THE UNIVERSITY OF MICHIGAN

COLLEGE OF ENGINEERING
Department of Mechanical Engineering

Final Report

COMPARATIVE MACHINABILITY OF MBMC-1 AND AISI 4130 STEEL

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UMRI Project 03690

under contract with:

INGERSOLL DIVISION
BORG-WARNER CORPORATION
KALAMAZOO, MICHIGAN

administered by:

THE UNIVERSITY OF MICHIGAN RESEARCH INSTITUTE ANN ARBOR

October 1960

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ABSTRACT

Both tool life and cutting force studies were made on the two work materials in both the as-forged and heat-treated or hardened condition. In general, the MBMC-1 steel was more difficult to cut. However, it was feasible to cut it satisfactorily at all test conditions except for turning the hardened material with high-speed steel tools. Quantitative data provide a general guide for shop practice.

I. STATEMENT OF THE PROBLEM

The principal objective was to determine whether the newly developed, high-strength steel MBMC-1 exhibited any unique characteristics which would make it particularly difficult to machine. For this purpose it is necessary to explore tool wear behavior as well as force and energy requirements at a number of different conditions such as turning, drilling, and milling. Since many of the quantitative data cannot be interpreted on an absolute basis, it was decided to obtain comparable information for AISI 4130 steel which is functionally similar to MBMC-1.

II. GENERAL CONCLUSIONS

It was determined that, although the MBMC-1 steel does exhibit some unique machining properties, it can be machined with no great difficulty, particularly in the as-forged condition. When it is hardened it cannot be cut readily with high-speed steel tools but it can be cut quite satisfactorily with both sintered carbide and ceramic tools.

III. DEFINITION OF MACHINABILITY

To avoid misconception, machinability should be defined in specific terms. Two criteria, used to compare the relative machinability of the test materials, have been selected for this investigation. One is the magnitude of cutting force required to machine the materials, using several types of operations and at varying sizes of cut. Low cutting forces are more desirable than high cutting forces and demonstrate better relative machinability from this viewpoint.

Relative machinability may also be based on tool life. A material that exhibits a longer tool life than another is considered to have better machinability from this viewpoint.

Unfortunately, a high machinability rating based upon one criterion does not always indicate corresponding advantages with respect to other relevant machining criteria. Materials that cut with lower forces do not necessarily exhibit better tool life.

Force measurements obtained with sharp cutting tools are not indicative of the nature of tool wear that will result if the cut is continued. A material may show a low force at the start of cut but exhibit a poorer tool life than a material which shows a higher starting force; this could be accounted for by different wear rates not reflected in the forces.

The term "better machinability," if properly applied, should be considered only in terms of the criteria of interest. References such as surface finish and dimensional stability have not been studied *per se* in this work and specific comments pertaining to these items should not be considered conclusive.

A fundamental study of the type conducted is intended to bring out any pronounced differences that might exist, but the conclusions from any investigation are limited to the actual testing conditions. If, for example, sintered carbide tools are used in a study of tool life, the findings of relative machinability could be of a different order from those obtained with high-speed steel tools.

IV. THE MATERIALS INVESTIGATED

TABLE I

HARDNESS AND SIZE OF TEST SPECIMENS

Work Piece Identification	Size of Work Piece, in.	Hardness		
		Brinell** Reading (mm)	Brinell Reading (mm)*	Average Hardness Number
4130-1-H (heat-treated)	5 OD x 24	2.8	2.85	461
4130-2-H	5 OD x 24	2.6	2.85	461
4130-3-AF (as-forged)	5 OD x 24	4.6	4.7	163
4130-4-AF	5 OD x 24	4.55	4.45	183
4130-5	1 x 2 x 36	4.5	4.65	167
B.W.-1-H (heat-treated) MBMC-1	5 OD x 24	2.95	3.05	401
B.W.-2-H	5 OD x 24	2.7	2.85	461
B.W.-3-AF (as-forged)	5 OD x 24	4.3	4.4	187
B.W.-4-AF	5 OD x 24	4.3	4.0	229
B.W.-5	1 x 2 x 36	4.3	4.4	187

*Obtained at University of Michigan with a 10-mm steel ball and 3000-kg load.
**Provided by sponsor.

V. TEST PROCEDURES AND RESULTS

A. TOOL LIFE WITH HIGH-SPEED STEEL TOOLS

Work specimens used were in the form of cylinders, with an approximate OD of 5-1/4 in. and 24 in. long.

Each test consisted of a lathe turning cut at a constant size of cut and cutting velocity until complete tool breakdown occurred. The total elapsed cutting time, from starting point to failure, constitutes the tool life for those operating conditions. The cutting speed was changed for each tool-life test, thus providing a relationship between velocity and tool life.

Each material was subjected to such tests until enough individual points were obtained to define both level and slope of the velocity, tool-life line on logarithmic coordinates.

Upon the conclusion of each individual test and prior to the subsequent test, a cleanup cut was taken to avoid any possible effects of work-hardening from the previous tool failure.

Test Conditions and Equipment.—Two Monarch engine lathes equipped with variable-speed drives were used for all tests in this series. All machining was done dry, that is, without a cutting fluid. Standard 3/8-in.-square "Mo-Max," high-speed steel tool bits were ground to the signature, 0, 8, 6,6,6, 15, 1/32. The roughing cuts on the as-forged materials were made at a feed rate of 0.015 ipr and a depth of 0.100 in. For the finishing cuts on the same materials the feed was 0.0052 ipr and the depth was 0.020 in. In cutting the 4130 heat-treated material, the feed rate was 0.0075 ipr and the depth was 0.050 in. Attempts at cutting the heat-treated MBMC-1, resulted in an extremely poor cutting action and no consistent data could be obtained at any size of cut.

Test Results.—Figures 1 through 3 contain test results plotted on log-log coordinates. The trends are shown as straight lines which may be described by equations of the general form, $VT^n = C$, where:

V = cutting velocity (at OD) in fpm,
T = tool life in minutes,
C = a proportionality constant, and
n = slope of the tool-life line.

In all cases, the lines represent average performance but dispersion of points around the individual lines is not pronounced.

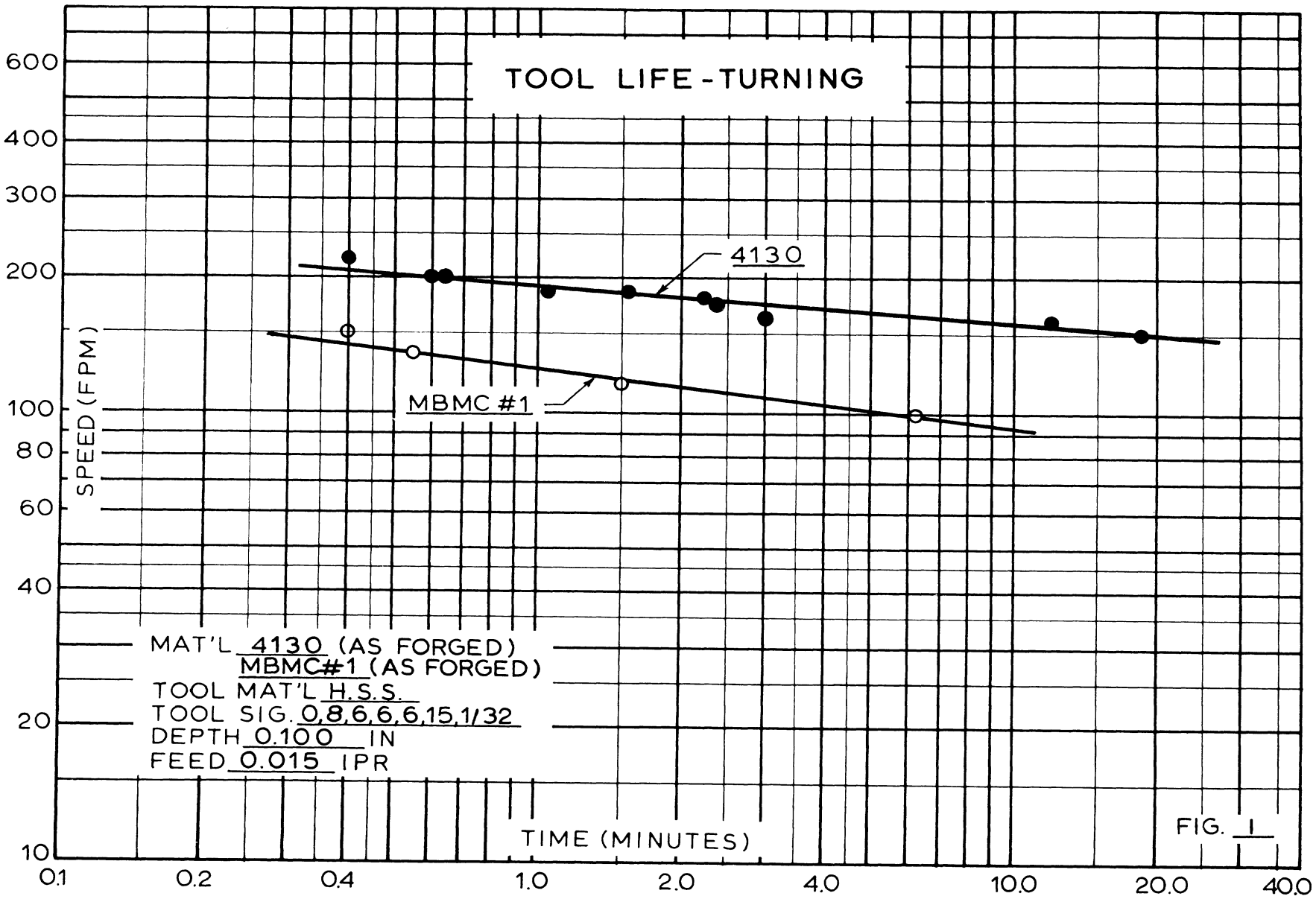

Fig. 1. Tool-life: Rough turning with high-speed steel (as-forged).

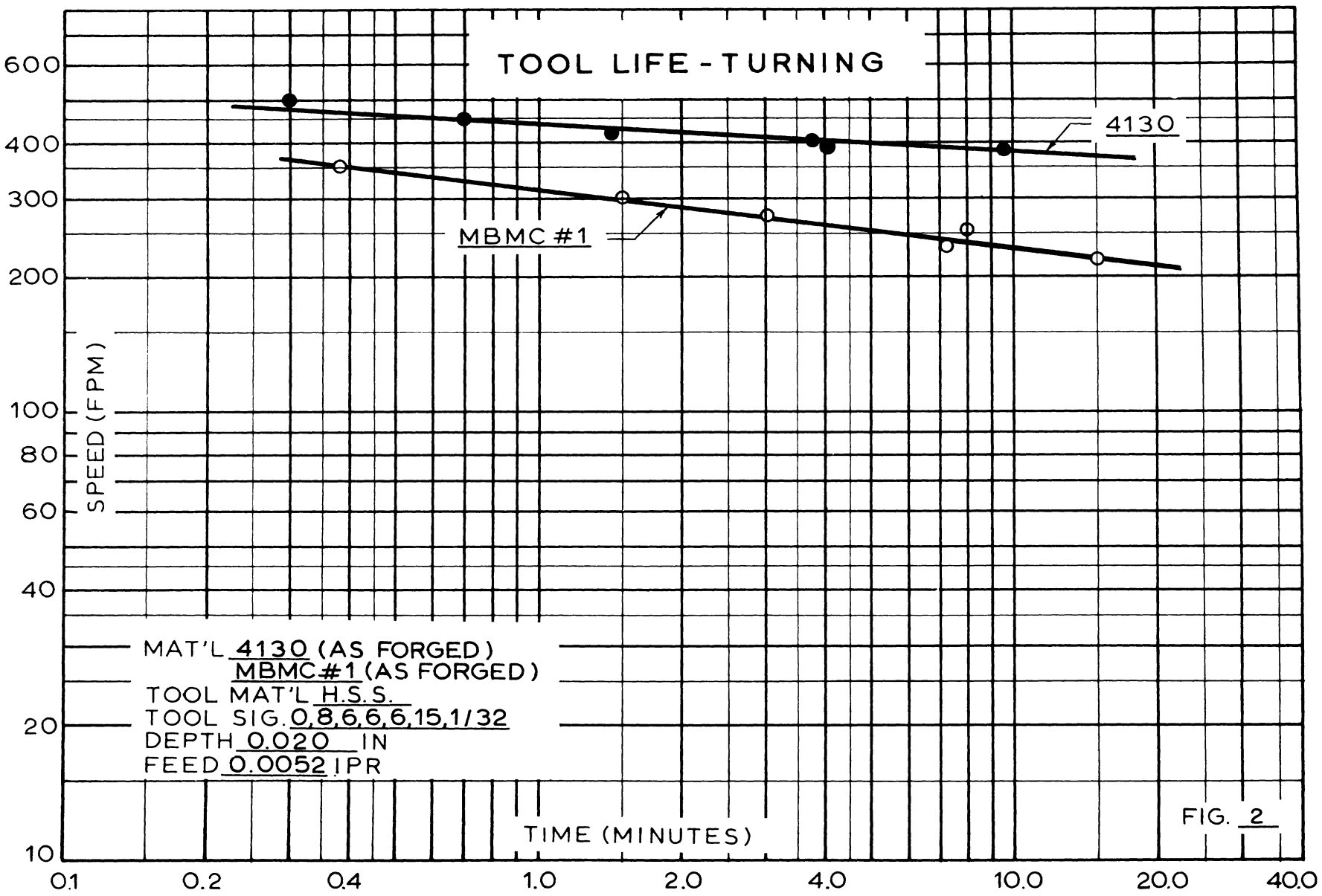

Fig. 2. Tool-life: Finish turning with high-speed steel (as-forged).

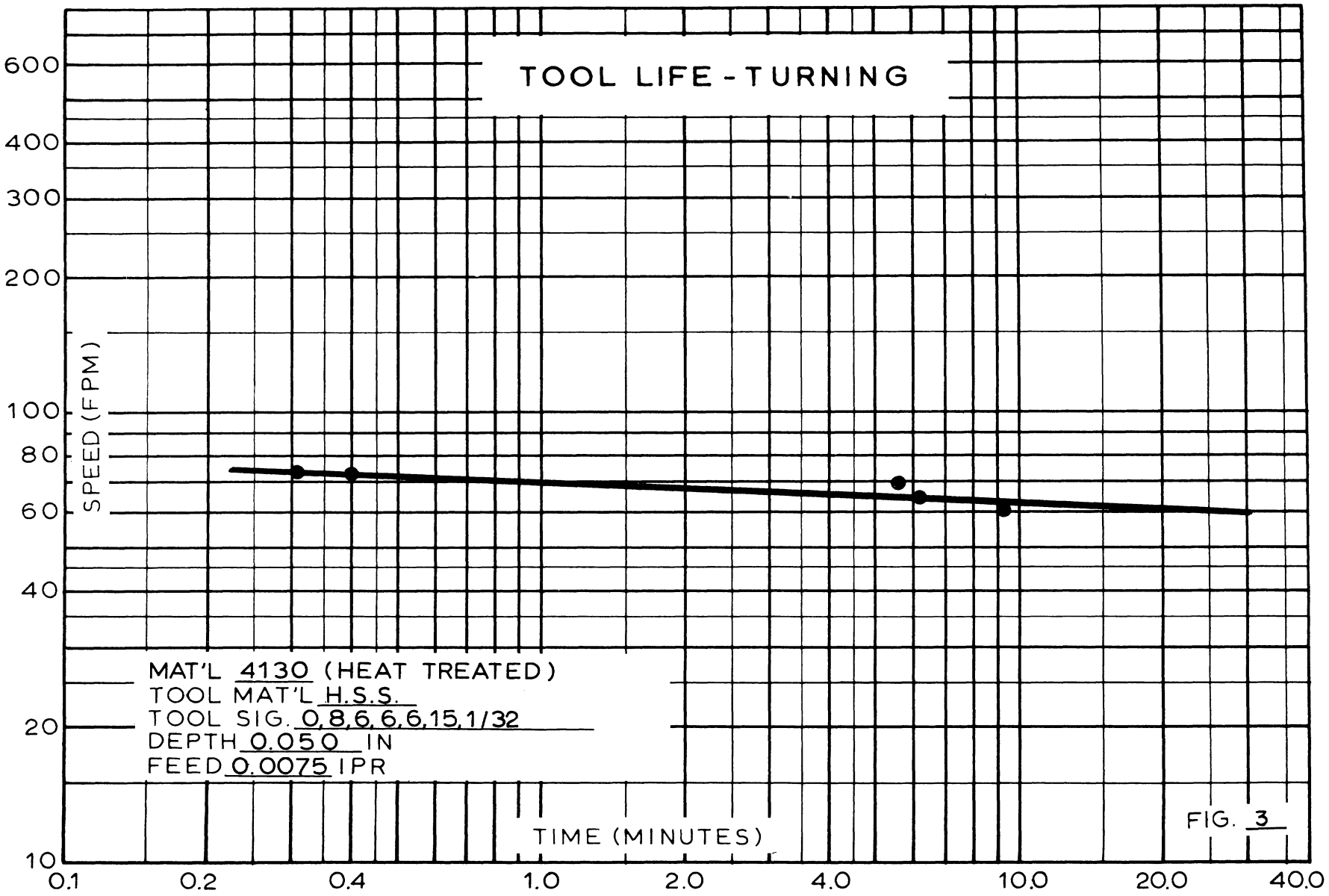

Fig. 3. Tool-life: Finish turning with high-speed steel (heat-treated 4130).

Equations for the resulting tool-life lines are summarized in Tables II and III.

TABLE II

TOOL LIFE WITH HSS TOOLS AND
AS-FORGED WORK MATERIALS

Material	Equations	
	Roughing Cuts*	Finishing Cuts**
4130	$VT^{0.078} = 192$	$VT^{0.0550} = 440$
MBMC-1	$VT^{0.12} = 125$	$VT^{0.12} = 315$

*Depth = 0.100 in.; Feed = 0.015 ipr.
**Depth = 0.020 in.; Feed = 0.0052 ipr.

TABLE III

TOOL LIFE WITH HSS TOOLS AND
HEAT-TREATED WORK MATERIALS

Material	Equations	
	Roughing Cuts*	Finishing Cuts
4130	$VT^{0.0682} = 71.3$	**-----
MBMC-1	**-----	**-----

*Depth = 0.050 in.; Feed = 0.0075 ipr.
**Cutting behavior at these conditions proved to be impractical and the erratic quantitative results are irrelevant.

Conclusions

(1) Both AISI 4130 and MBMC-1 demonstrate orderly behavior in the as-forged condition when cut at both roughing and finishing conditions.

(2) It is impractical to try to remove substantial amounts of MBMC-1 by cutting it in the heat-treated condition with high-speed steel tools.

(3) The steeper slopes of the tool-life lines for the MBMC-1 indicate that tool wear is more abrasive in nature than when cutting AISI 4130 steel.

(4) Cutting speeds for MBMC-1 should be approximately 40% lower than those found to be appropriate for AISI 4130 steel.

B. TOOL LIFE WITH CARBIDE TOOLS

Procedure.—The same specimens used for the HSS tool study in (A) were used for this series of tests. Test procedure consisted of operating a cutting tool at a given velocity, feed rate, and depth of cut. The carbide insert was removed from the toolholder at predetermined time intervals and the flank and rake face were examined under a toolmaker's microscope. The wear on the flank of the cutting tool was measured and recorded. This procedure was continued until a typical carbide wear pattern was established.

Test Conditions.—The machines were the same as those reported in (A). The tools were 1/2-in.-square, mechanically held blanks. The Kennametal toolholders provided a tool signature of -5, -5, 5, 5, 15, 15, 1/32. The sizes of cut for both roughing and finishing of both the as-forged and the heat-treated materials were the same as used for machining the as-forged material with high-speed steel tools. Unlike high-speed steel tools, carbides do not fail abruptly. Instead, the wear is gradual and point of failure is arbitrarily defined by a limiting amount of wear. Consequently, the tools were examined at regular intervals and the wear measured.

Test Results.—The results of tool wear measurements are shown plotted against elapsed cutting time in Figs. 4 to 13 inclusive. These represent a significant range of cutting conditions and carbide grades with both work materials.

Figures 4, 5, and 6 show the behavior for the as-forged materials. Three different grades of carbide were tried with a roughing cut on the MBMC-1. The results in Fig. 4 show that Carboloy-350 was best when compared to grades 370 and 883. This indicates that MBMC-1 is not particularly abrasive in the cutting behavior despite its silicon content.

Figure 5 gives a comparison of MBMC-1 with AISI 4130 for roughing cuts and Fig. 6 gives a similar comparison for finishing cuts. The results indicate that both materials can be cut at substantially the same speeds and sizes of cut while in the as-forged condition.

Test results for the heat-treated condition are summarized in Figs. 7 to 13 inclusive, Figs. 7 to 10 for roughing cuts and Figs. 11 to 13 for finishing cuts. Once more Carboloy-350 was the best grade of carbide as indicated in Figs. 8 and 9. Combining this experience with the variable speed tests of Fig. 7 led to the comparison plotted in Fig. 10 which shows that cutting speed for

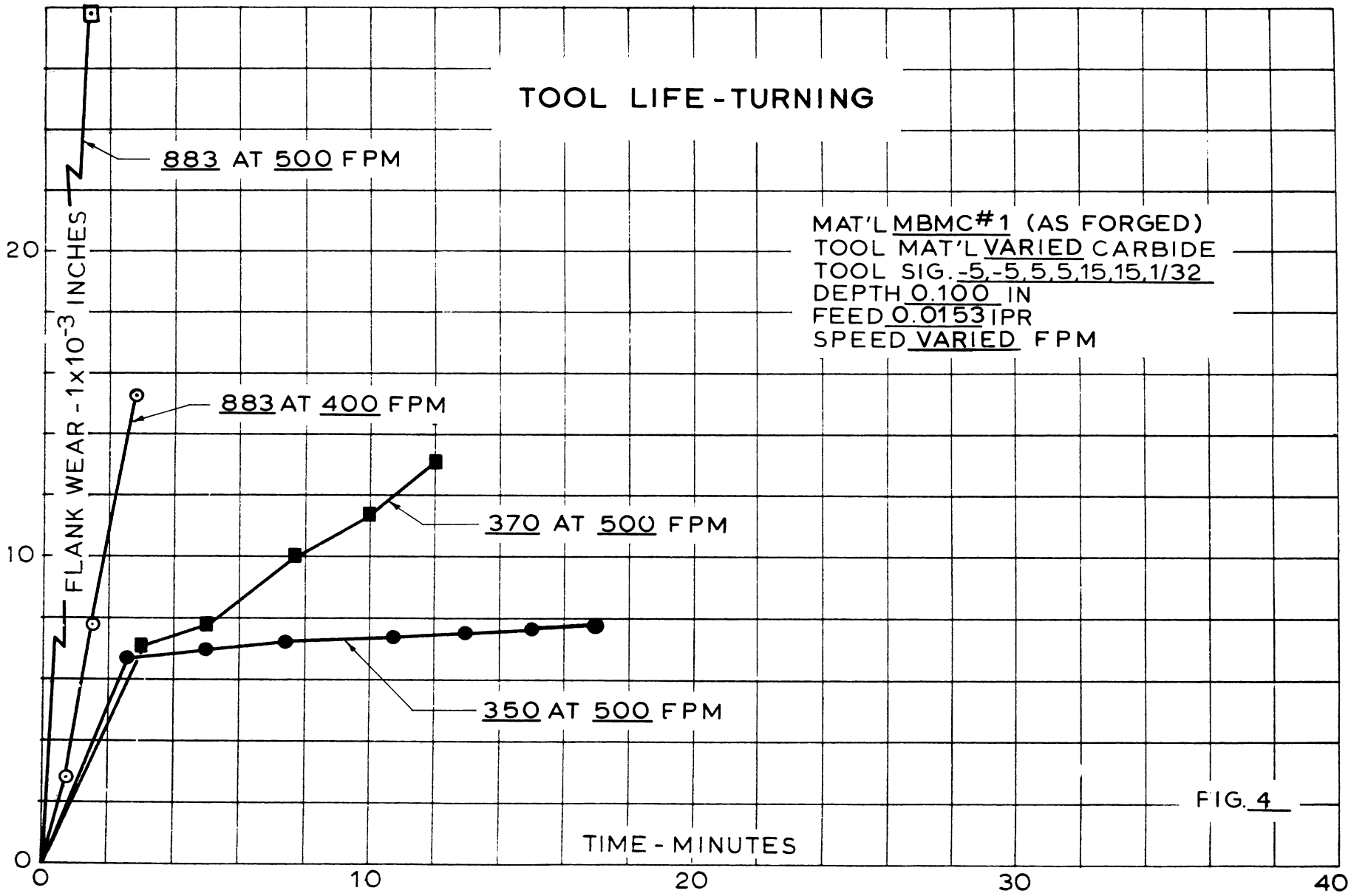

Fig. 4. Tool-life carbides.

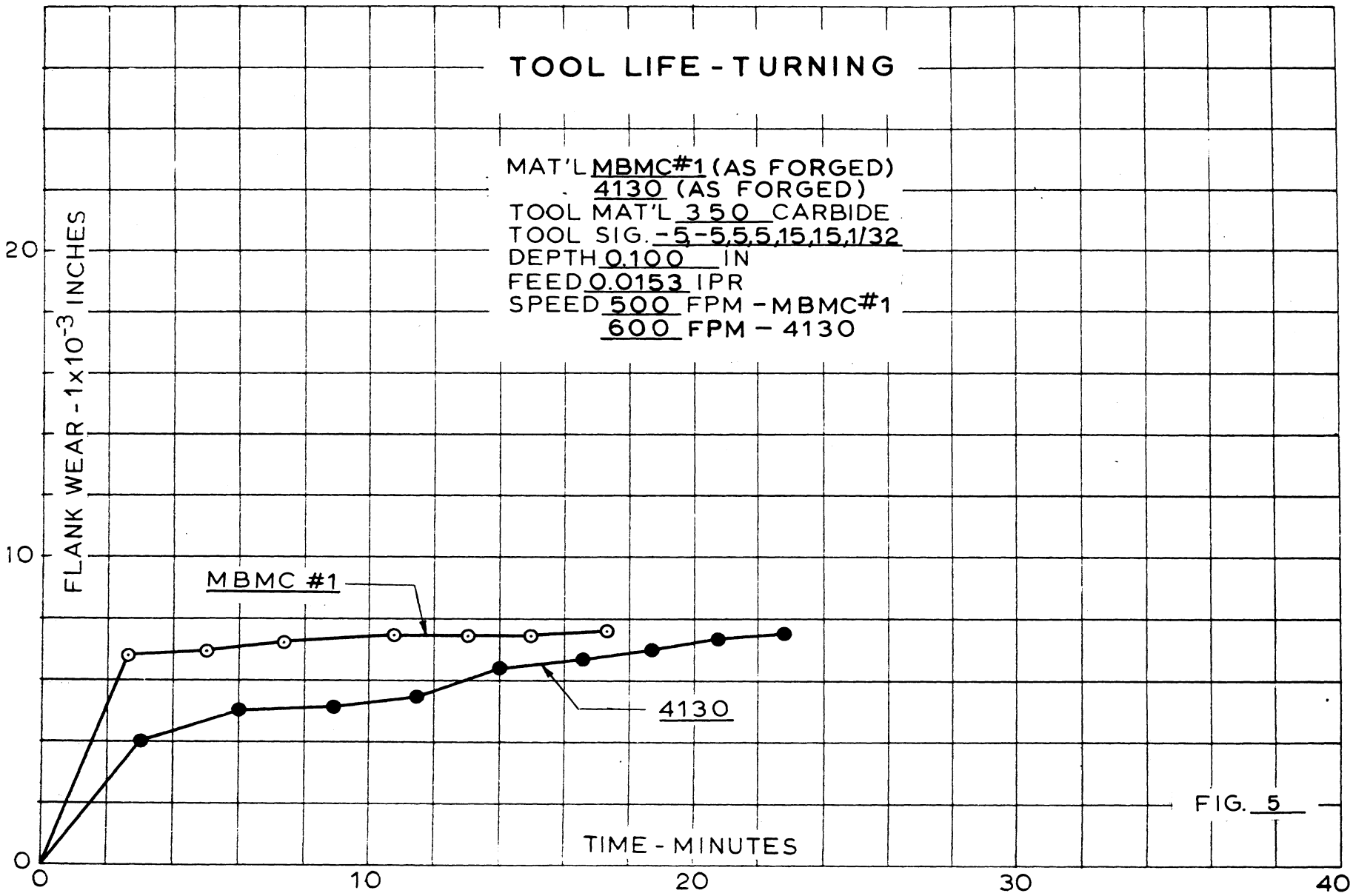

Fig. 5. Tool-life carbides.

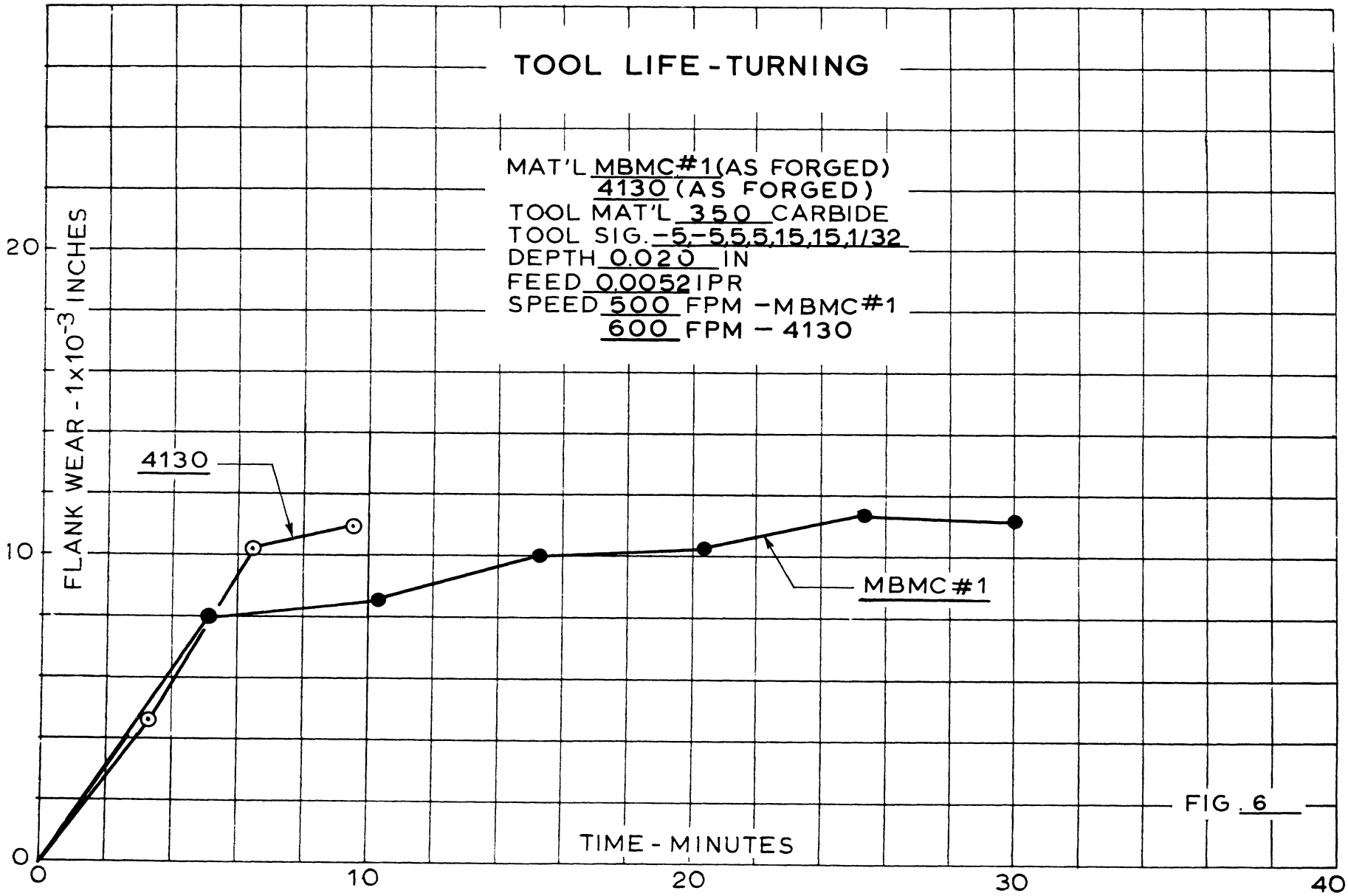

Fig. 6. Tool-life carbides.

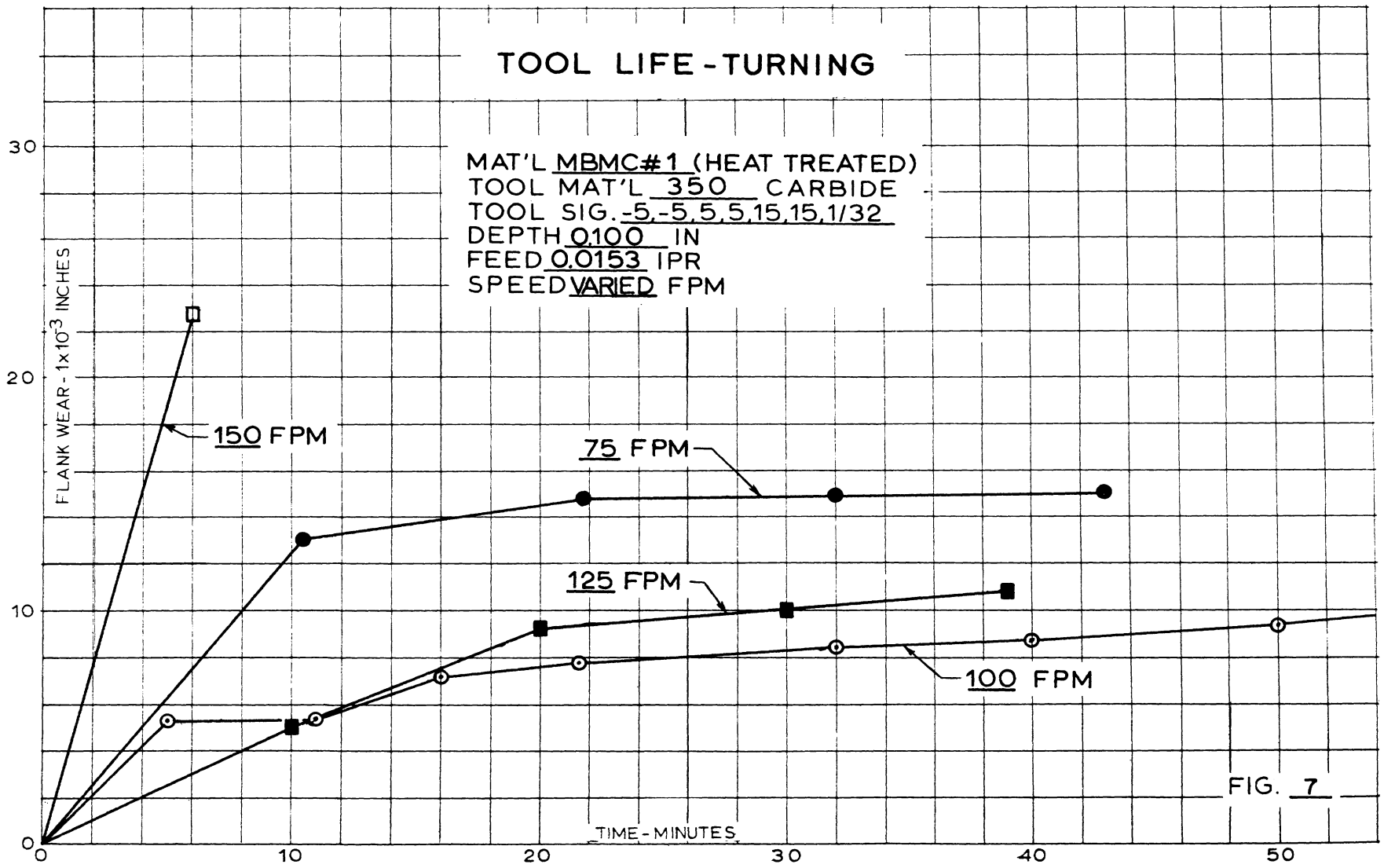

Fig. 7. Tool-life carbides.

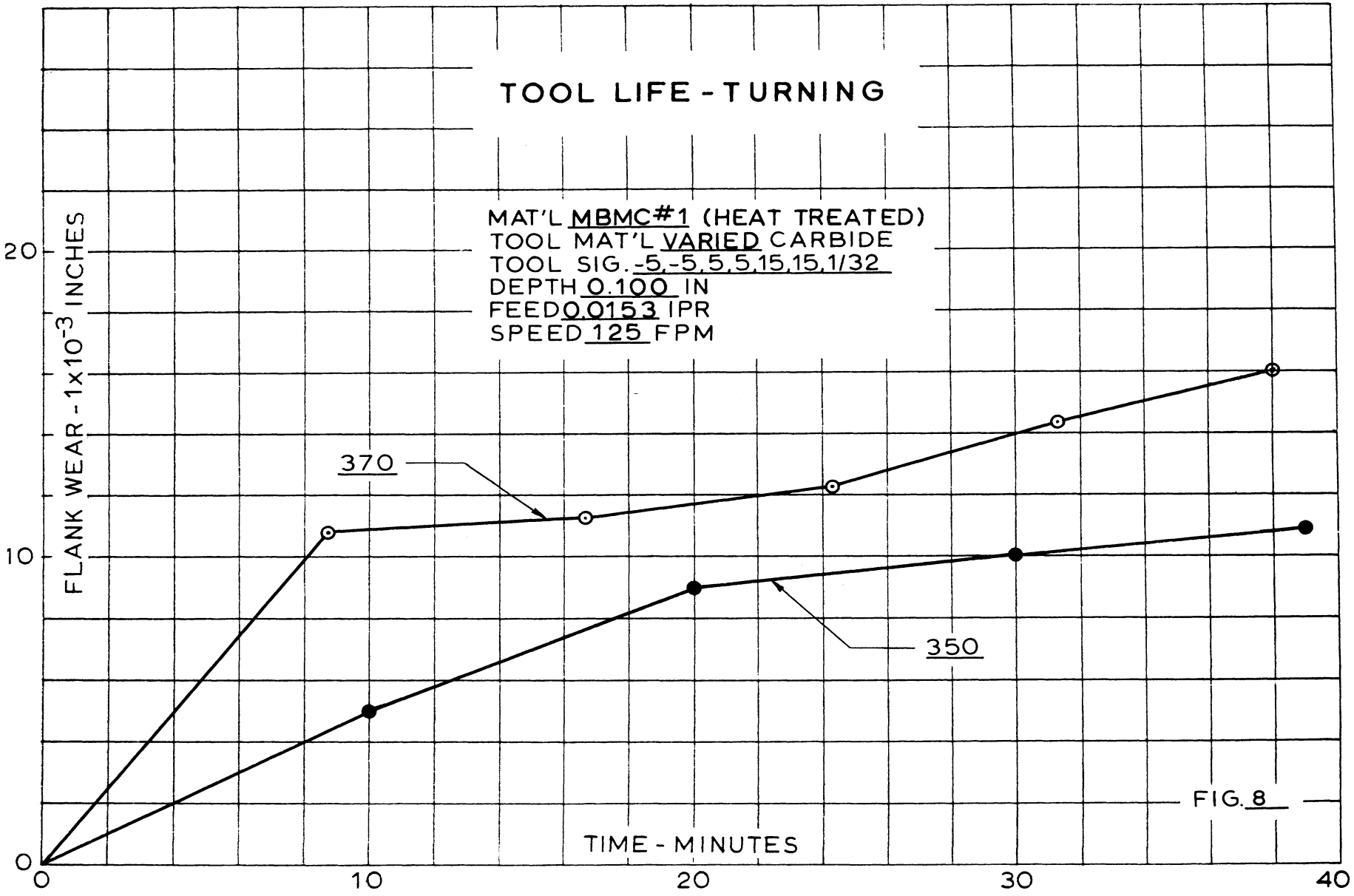

Fig. 8. Tool-life carbides.

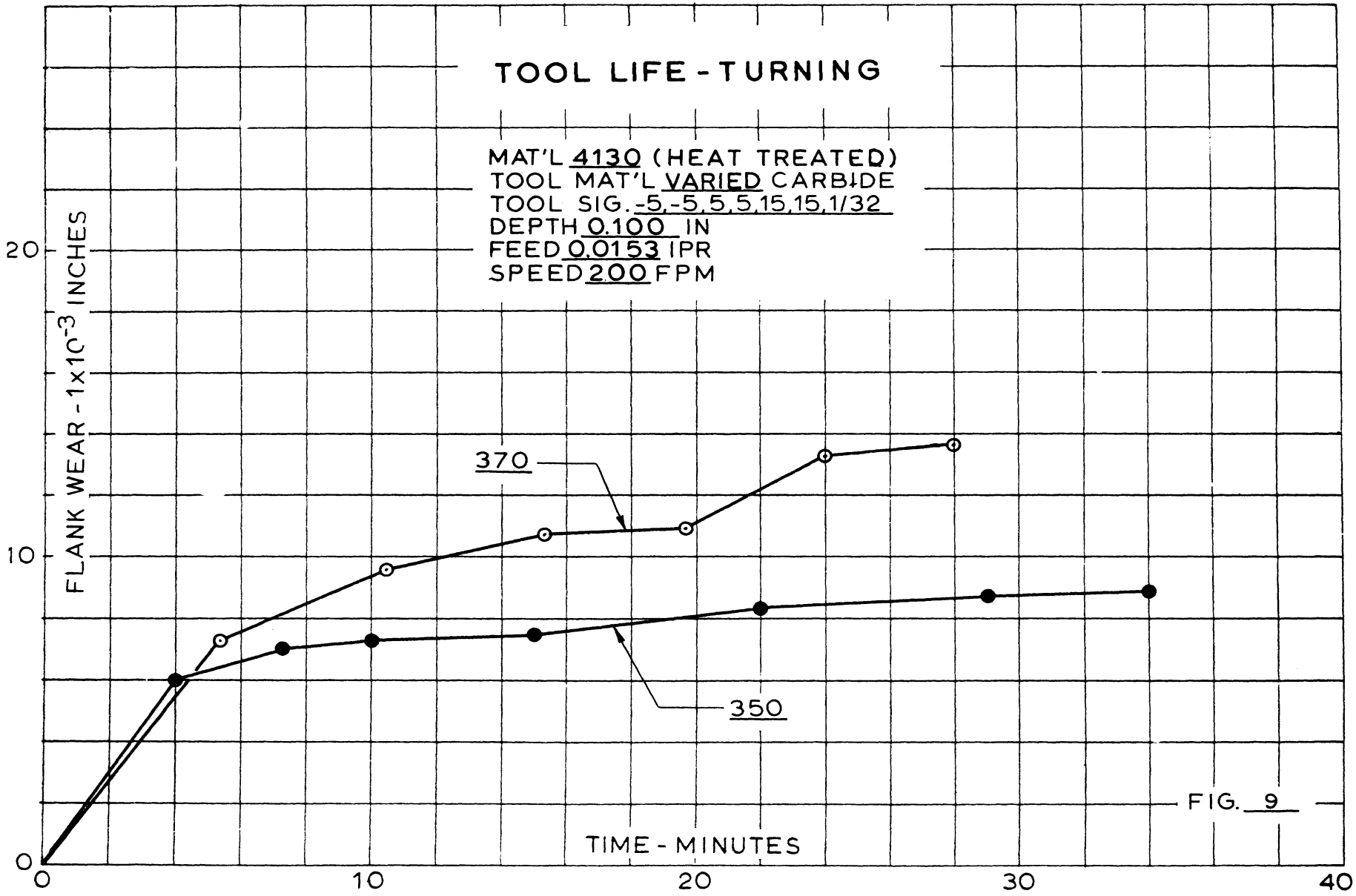

Fig. 9. Tool-life carbides.

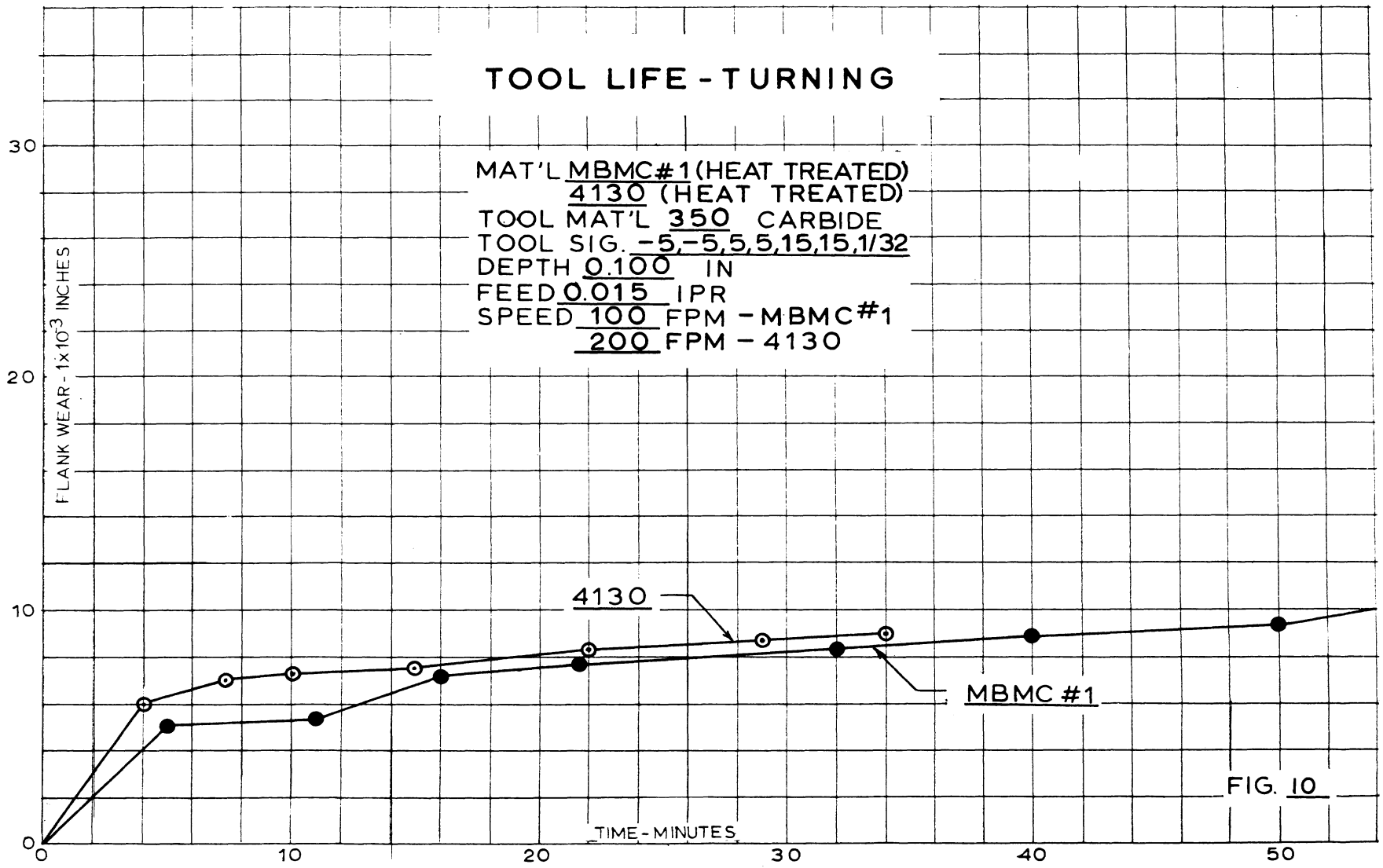

Fig. 10. Tool-life carbides.

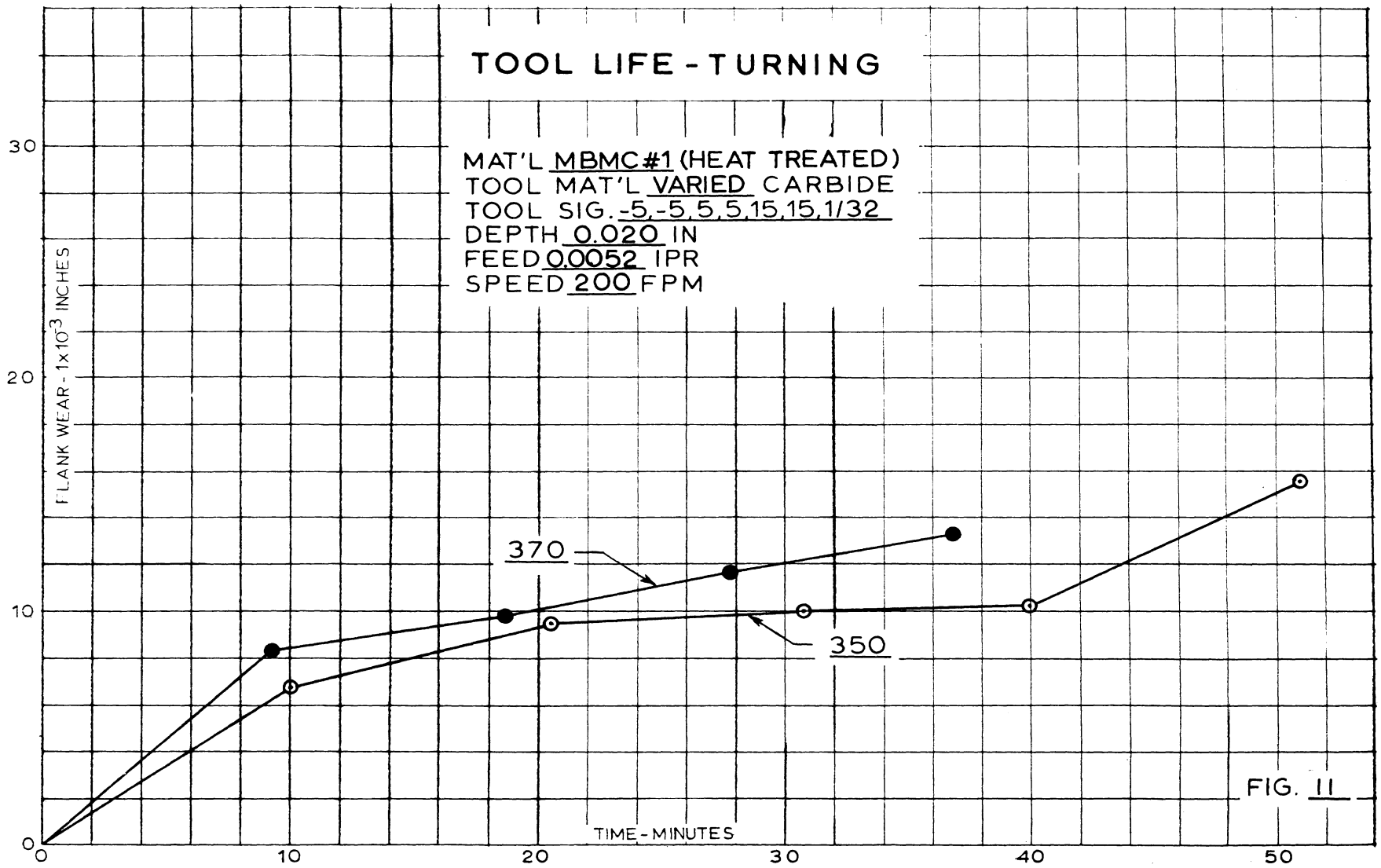

Fig. 11. Tool-life carbides.

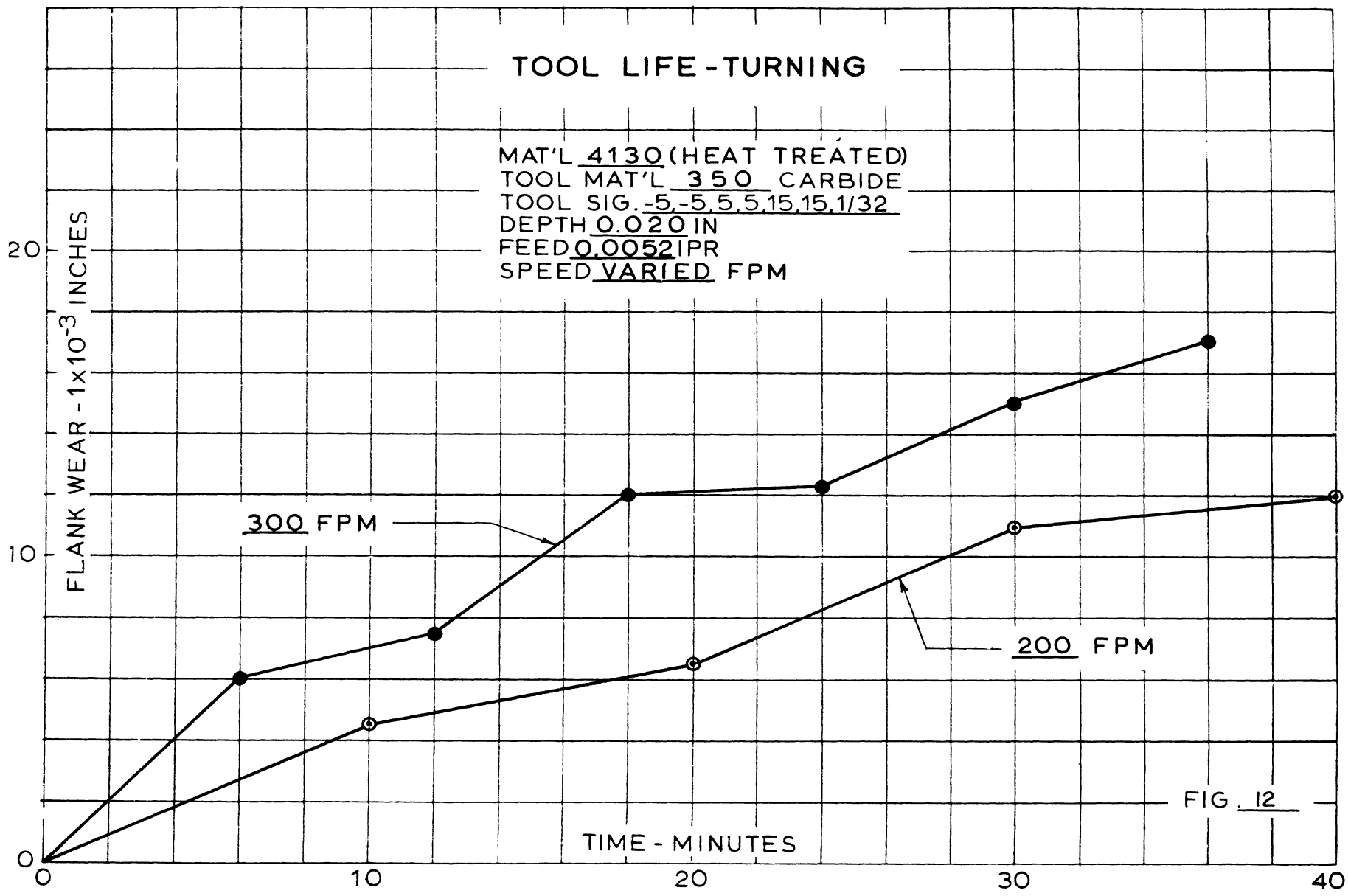

Fig. 12. Tool-life carbides.

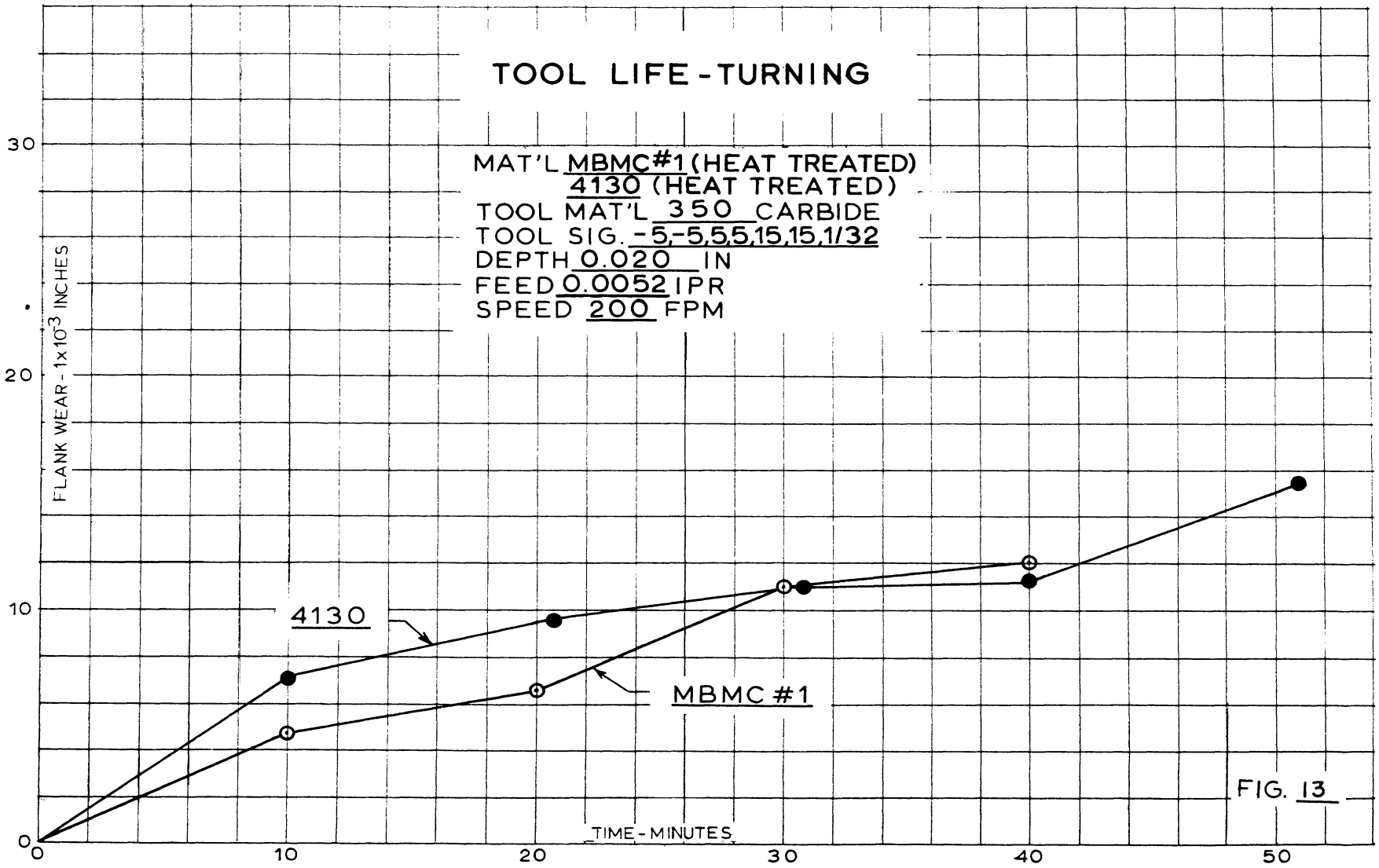

Fig. 13. Tool-life carbides.

the heat-treated MBMC-1 must be reduced 40-50% below that for hardened AISI 4130 for roughing cuts. On the other hand, Figs. 11 to 13 show that MBMC-1 can be cut at approximately the same speed as AISI 4130 for finishing cuts.

Conclusions

(1) Carboloy Grade-350 carbide or equivalent is best for both MBMC-1 and AISI 4130 steels in both the as-forged and the hardened conditions.

(2) MBMC-1 can be cut at the same conditions as AISI 4130 except for roughing cuts on hardened material.

(3) Cutting speeds for hardened MBMC-1 must be reduced 40-50% below those used for rough-turning of hardened AISI 4130 steel.

C. CUTTING FORCES-TURNING

The hardened materials only were subjected to a series of turning tests to determine the magnitude of cutting forces with carbide tools since the tool-life tests indicated that this type of tool material must be used for the heat-treated MBMC-1. Similar information for high-speed steel tools and as-forged work materials was obtained by drilling and milling as reported in (D) and (E).

Test Conditions and Procedure.—The feed rate and the depth of cut were varied in several combinations while the tool shape, tool material, and cutting speed were held constant. All work materials were subjected to the same test procedure wherein readings of cutting force (perpendicular to the plane of tool motion) and feeding force (parallel to axis of work rotation) were obtained for lathe turning cuts.

A 14-in. swing Monarch engine lathe was operated at spindle speeds which produced surface velocities of 200 fpm for the heat-treated 4130 and 100 fpm for the heat-treated MBMC-1 steels, respectively. Feed rates for the 4130 were 0.0038, 0.0076, and 0.0153 ipr, while the depth of cut was maintained constant at 0.100 in. Similarly, the effect of depth of cut was evaluated at depths of 0.020, 0.040, 0.060 and 0.100 in. with the feed held constant at 0.0076 ipr. Feed rates for the MBMC-1 were 0.0028, 0.0038, 0.0056, 0.0076, 0.0112 and 0.0153 ipr, while the depth of cut was constant at 0.100 in. Corresponding depths of cut for a constant feed rate of 0.0076 ipr were 0.020, 0.030, 0.040, 0.060, 0.080 and 0.100 in. The tool signature for all tests was -5, -5, 5, 5, 60, 30, 1/32.

Readings of feeding and tangential forces were obtained simultaneously on a dynamometer equipped with electric-resistance strain gages. No cutting fluid was used.

Test Results.—The effects of feed rate and depth of cut on the cutting or tangential force are shown in Fig. 14. The 4130 steel exhibits a true exponential trend. The equation for this line takes the general form $F_c = Kf^x d^y$, where:

F_c = cutting force in lbs.,
K = a proportionality constant,
f = feed rate in ipr,
d = depth of cut in in., and
x and y = exponents.

Table IV contains the equations derived for this material. The MBMC-1 exhibits nonlinearity and discontinuity. Consequently the equations represent only the maximum forces. This phenomenon appears to be sensitive to the rate of energy release and probably to temperature as well. Spot sampling indicates that abrupt increases in forces occurred at lighter cuts when the cutting speed was higher.

The effects of feed and depth on the feeding force are shown in Fig. 15. An exponential trend is clearly shown for the 4130, but again the MBMC-1 exhibits unstable cutting at certain combinations of conditions.

TABLE IV

SUMMARY OF CUTTING FORCE EQUATIONS

Material	Equations	Force Component
4130	$F_c = 88{,}350f^{0.70}\ d^{0.83}$	Tangential
Inch	$F_f = 11{,}550f^{.40}\ d^{.84}$	Feeding
MBMC-1	$F_c = 63{,}500f^{.58}\ d^{.91}$	Tangential
Inch	$F_f = 8{,}100f^{.20}\ d^{.93}$	Feeding

D. DRILLING TORQUE AND THRUST

The two work materials (as-forged) were drilled at several different cutting conditions to determine the effects of feed rate and drill diameter on

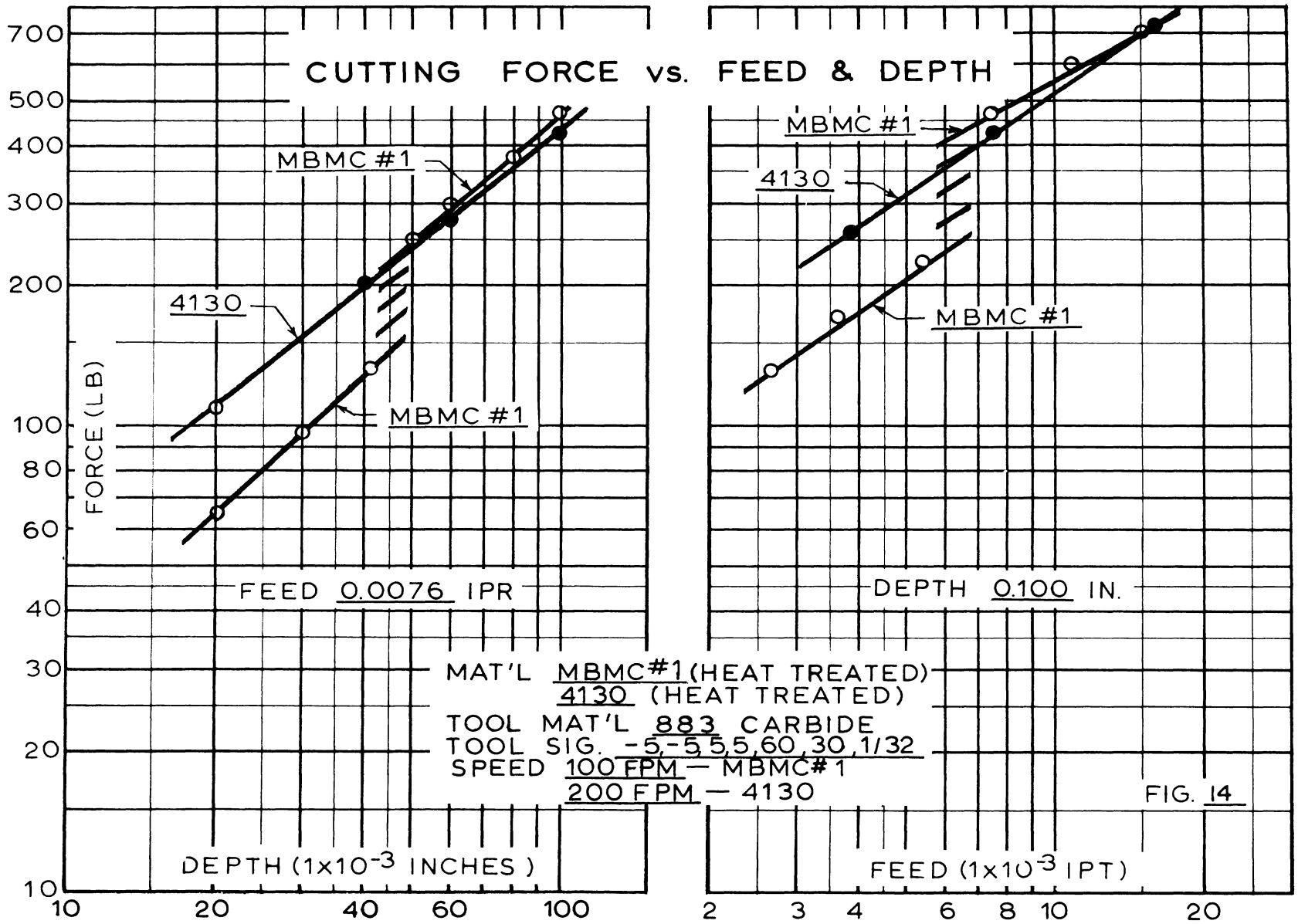

Fig. 14. Cutting force "F_c" vs. size of cut.

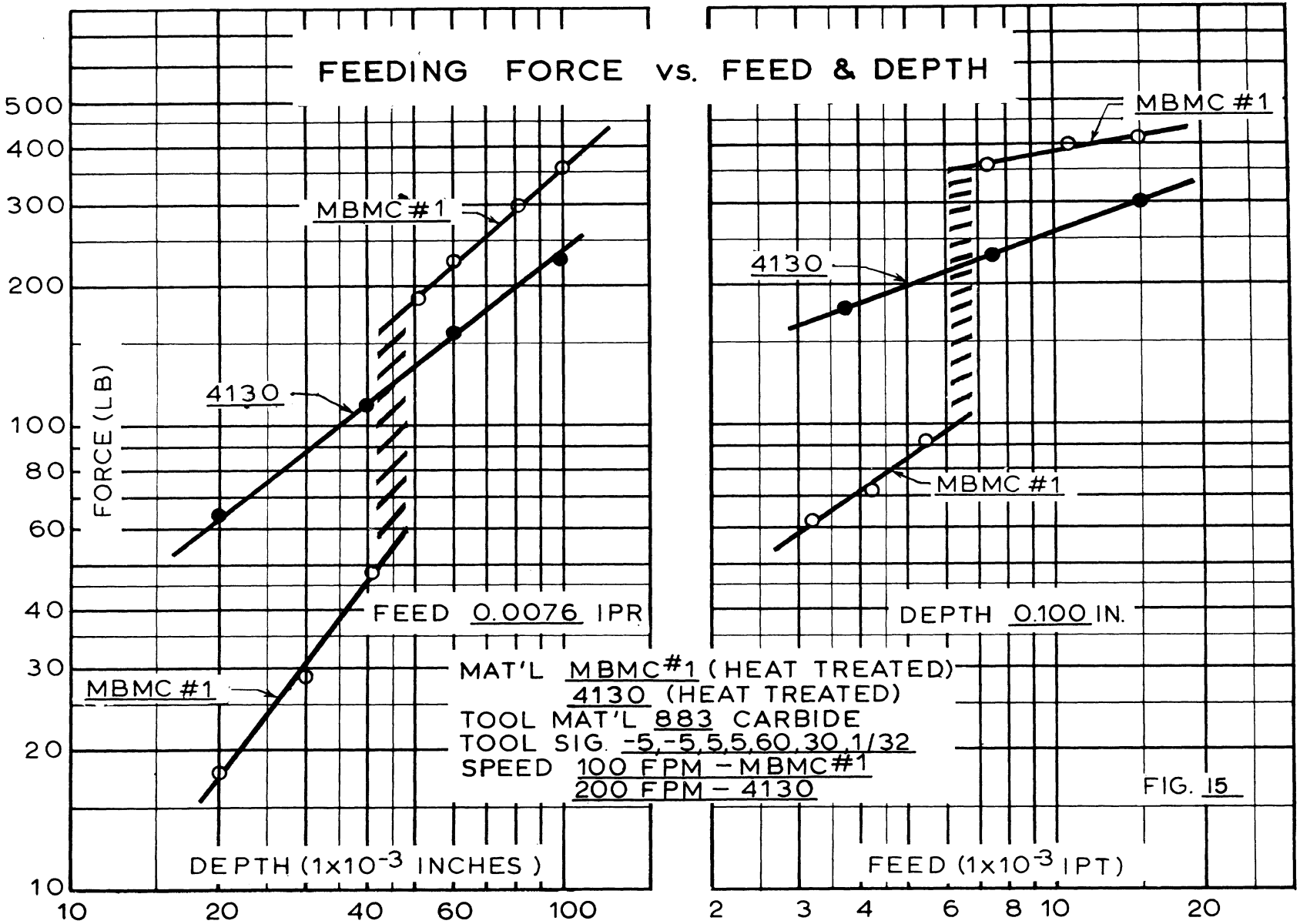

Fig. 15. Feeding force "F_n" vs. size of cut.

torque and thrust requirements.

Procedure.—Test specimens were in the form of rectangular pieces, 1 x 1-1/4 x 4 in. long. The workpieces were held in a vise on a dynamometer and drilled at a particular feed rate and cutting velocity. When the readings of torque and thrust stabilized, the cut was discontinued. The same procedure was followed for both work materials.

A sharp drill was used for each test. Several tests were duplicated to check the repeatability of the results.

Test Conditions.—All tests were conducted on a Fosdick 25-in., box column, upright drill press at a cutting velocity of 35 fpm. All drilling was done dry.

Drills were standard high-speed steel, two-fluted twist drills. They were ground to a point angle of 118° and a relief angle of 6°. The helix angle was 30°. Web thicknesses are listed below.

Drill Diam., in.	Web Thickness, in.
0.250	0.043
0.375	0.066
0.500	0.082
0.625	0.086

At constant drill diameter of 0.375 in., the feed rates were 0.005, 0.007, 0.009, and 0.011 ipr. At constant feed rate of 0.005 ipr, the drill diameters were 0.250, 0.375, 0.500 and 0.625 in.

A dynamometer containing wire-resistance strain gages was used to obtain readings of torque and thrust.

Test Results.—Figures 16 and 17 show the results plotted on logarithmic coordinates.

The effects of drill diameter and feed rate on cutting torque (lb-in.) and thrust (lb) show a uniform behavior or exponential trend. Such straight lines may be represented by equations of the general forms

$$T = Kf^aD^b \text{ and } B = Cf^xD^y$$

where:

T = cutting torque in lb-in. (sharp tools),
K = a proportionality constant,

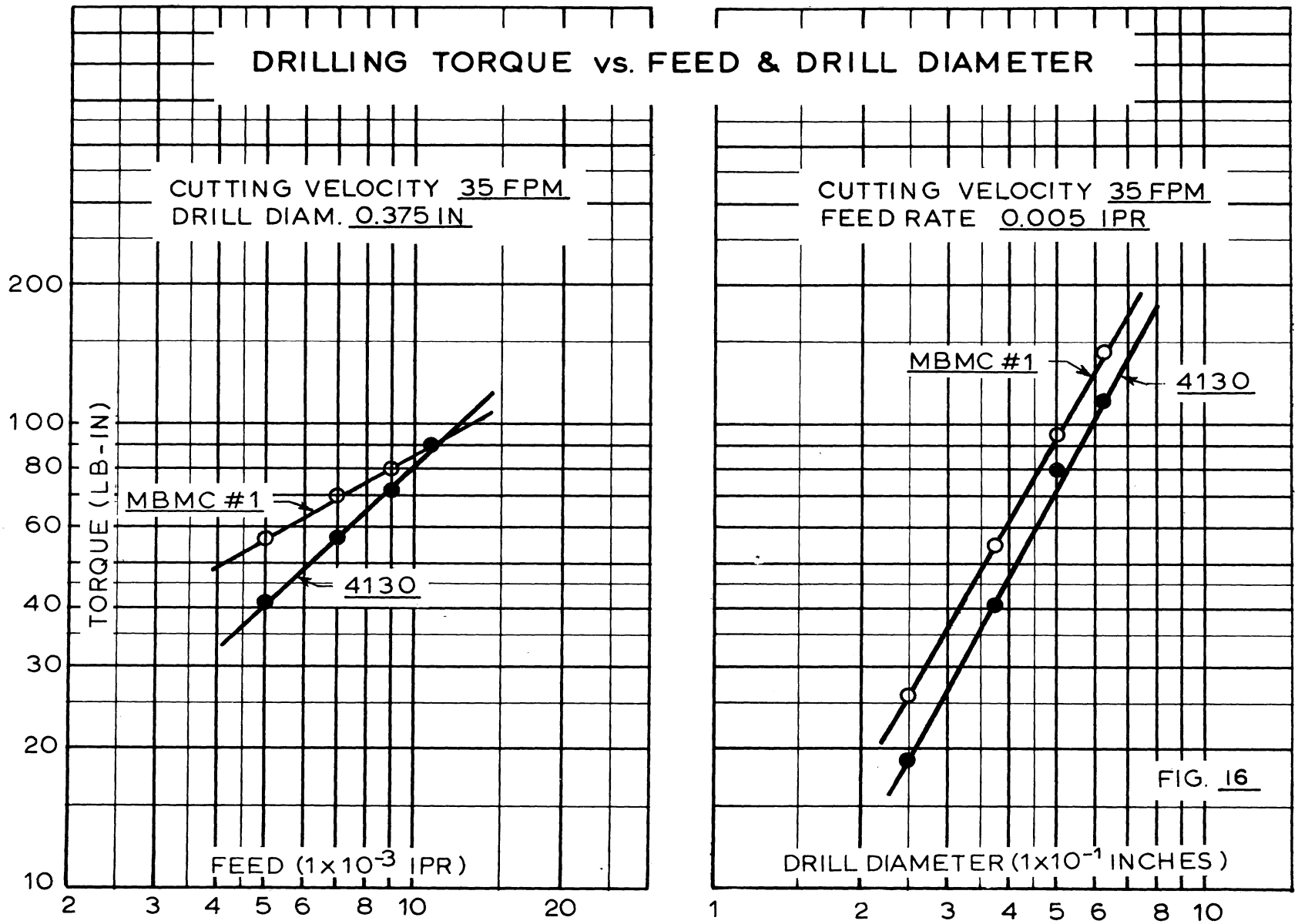

Fig. 16. Drilling torque vs. feed and drill diameter.

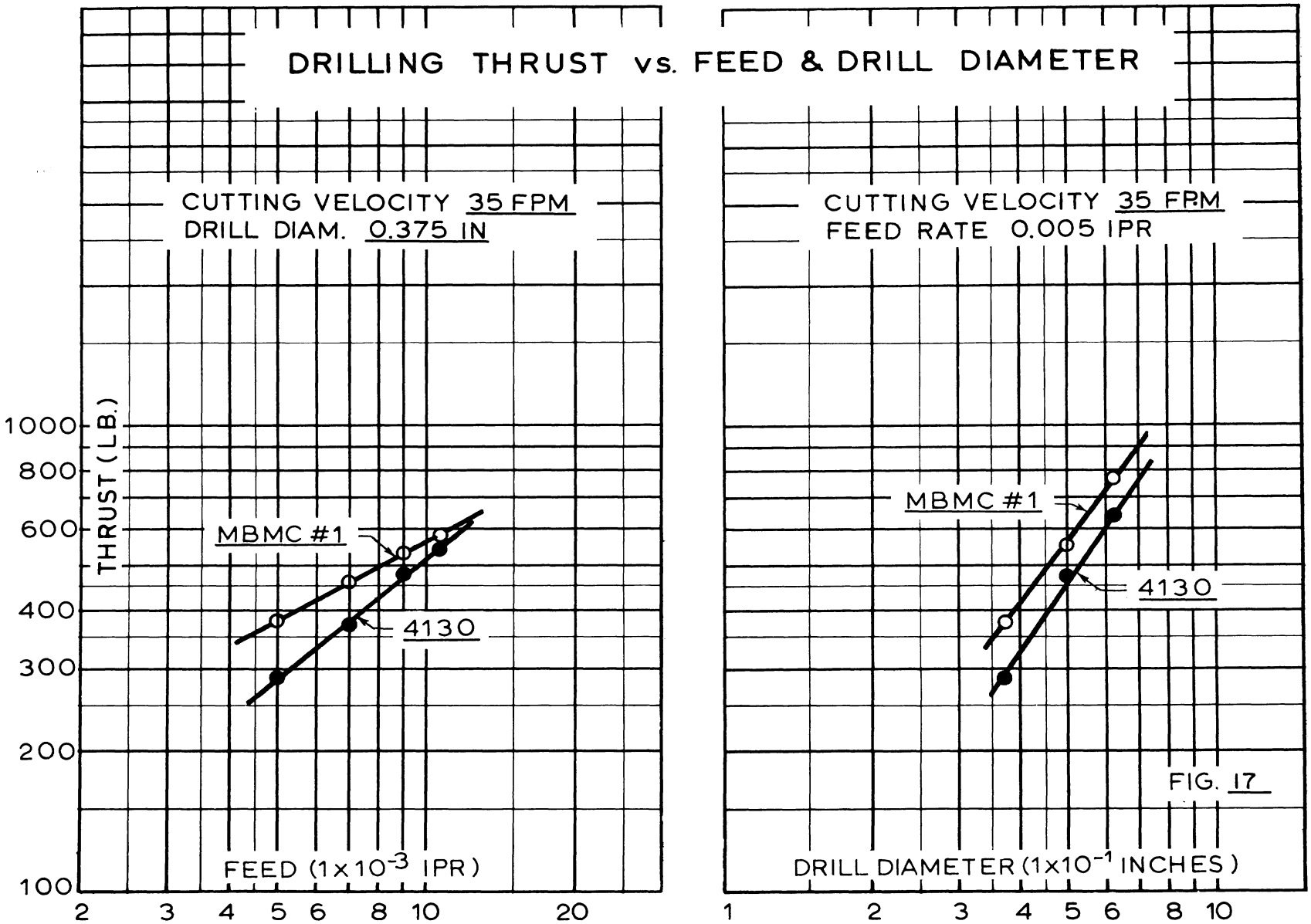

Fig. 17. Drilling thrust vs. feed and drill diameter.

f = feed rate, ipr,
D = diameter of drill, inches,
a and b = slopes of lines showing the effects of feed and drill diameter on torque,
B = thrust force in lb (sharp tools),
C = proportionality constant,
x and y = slopes of lines showing the effects of feed and drill diameter on thrust.

Tables V and VI contain the equations derived from the straight lines. These can be used to calculate the torque and thrust when drilling the two materials (as-forged) and are most applicable within the range of variables actually used in this study.

TABLE V

DRILLING TORQUE AS A FUNCTION OF FEED RATE AND DRILL DIAMETER

Material	Equations
4130	$T = 47{,}650f^{0.96}D^{2.03}$
MBMC-1	$T = 7{,}230f^{0.57}D^{1.88}$

TABLE VI

DRILLING THRUST AS A FUNCTION OF FEED RATE AND DRILL DIAMETER

Material	Equations
4130	$B = 76{,}450f^{0.77}D^{1.54}$
MBMC-1	$B = 30{,}850f^{0.58}D^{1.38}$

Conclusions

(1) The effect of feed rate on torque is more pronounced for the 4130 material as can be concluded from the slope of the lines.

(2) At the higher feed rate the torque for both the MBMC-1 and 4130 are the same for the given drill diameter.

(3) The MBMC-1 exhibited higher torque readings consistently relative to the effect of drill diameter.

(4) The effect of feed rate on thrust is also more pronounced for the 4130 material.

(5) Effect of drill diameter on drill thrust resulted in consistently higher forces for the MBMC-1 material.

(6) The most important difference between the two work materials is that the MBMC-1 does not cut as well nor as efficiently at small feed rates.

E. ENERGY REQUIREMENTS

Energy requirements were measured directly with a pendulum type dynamometer in a milling cut. High-speed steel tools with a rake angle of 8° simulated average shop conditions.

Test Conditions and Procedure.—The HSS cutting tool had a width of 0.245 in., 8° radial rake angle, 6° side clearance angles, and 12° end clearance angle. Ten cuts were made at a depth of cut of 0.100 in. and a feed setting of 0.003 ipt; the work advanced 0.003 in. for each successive cut. After the above cuts were made, tests were run at a feed setting of 0.006 ipt for ten cuts, then changed to 0.010 ipt for another ten cuts. The above sequence of feed settings was repeated at depths of cut of 0.060 in., and 0.020 in., ten cuts being taken for each combination. The same procedure was used for both work materials.

Test Results.—Figures 18 and 19 show the results plotted on logarithmic coordinates.

The effects of feed (ipt) and depth of cut upon the energy requirements can be expressed by the equation:

$$E = Kf^x d^y$$

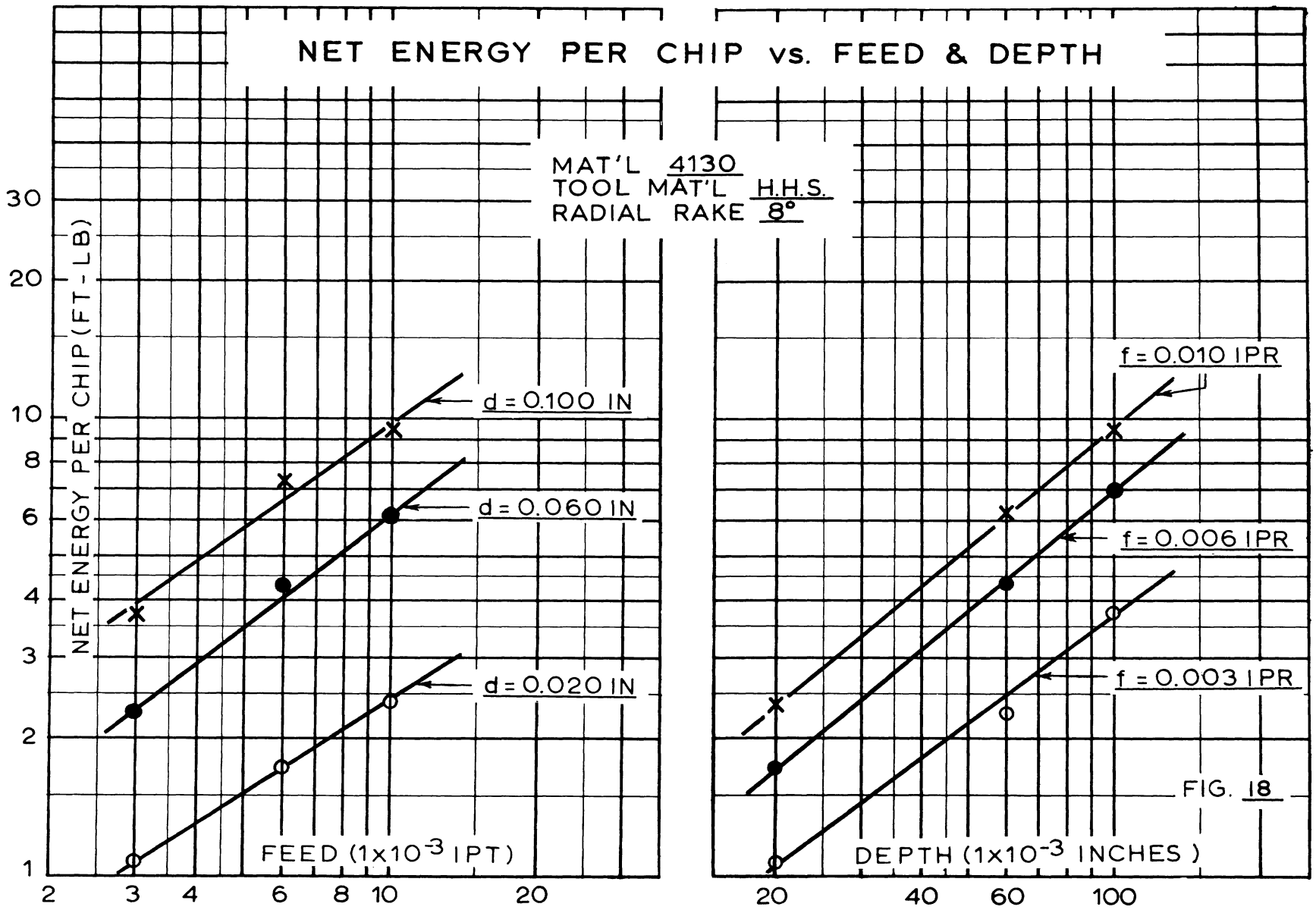

Fig. 18. Cutting energy for AISI 4130 steel.

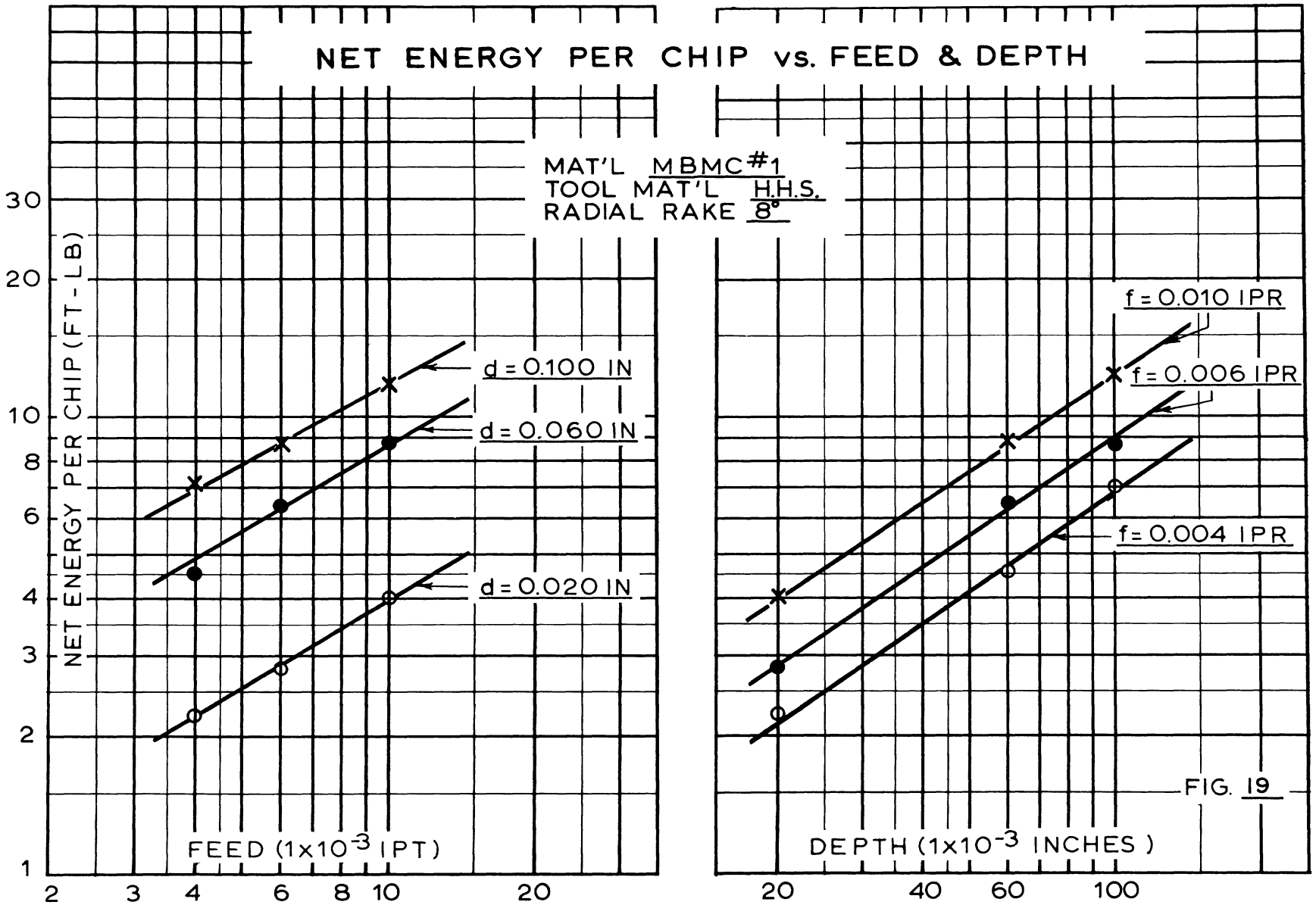

Fig. 19. Cutting energy for MBMC-1 steel.

where:

E = energy in ft-lb per chip,
K = a proportionality constant for calculating energy,
f = feed in inches per tooth,
d = depth of cut in inches,
x and y = slopes of lines showing the effects of feed and depth on the energy required to cut.

Table VII contains the equations derived from the straight lines shown in Figs. 18 and 19.

TABLE VII

CUTTING ENERGY FOR MILLING

Material	Energy Equations	Unit HP_c*
4130	$E = 2{,}200f^{0.76}d^{0.84}$	1.16
MBMC-1	$E = 873f^{0.60}d^{0.70}$	1.48

*Feed, 0.010 ipt; depth, 0.100 in.

Conclusions

(1) The energy required to cut the MBMC-1 is consistently higher for all combinations of cutting conditions.

(2) Both materials exhibit a common characteristic relative to the effect of feed versus the effect of depth. The above equations show that the energy per chip increases with an increase in feed and depth of cut only as the 0.60 power of the feed and the 0.70 power of the depth of cut for the MBMC-1. For the 4130 the same is true, the power of the feed being 0.76 and 0.84 for the depth of cut. This indicates the desirability of taking heavy feeds from a power standpoint. This property is common to most metals.

VI. SPECIFIC CONCLUSIONS

(1) Tool Life with High-Speed Steel Tools

(a) Cutting speeds for the as-forged MBMC-1 must be about 40% lower than for as-forged 4130.

(b) It is impractical to cut heat-treated MBMC-1 with high-speed steel tools.

(2) Tool Life with Carbide Tools

(a) Carboloy Grade 350 or equivalent is satisfactory for both steels in both the as-forged and hardened conditions.

(b) As-forged MBMC-1 can be cut at speeds about 80% as high as for as-forged 4130.

(c) Hardened MBMC-1 must be cut at about 50%-70% of the speed for hardened 4130.

(3) Tool Life with Ceramic Tools

(a) It is feasible to turn both as-forged and hardened MBMC-1 at speeds from 600 to 1000 fpm.

(4) Cutting Forces

MBMC-1 produces substantially higher cutting forces than 4130 in both the as-forged and hardened conditions. Consequently, it is necessary to provide substantial rigidity to obtain satisfactory tool life, surface finish, and size control.

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