relationship between force and feed and depth.

Table II contains the equations derived from the lines on Figs. 5 and 6. Since the results for the 18-8M and 18-8MA materials were almost identical, a single line was drawn through those points so the same force equation applies to both materials.

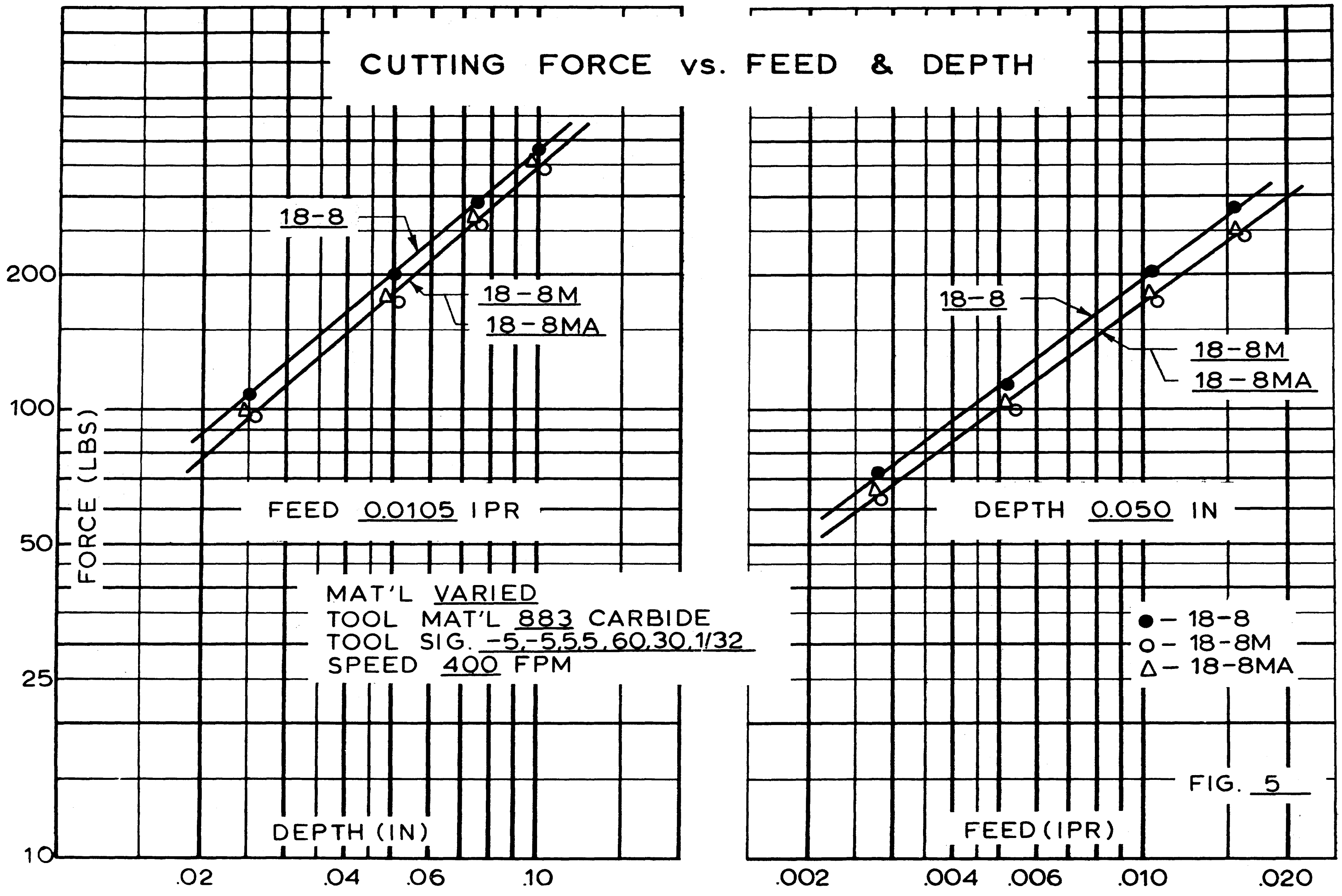

Fig. 5. Cutting force vs. feed and depth (turning).

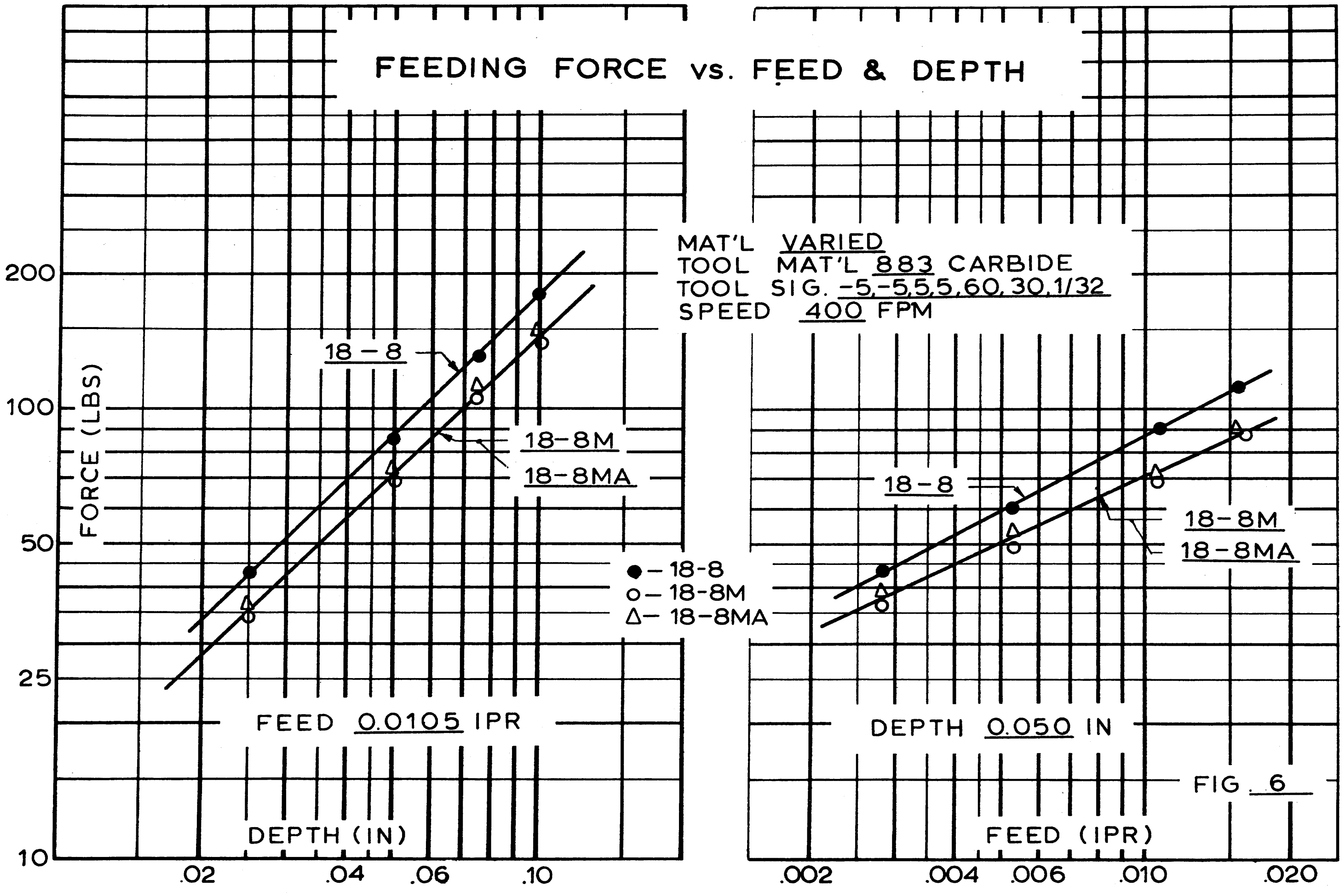

Fig. 6. Feeding force vs. feed and depth (turning).

TABLE II

*EMPIRICAL EQUATIONS FOR CUTTING AND FEEDING FORCES AS A FUNCTION OF FEED AND DEPTH

Work Material	Cutting Force	Feeding Force
18-8	$F_c = 115{,}000\ f^{.8}\ d^{.9}$	$F_f = 22{,}000\ f^{.55} d^{1.0}$
18-8M and 18-8MA	$F_c = 96{,}500\ f^{.77}\ d^{.93}$	$F_f = 14{,}100\ f^{.5}\ d^{1.0}$

*Based upon sharp tools and the conditions described under "TEST CONDITIONS."

Conclusions

(1) The 18-8M and 18-8MA materials require approximately the same magnitude of cutting force for a given size of cut. This same conclusion also applies to feeding force.

(2) The 18-8 material requires larger forces in turning than either of the other materials. This result was consistent and was more pronounced in regard to the feeding force as compared to the cutting force.

(3) Regardless of material, both forces are more sensitive to changes in depth of cut than to changes in feed rate. This sensitivity is more pronounced in regard to the feeding force.

(4) The influence of size of cut upon both forces is orderly and predictable within the range of test conditions used.

C. DRILLING TORQUE AND THRUST

Each work material was subjected to a series of tests that would indicate the effects of feed rate and drill diameter on the magnitudes of cutting torque and thrust.

Procedure.—Test specimens were clamped in the collet of a dynamometer. Using a particular combination of test conditions, a cut was made until readings of torque and thrust reached a stable level. This procedure was then continued until each work material had been tested at a variety of feed rates and drill diameters.

Test Conditions.—These tests were conducted on a Fosdick Upright Drill Press at a cutting velocity of approximately 35 feet per minute. All tests were run without a cutting fluid.

Two-fluted twist drills of high-speed steel ground to a point angle of 118° and having a helix angle of 30° were employed. One series of tests was run with a constant drill diameter of 0.375 inches and feed rates of 0.005, 0.007, 0.009, and 0.011 inches per revolution. For the second group of tests the feed rate was kept at 0.005 inches per revolution while drill diameters of 0.250, 0.375, 0.500, and 0.625 inches were used. A wire-resistance strain-gage dynamometer served for measuring torque and thrust.

Test Results.—Figure 7 shows that results of torque versus feed rate and drill diameter plotted on log-log graph paper while Fig. 8 repeats this plot for thrust. These data can be represented quite reliably by straight lines which yield equations of the general forms $T = Kf^aD^b$ and $B = Cf^xD^y$, where:

T = cutting torque in pound-inches
B = thrust force in pounds
K and C = appropriate proportionality constants
$a, b, x,$ and y = slopes of lines showing the influence of feed rate and drill diameter on torque and thrust, respectively
C = drill diameter in inches
f = feed rate in inches per revolution

Table III contains the equations derived from the plots of the test results. These equations are reliable within the limitations of the test conditions utilized and are applicable for sharp tools. Changes in drill point geometry or the use of worn drills could lead to entirely different results; therefore, these equations should be considered as a means of making relative comparisons among the three materials for similar cutting conditions.

TABLE III

*EMPIRICAL EQUATIONS FOR DRILLING TORQUE AND THRUST
AS A FUNCTION OF FEED RATE AND DRILL DIAMETER

Work Material	Torque	Thrust
18-8	$T = 7{,}340\ f^{.58}\ D^{1.95}$	$B = 28{,}200\ f^{.54}D^{1.56}$
18-8MA	$T = 14{,}100\ f^{.73}D^{1.95}$	$B = 58{,}000\ f^{.74}D^{1.32}$
18-8M	$T = 13{,}100\ f^{.73}D^{1.95}$	$B = 50{,}000\ f^{.74}D^{1.32}$

*For sharp tools and conditions stated under "TEST CONDITIONS."

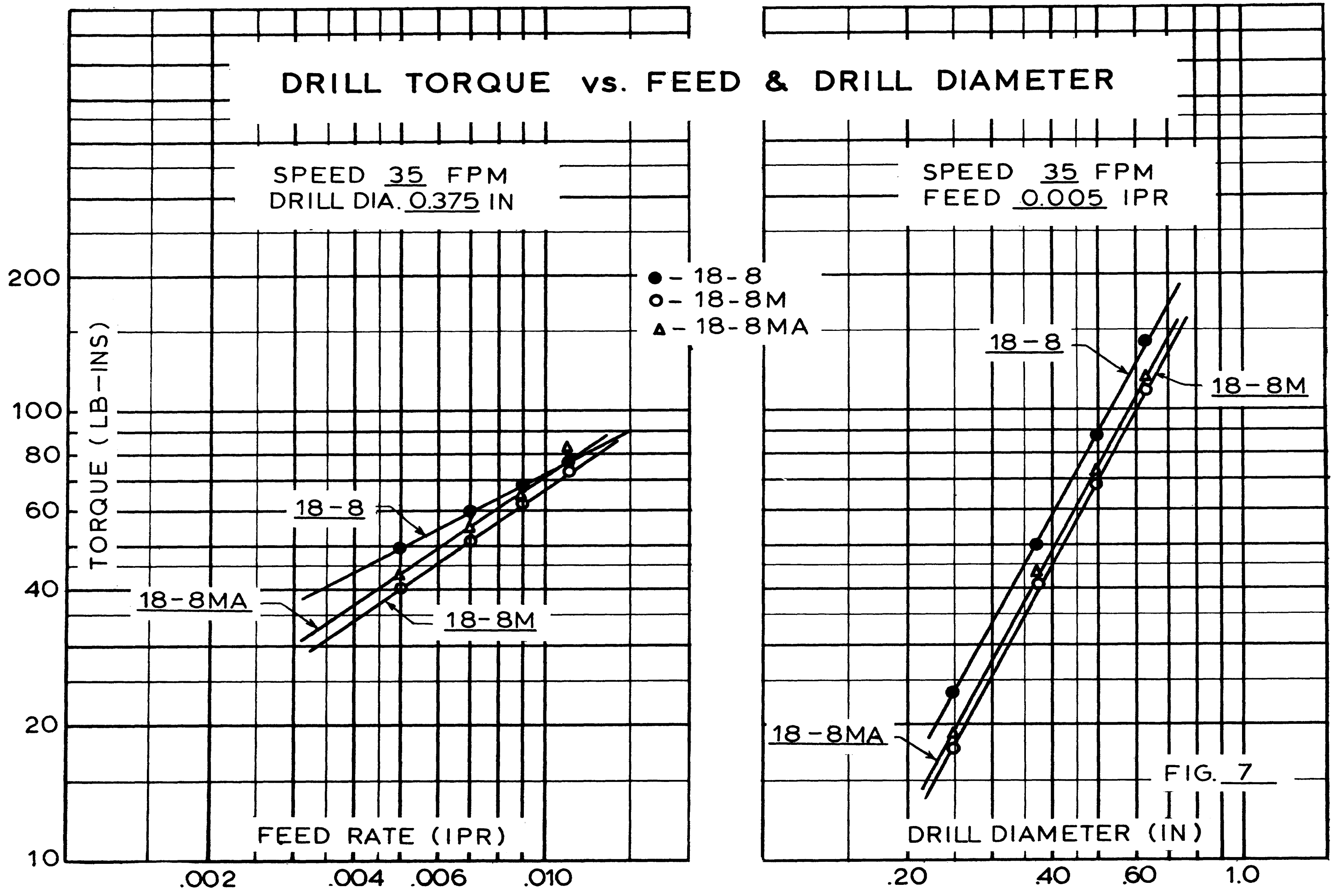

Fig. 7. Drill torque vs. feed and drill diameter.

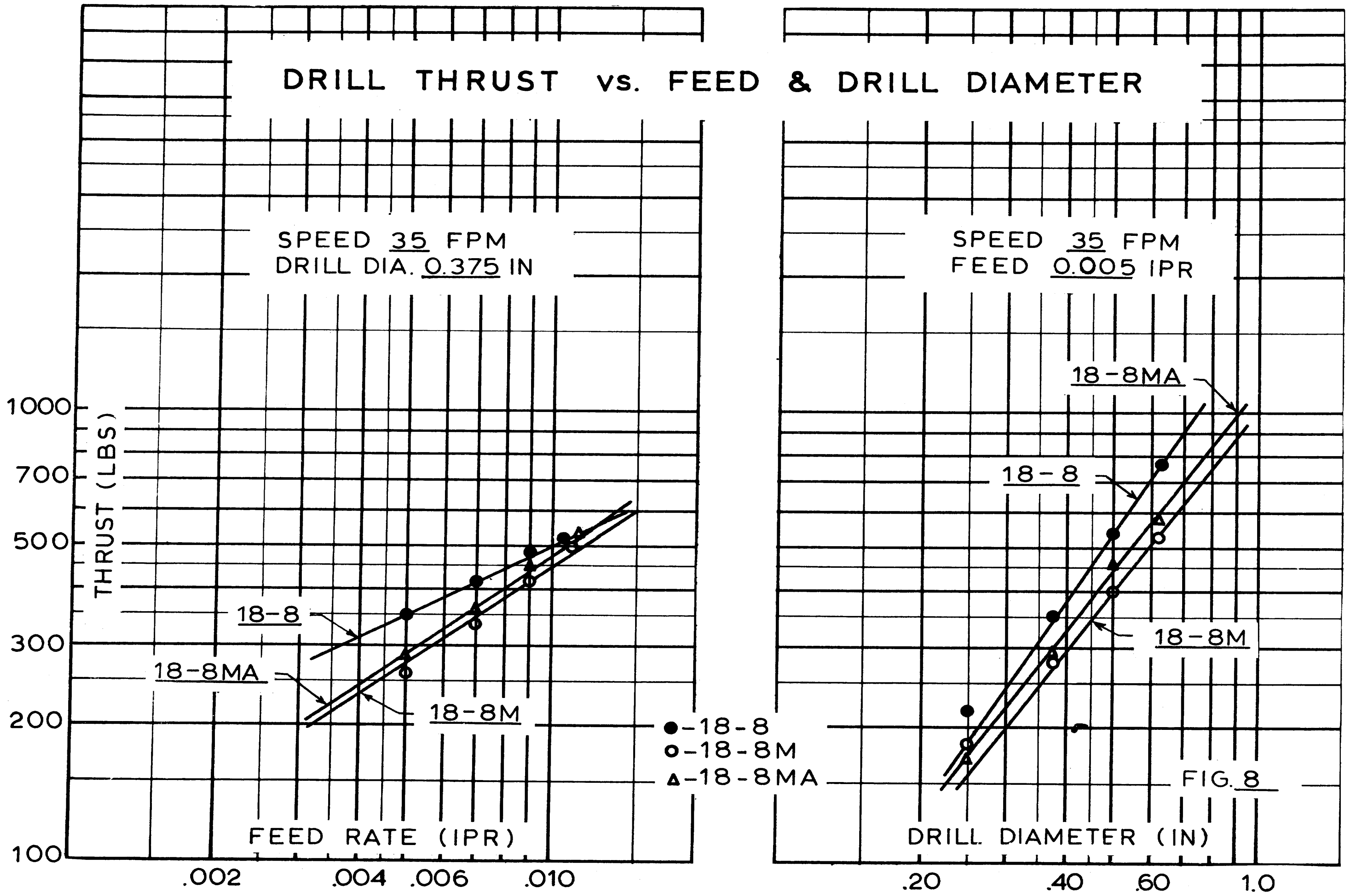

Fig. 8. Drill thrust vs. feed and drill diameter.

Conclusions

(1) Torque and thrust requirements are lowest for the 18-8M material although the absolute magnitudes are not substantially different as compared to the remaining two materials.

(2) The behavior of the 18-8M and 18-8MA materials is very similar, whereas the feed effect on the 18-8 material shows a less sensitive influence on torque and thrust than does the feed effect on the other two materials. This is exhibited by the flatter slopes.

D. MILLING POWER

Each material was subjected to a number of milling tests that would indicate the influence of feed rate and depth of cut on power requirements.

Procedure.—Test specimens of each material were prepared from the one-inch square stock. After clamping a specimen in position and producing a reference surface by taking a light cleanup cut, one combination of feed rate and depth of cut was established. A cut was started and after the power reading stabilized for a full cut, the test was completed. Such a procedure was repeated until the same sequence of tests had been performed on each work material.

Test Conditions.—A Kearney and Trecker, Model K, Number 2 Vertical Mill was used for this group of tests. The spindle speed was held constant at 61 rpm which produced a cutting velocity of 48 feet per minute at the cutter periphery.

The cutter was a 12-tooth, high-speed steel, shell end mill of three-inch outside diameter. Each tooth was set at a radial rake angle of 17°, axial rake angle of 15°, and ground at the point to provide a 3/64-inch chamfer at a 45° angle.

While the depth of cut was maintained at 0.100 inch, the feed rate was adjusted to give 0.00103, 0.00171, 0.00205, 0.00273, 0.0041, 0.0058, and 0.00837 inches per tooth, respectively. For the second group of tests the feed remained constant at 0.00205 inches per tooth while the depth of cut was set at 0.050, 0.075, 0.100, 0.125, 0.150, and 0.200 inches, respectively.

A graphic recording wattmeter indicated the input power required to perform each cut. From these readings the actual power delivered to the cutter was calculated.

Test Results.—Figure 9 shows the test points plotted on log-log graph paper. Each power reading has been converted to a value of unit horsepower at the cutter for comparative purposes. This quantity is an expression of the

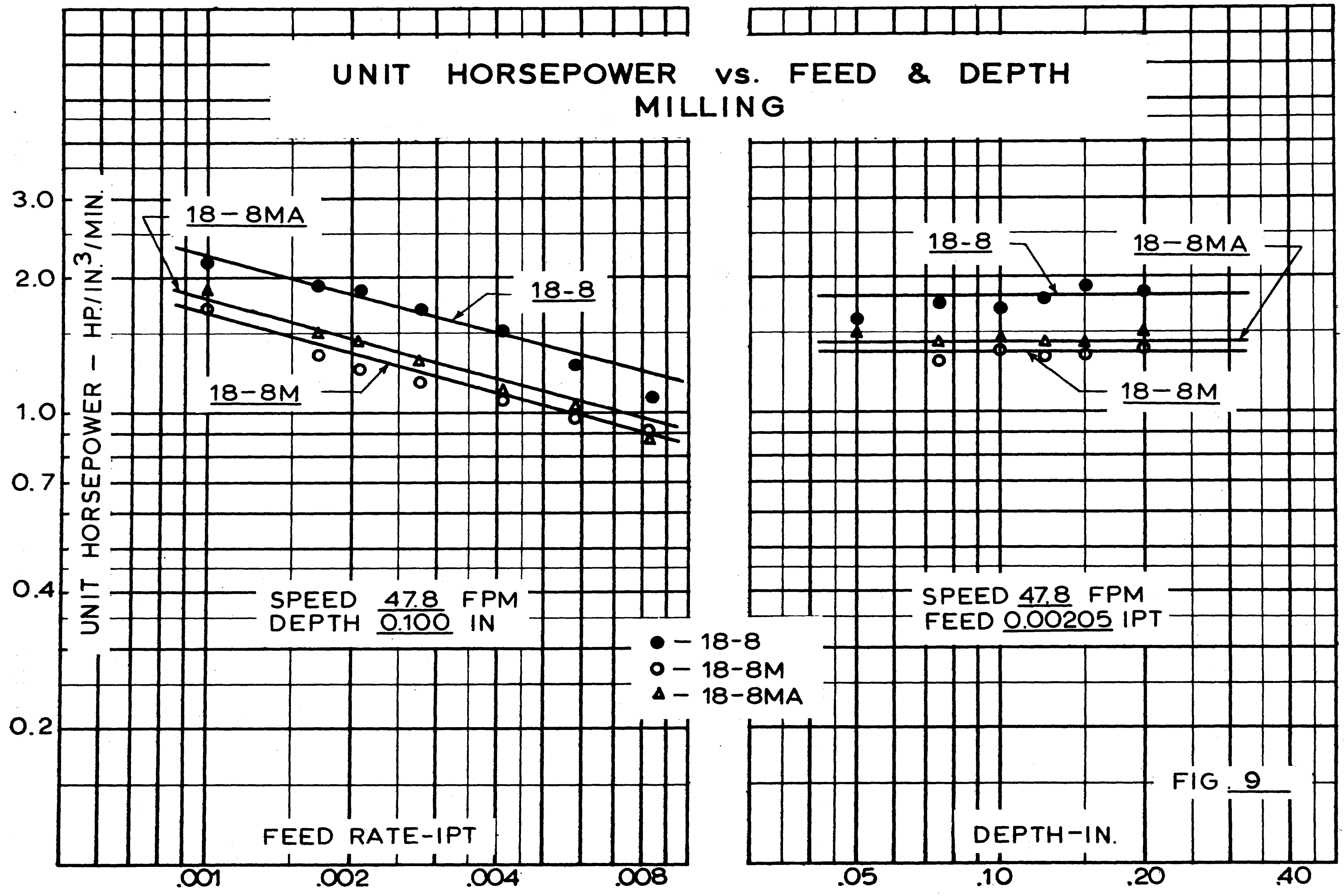

FIG. 9

Fig. 9. Unit horsepower vs. feed and depth (milling).

specific energy required to removal metal at the rate of one cubic inch per minute. The expression is:

$$\text{unit horsepower } (uHP_c) = \frac{\text{horsepower delivered to the cutter}}{\text{rate of metal removal (in.}^3\text{/min)}}$$

$$uHP_c = \frac{HP_c}{Fwd}$$

where:

F = table feed in inches per minute
w = width of cut in inches
d = depth of cut in inches
HP_c = horsepower at the cutter for a given size of cut.

The trends of points on Fig. 9 may be represented by straight lines as shown, and such behavior leads to equations of the general form $uHP_c = Kf^a d^b$, where:

f = feed rate in inches per tooth
d= depth of cut in inches
a and b = slopes of lines as plotted
K = proportionality constant
uHP_c = unit horsepower at the cutter.

From past experience, the depth of cut shows little if any influence on unit horsepower and the dispersion of points indicate no definite trend. Thus, it is felt that a horizontal line (slope equals zero) is most representative of average behavior. Negative slopes for the feed influence show that thicker chips are removed more efficiently than thinner chips from a power viewpoint.

Table IV contains the equations as derived from the plotted results of Fig. 9.

TABLE IV

*EMPIRICAL EQUATIONS OF UNIT HORSEPOWER AS A FUNCTION OF FEED RATE

Work Material	Equations
18-8	$uHP_c = 0.32\ f^{-.28}$
18-8MA	$uHP_c = 0.25\ f^{-.28}$
18-8M	$uHP_c = 0.23\ f^{-.28}$

*For conditions listed under "TEST CONDITIONS." Depth of cut has negligible effect.

Conclusions

(1) Power requirements are lowest when milling the 18-8M material; however, the 18-8MA material is not substantially different.

(2) Power requirements, when milling the 18-8 material, are definitely higher than those indicated for either of the other materials.

E. TAPPING TORQUE

Each material was tapped under similar conditions to determine if any differences were evident.

Procedure.—Specimens in the form of cylinders, 3/4-inch OD by 3/4-inch long, were drilled out with a 27/64-inch drill. This inside diameter was the pre-tap size for a 78% thread depth.

After clamping a specimen in the dynamometer a thread was tapped through the entire 3/4-inch length, then backed out. Readings of cutting torque and "back-out" or withdrawal torque were obtained. This approach was continued using each work material, with one series of tests being run dry while the second employed a sulphurized black oil as the cutting fluid.

Each individual test was conducted at least two times to check repeatability and a new tap was introduced for each test. The specimens were sectioned after being tapped and with the aid of a microscope, visual observations of the threads were made.

Test Conditions.—These tests were run on a Detroit Precision Tapping Machine operating at a constant speed of 74 rpm (10 feet per minute cutting velocity). High-speed steel, four-fluted, straight-flute, type GH3, 1/2-13-NC taps were used throughout. Torque readings were obtained with a wire-resistance strain-gage dynamometer.

Test Results.—Figure 10 shows the test results plotted in the form of bar charts. Tapping the 18-8 material dry led to wide variations between the maximum and average tapping torques, so this test was repeated four times. In one instance the tap broke before the complete thread was finished. The break in the bar chart for this material implies that the torque level is at least 750 pound-inches.

Visual observations of the threads showed the 18-8M and 18-8MA materials produced smoother threads than did the 18-8 grade.

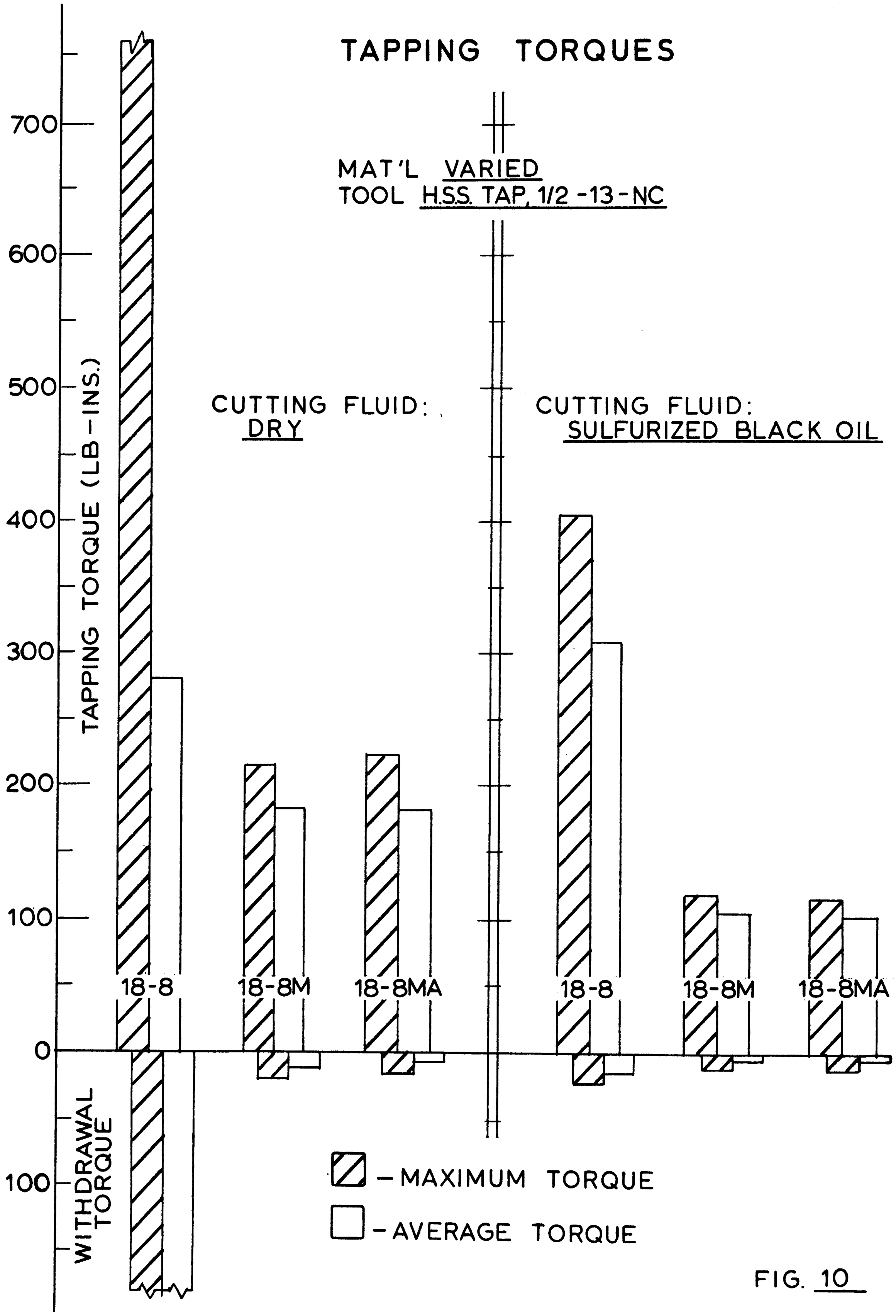

FIG. 10

Fig. 10. Tapping torques.

Conclusions

(1) There was little difference between the 18-8M and 18-8MA materials for similar test conditions.

(2) The 18-8 material required a substantially higher tapping and withdrawal torque than did either of the other materials.

(3) The use of a cutting fluid reduced the level of tapping torque compared to dry cutting regardless of the material used.