THE UNIVERSITY OF MICHIGAN RESEARCH INSTITUTE
ANN ARBOR, MICHIGAN

Final Report

SOME MACHINABILITY STUDIES ON EATON PERMANENT MOLD IRON

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UMRI Project 2675

EATON MANUFACTURING COMPANY
VASSAR, MICHIGAN

July 1958

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ABSTRACT

The machinability tests conducted in this study were designed to be typical of commercial conditions. The results of cutting Eaton Permanent Mold Iron (EPMI) indicate that:

(1) positive rake tools are appreciably better than negative rake tools;
(2) K6 is a good grade of carbide, although K8 and K11 are somewhat better;
(3) optimum cutting, in terms of metal removal, occurs at a speed of about 350 fpm;
(4) the feed for maximum metal removal per tool grind is about 0.011 ipr;
(5) the machinability of EPMI is considerably better than pearlitic gray iron of the same hardness and nearly as good as ferritic gray iron of much lower hardness.

INTRODUCTION

This project was initiated by the Eaton Manufacturing Company to fulfill three objectives: first, to determine the optimum machining conditions for annealed permanent mold iron in a turning operation; second, to conduct tool-life tests on the first 1/8-in. depth of the castings so that optimum machining rates could be determined (the five variables to be investigated for the second objective were: cutting speed, rake angle, tool material, feed,and depth of cut); and third, to conduct selected tool-life tests on the interior or "base metal" of the castings to develop data that could be directly compared to published data of the Gray Iron Founders Society.

Other factors were discussed in planning this program with a view toward further investigation. One of particular interest was the possibility of cleaning the castings prior to machining to improve the machinability of the cast surface.

TEST PROCEDURE

All the machining tests were conducted on a modified, 12-in. swing Monarch engine lathe equipped with a General Electric "Thymotrol" Variable Speed Drive that permitted constant cutting speed at all conditions of load. The tool life of the carbide tools was determined by measuring the wear on the tool flank by means of a tool-maker's microscope equipped with a measuring dial graduated to ten-thousandths (.0001) of an inch. Standard practice in machinability studies with carbide tools was followed. That is, the cutting was interrupted after periodic intervals and the progression of the tool wear recorded. The tool life of the high-speed steel tools was determined by running them to complete failure, that is, until the flank wore away to such an extent that the tools no longer cut any metal. This also is customary practice in machinability studies.

All the tests were conducted dry; in other words, no cutting fluids were used. The cutting times were measured by means of a stop watch whereas the cutting speed was measured by means of a "cut-meter," a tachometer with a 6-in. disk that rotates with the work and records the cutting speed directly in feet per minute rather than revolutions per minute.

The work material tested consisted of regular production-run castings as shown in Fig. 1. The actual machining procedure was performed as follows.

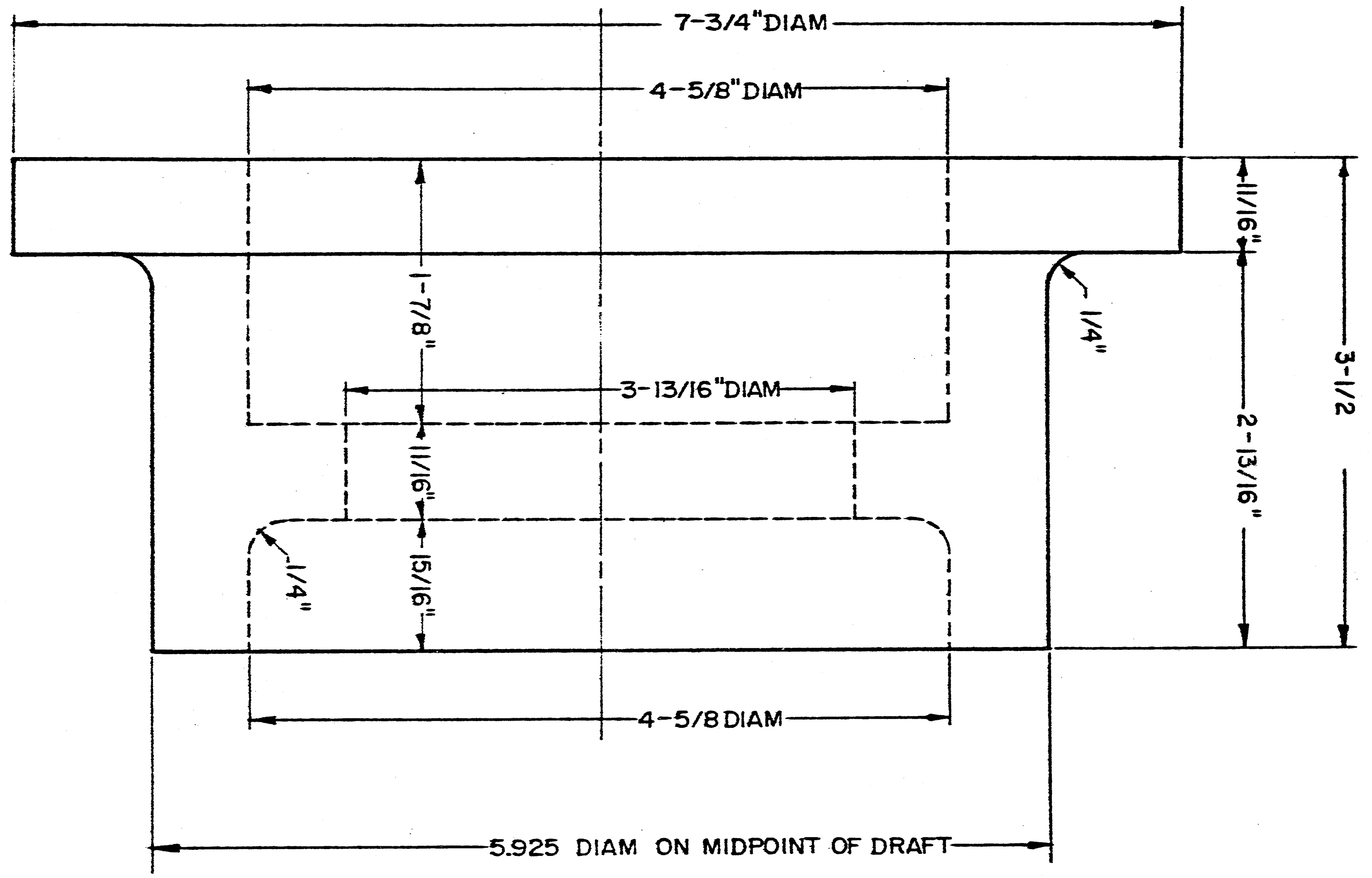


Fig. 1. Casting used in turning tests. Material: Eaton Permanent Mold Iron.

The casting was clamped in a four-jaw chuck on the 7-3/4-in. diameter. It was positioned in the chuck so that the 5.925-in. diameter was concentric to the axis of rotation within ±0.005 in. Then with the work rotating at the proper speed, the cutting tool was positioned 1-1/4 in. from the free end of the 5.925-in.-diam. cylinder and fed in radially by hand until the tool just touched the casting surface. The tool and lathe carriage were then moved beyond the free end of the casting, and the tool was fed in radially a distance of 0.100 in. to obtain the depth of cut. Because of the draft on the casting, the depth of cut near the free end of the casting was about 0.080 in. while near the 7-3/4-in.-diam. shoulder the depth of cut was about 0.120 in. This variation would not have any measurable effect on the results. The length of cut was restricted to 2-1/2 in. along the 5.925-in.-diam. cylinder to avoid machining into the 1/4 in. radius at the shoulder. By this means 4.64 cu. in. of metal were removed from each casting during the surface cut. The cut was stopped after the tool had cut for only 0.1 min. (or after the tool had just cut through the flat surface) and the wear was measured. On the first casting of each series of tests the wear was measured again after one-half of the cylinder was cut. On all the other castings, the wear was measured only after the initial break-through and again after the casting was completely machined.

TEST CONDITIONS

At the first conference held after the project was initiated, the following outline of tests was agreed upon.

I. With K6 grade, -5, -5 rake, f = 0.006 ipr, d = 0.100 in., machine 2 castings at each of the following speeds: 500, 700, and 800 fpm (to determine optimum speed for machining tests).

II. With K6 grade, f = 0.006, d = 0.100, speed = 600 fpm, machine castings with rake angles of -5, -5; 0,0; 0, +5. (-5, -5 rake was repeated for verification.)

III. Run the most promising tool (0, +5) to a total of 20 castings.

IV. With K6 grade, f = 0.006, d = 0.100, V = 600 fpm, determine machinability of base (interior) material by taking 3 additional cuts on already machined castings. Use both (0, +5) and (-5, -5) rake tools.

V. With (-5, -5) rake, f = 0.006, d = 0.100, V = 600, machine 8 castings with each of the following grades: K1, K8, and K11.

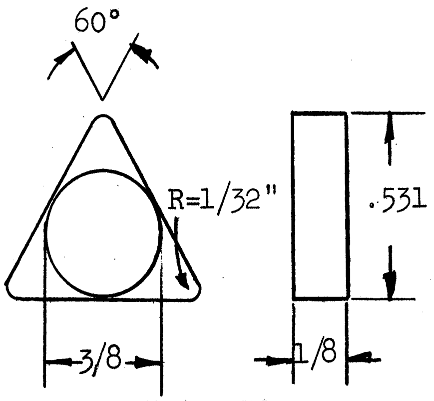
VI. With K6 grade, (-5, -5) rake, and V = 600 fpm, machine 8 castings with the following combinations of feed and depth:

a. $f = 0.003$ $d = 0.100$
b. $f = 0.012$ $d = 0.100$
c. $f = 0.006$ $d = 0.050$
d. $f = 0.006$ $d = 0.025$

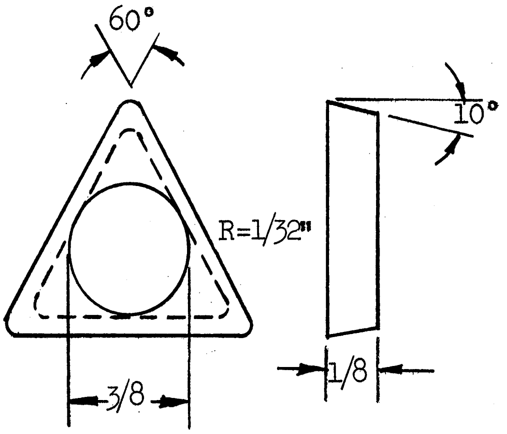
VII. Repeat step VI with (0, +5) rake tool.

VIII. With H. S. S. tools of 8, 14, 6, 6, 6, 15, 3/64 in. R; $f = 0.006$, $d = 0.100$; run tool-life tests with fives up to 20 min.

DIMENSIONS OF INSERTS



BT122-P2
All surfaces ground.



BTC-12
Ground top and bottom.

HIGH-SPEED STEEL TOOLS:

Type: 18W, 4Cr, 1Va.
Size: 3/8-in. square
Shape: 8° back rake; 14 side rake; 6° end and side clearance; 6° end cutting; 15 side cutting edge; 3/64-in. radius.

CUTTING TOOLS

The cutting tools used in this study are summarized in Table I. All the tools were obtained from commercial stock. The carbide tools were the triangular "throw-away" type that require no grinding when used with either the standard negative or positive rake angles. The negative-rake tools have six usable cutting edges since both the top and bottom faces can be used, whereas the positive-rake tools have only three cutting edges. To obtain the zero rake angles, the top face of the standard positive-rake-angle tools were ground.

TABLE I

SUMMARY OF CUTTING TOOLS
CARBIDE TOOLS: KENDEX BUTTON TOOLS

Grade*	Rake Angles		Tool Holder No. (Right Hand)	Insert No.	Rockwell "A" Hardness	Recommended Application
	Back	Side				
K1	-5	-5	KTAR-12	BT-122P2	90.0	For heavy cuts on cast iron.
K6	-5	-5	KTAR-12	BT-122P2	92.0	General purpose for cast iron.
	0	0	KTAR-12C	BTC-12X*		
	0	+5	KTAR-12C	BTC-12		
K7	0	+5	KTAR-12C	BTC-12	93.5	For high-velocity cuts on steel.
K8	-5	-5	KTAR-12	BT-122P2	92.5	For light cuts on cast iron.
K11	-5	-5	KTAR-12	BT-122P2	93.0	For fine finishing cuts on cast iron.

*
Reground from BTC-12

During cutting, all the tools were mechanically clamped in a standard 3/4 in. by 3/4-in. by 4-1/2-in. tool holder.

The high-speed steel tools were standard 3/8-in. square 18-4-1 type ground to the shape specified in Table I. Special care was taken to be sure that all tools were ground to exactly the same angles and that none of them were "burned" or heat-checked during grinding.

DISCUSSION OF RESULTS

For clarity and ease of reference, the discussion of results is broken up into distinct sub-headings according to the various parameters studied.

A. OPTIMUM MACHINING CONDITIONS FOR TURNING TEST

Since the sponsor desired that these machinability tests resemble as much as possible the actual production machining conditions that permanent mold castings are subjected to and at the same time obtain research data that could best be compared to other published data, it was decided that a depth of cut of 0.100 in. and a feed of 0.006 ipr would be standardized in these tests, except when the feed and depth would be studied as variables.

Carbide tools of the "throw-away" or button type were selected because this type is gaining widespread usage in the production machining of cast iron, and since they are finish-ground by the tool manufacturer, it was not necessary to grind the tools for these tests. Kennametal grade K6 was selected as the standard tool grade for most of these tests. However, some tests were run with both harder and softer grades.

Optimum cutting speed was determined by machining two castings each at speeds of 500, 700, and 800 fpm. The tool wear at 800 fpm was found to be too great and it was doubtful if the wear at 500 fpm would be sufficient to justify extrapolation to 0.030 in. Consequently, a cutting speed of 600 fpm was selected as the test speed for all conditions except where the speed was to be a variable.

B. EFFECT OF RAKE ANGLES ON TOOL PERFORMANCE

Eight castings were machined with each of the three rake-angle combinations. The results of these tests are shown graphically in Fig. 2 where both the average tool wear and the maximum tool wear are plotted as a function of each of the following: number of castings machined, number of minutes of actual cutting time and cubic inches of metal removed. The tool wear along the flank was not uniform so both maximum and average values were determined.

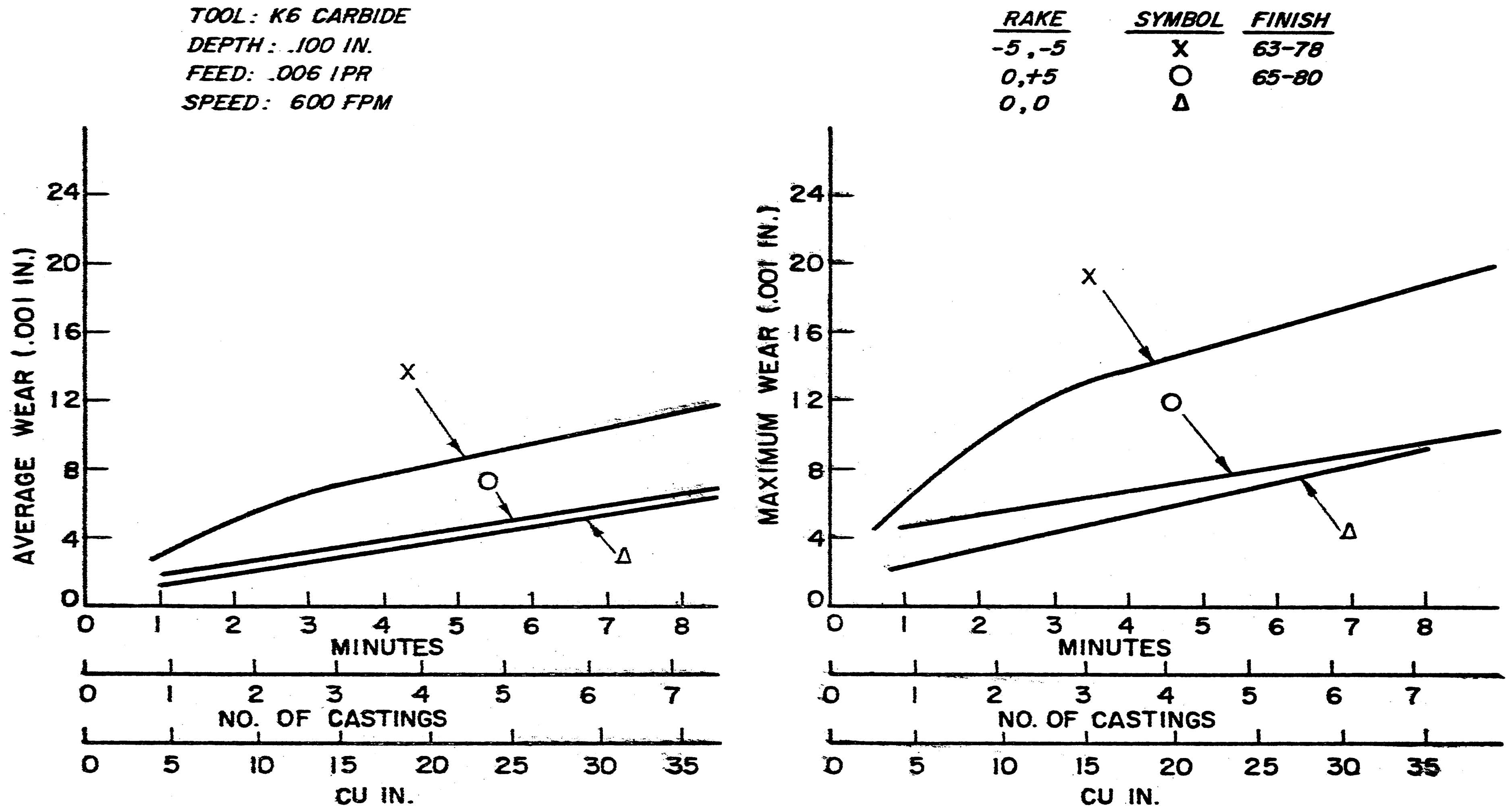


Fig. 2. Effect of rake angle on tool wear.

Figure 2 illustrates clearly that the negative-rake-angle tool (-5, -5) wore more rapidly than either the zero-rake (0, 0) or the positive-rake (0, +5) tools. This is in agreement with the general machinability tables that have been compiled in the past for the common engineering metals. In machining the surface of Eaton Permanent Mold Iron, there is a difference in tool wear between the zero-rake and the positive-rake tools. This is illustrated in the bar graphs of Fig. 3.

The superior performance of the positive-rake tool over the negative-rake tool is clearly shown in Fig. 3. On the basis of 0.030-in. maximum wear, the negative-rake tool can remove only 75 cu. in. of EPMI (Eaton Permanent Mold Iron), whereas the positive-rake tool can remove 160 cu. in., or more than twice as much. Both of these rates compare very favorably with the 40 cu. in. reported for flake graphite cast iron of 195 BHN on page 242 of the ASME _Manual On Cutting of Metals_ (second edition). The most significant result of these particular tests is that positive-rake tools will remove twice as much metal as negative-rake tools. This could justify the use of positive-rake, "throw-away" tools even though tool cost is higher.

C. VALIDITY OF EXTRAPOLATION

The validity of extrapolating tool-wear data from a limited number of castings was checked. An analysis of Fig. 2 yielded the following relationships for the positive-rake tool:

$$W_m = 4 + .9\ N \qquad (1a)$$

or

$$W_m = 4 + .2\ C \qquad (1b)$$

$$W_a = 1 + .75\ N \qquad (2a)$$

or

$$W_a = 1 + .16\ C \qquad (2b)$$

W_m and W_a are the maximum wear and average wear, respectively, expressed in thousandths of an inch; C is the cubic inches of metal machined; and N is the number of castings machined. From these relationships, it was predicted that, if 20 castings were machined, the maximum wear would be 0.022 in. and the average wear would be 0.016 in. After these calculations were made, 12 additional castings were machined with the original tool; the results are plotted in Fig. 4.

The wear increased uniformly during the entire series of these tests, and the maximum wear after machining the 20 castings was 0.024 in. and the average wear was 0.017 in. These values of actual wear are only slightly higher than the predicted values. By similar calculations, it could be accurately predicted that 0.030-in. maximum wear would occur with 30 castings or 140 cu. in. (4.64 cu. in. per casting).

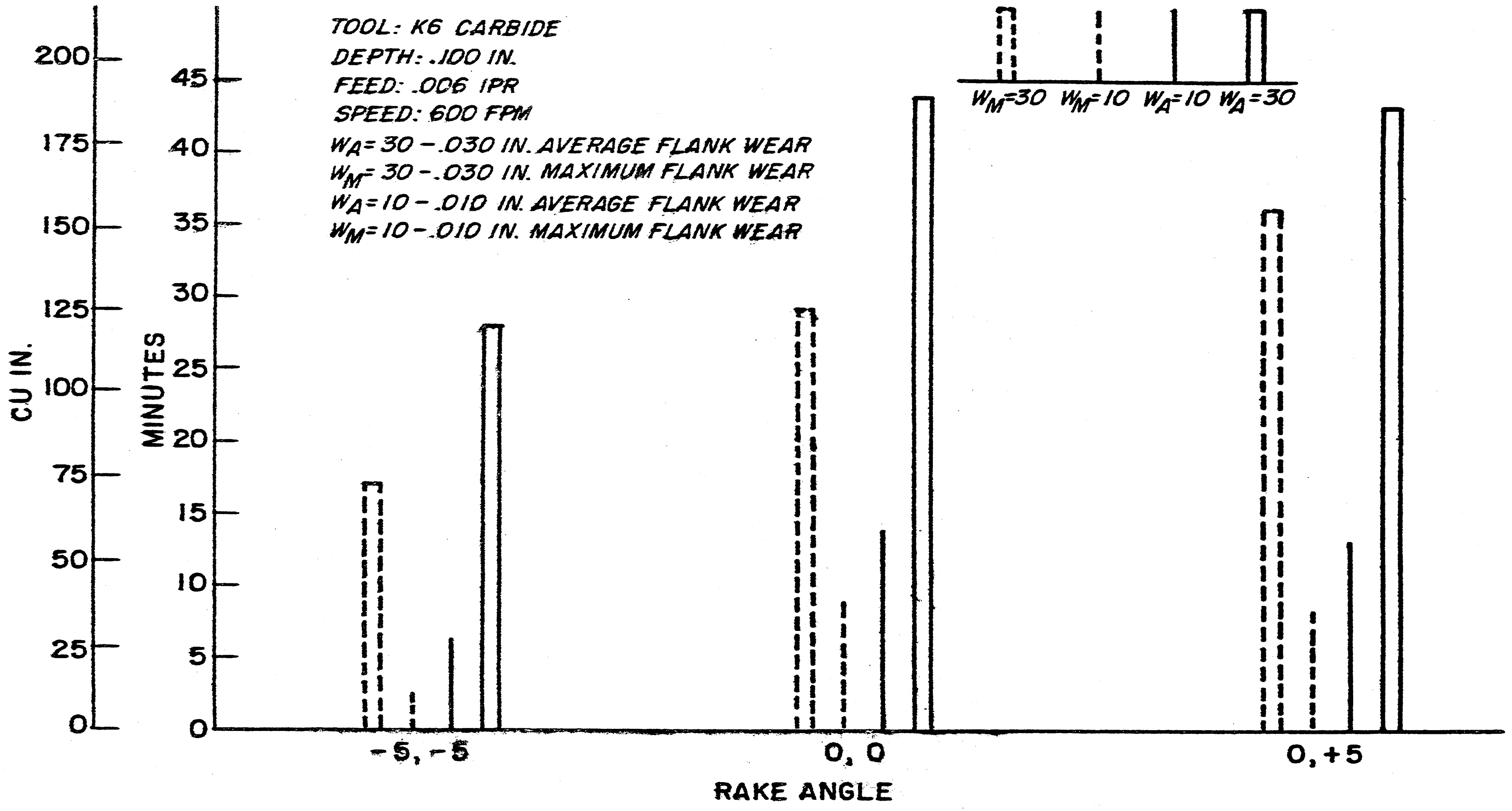


Fig. 3. Effect of rake angle on tool life and metal removal. (Values for .030 wear were extrapolated.)

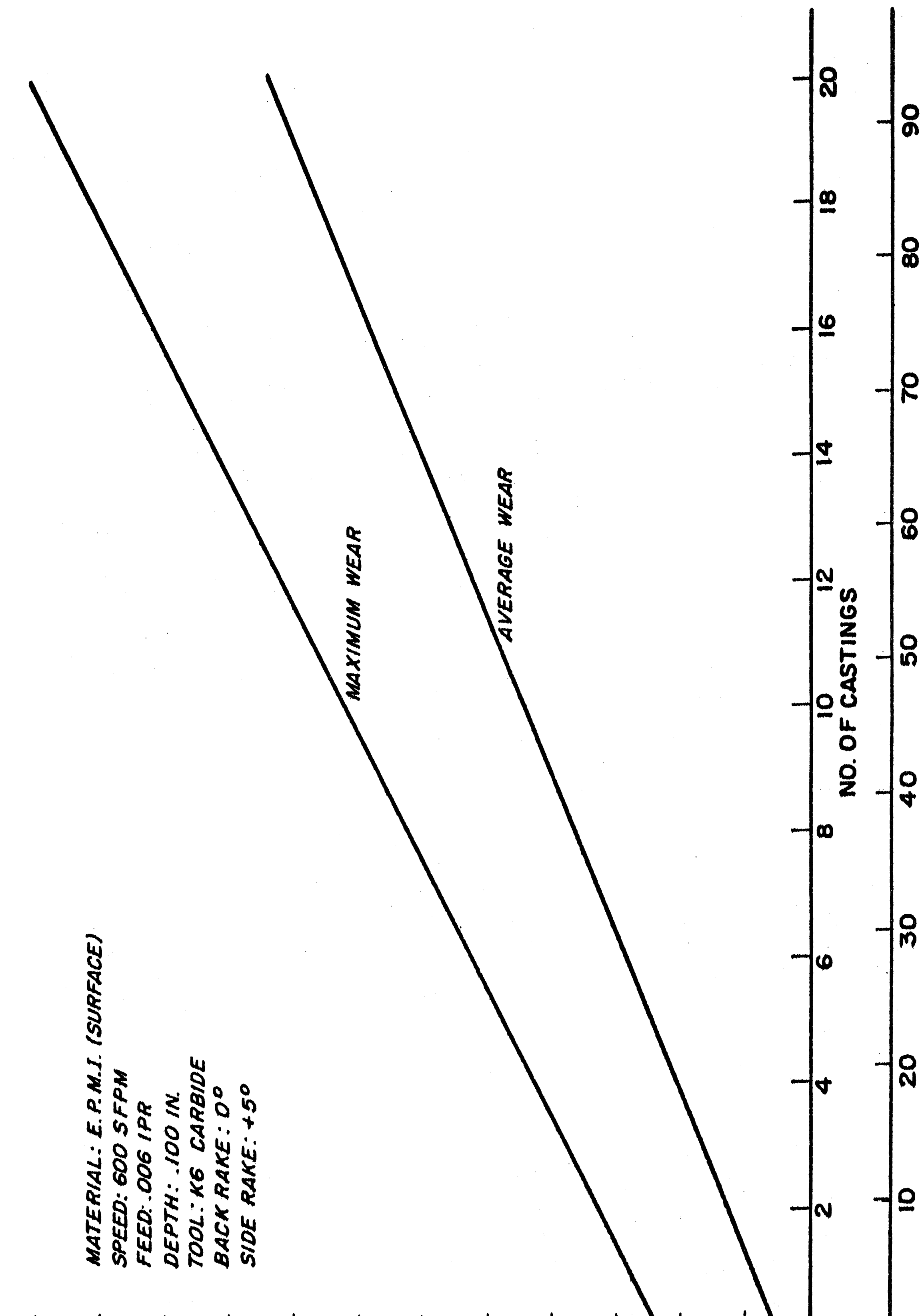


Fig. 4. Tool wear on surface metal.

D. RELATIVE MACHINABILITY OF SURFACE METAL

Step IV of the initial outline was included to compare the machinability of the base or interior metal with the machinability of the cast surface. The standard cutting conditions were used with both the negative-rake and the positive-rake tools. After the initial surface cut three additional cuts were made on each casting. The spindle speed was increased for each successive cut to maintain a constant cutting speed of 600 fpm.

The results obtained with the negative-rake tool are plotted in Fig. 5; both the maximum and average wear increased very uniformly. To create 0.030-in. maximum wear, 135 cu. in. of metal would have to be machined; to create the same average wear, 157 cu. in. of metal would have to be machined. It is evident that, on the basis of maximum wear, the machinability of the cast surface is only half that of the base material.

The results with the positive-rake tool are shown in Fig. 6. The rate of wear was very slow initially, but after the wear reached 0.010 in., the rate increased very rapidly. The volumes of metal that can be removed with positive-rake tools as determined here may be conservative. Before the maximum wear and the average wear would reach the failure value of 0.030 in., 160 cu. in. and 250 cu. in. of metal, respectively, could be machined. These values may be compared to 130 cu. in. and 180 cu. in. of surface metal that can be removed under similar conditions. This also shows the abrasive nature of the cast surface.

The abrasiveness of cast surface is also very evident when high-speed tools are used. For example, in Fig. 23 it is apparent that, for a cutting speed of 300 fpm, the tool life when machining the surface is 2 min, whereas when machining the base metal the tool life is 80 min or 4,000% longer. Figure 24 shows that 4 cu. in. of surface metal can be removed and 56 cu. in. of base metal can be removed per tool grind when machining at 300 fpm.

E. COMPARISON OF SEVERAL GRADES OF CARBIDE

All four grades of carbide tools that are recommended for machining cast iron (wear-resistant type) as well as one steel cutting grade (crater-resistant type) were tested; these tools are described in Table I.

The results obtained with the cast iron grades are shown in Figs. 7 and 8. As was expected, the wear rate with the softest grade (K1) was the greatest and that for the hardest grade (K11) was the least. However, as may be clearly seen in Fig. 7, the rate of wear of the K1 grade of carbide is much greater than the rate of wear of the K6, K8, and K11 grades. The rates of wear of the latter three grades, as indicated by the slopes of the wear curves, are approximately the same. The significant difference between these three grades is the amount of wear that occurs during machining of the first few castings.

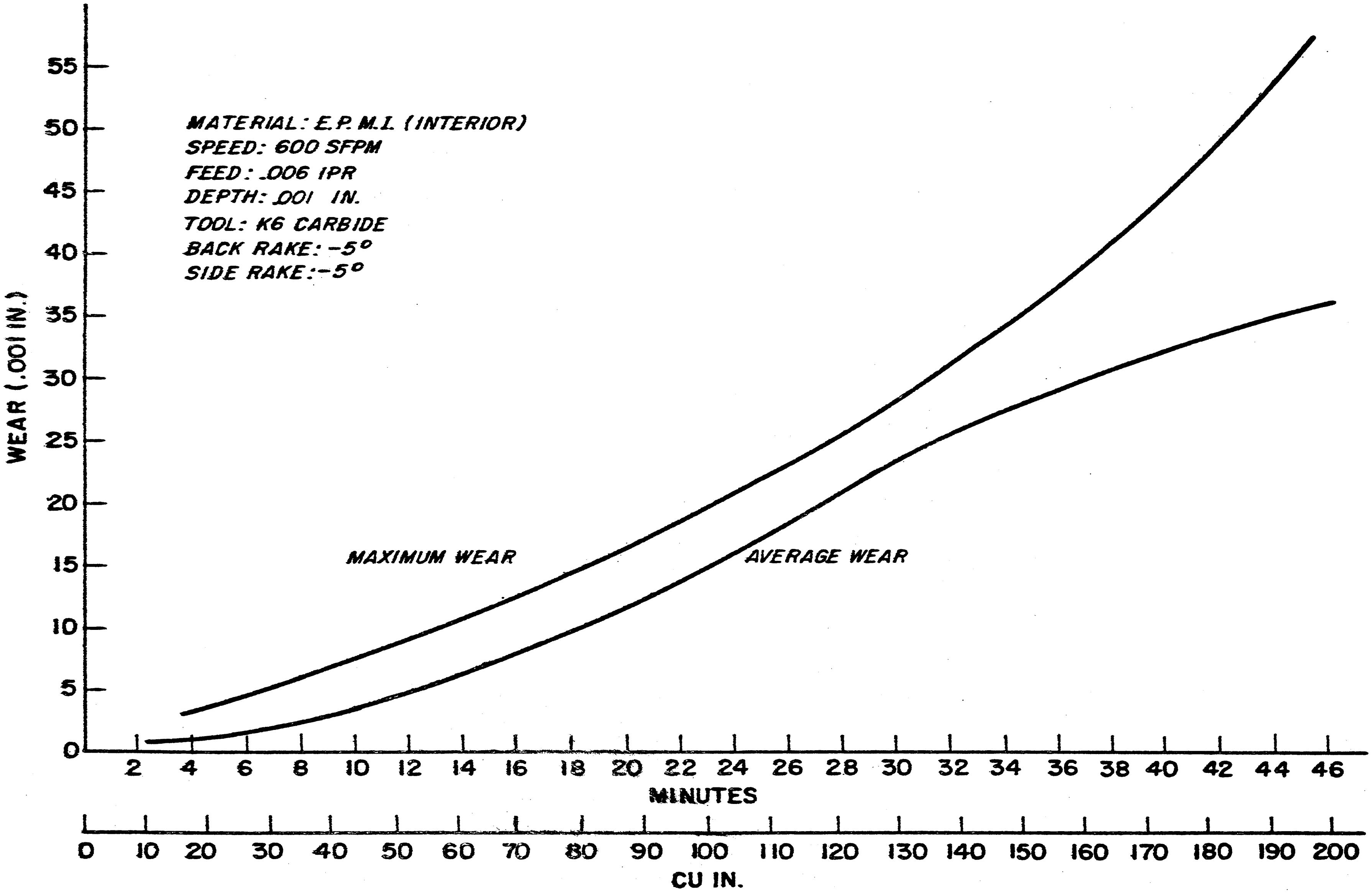


Fig. 5. Tool wear on base metal.

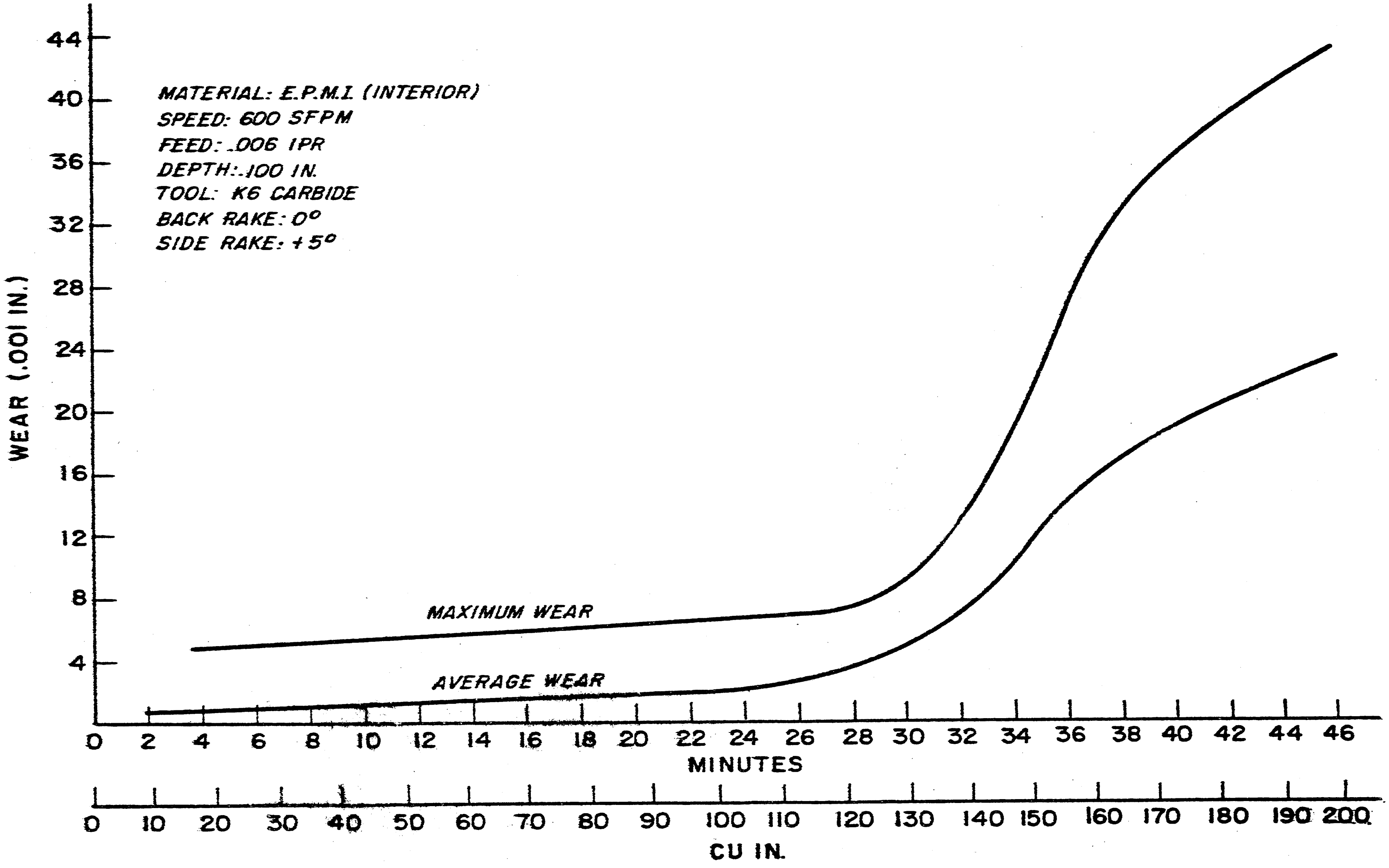


Fig. 6. Tool wear on base metal.

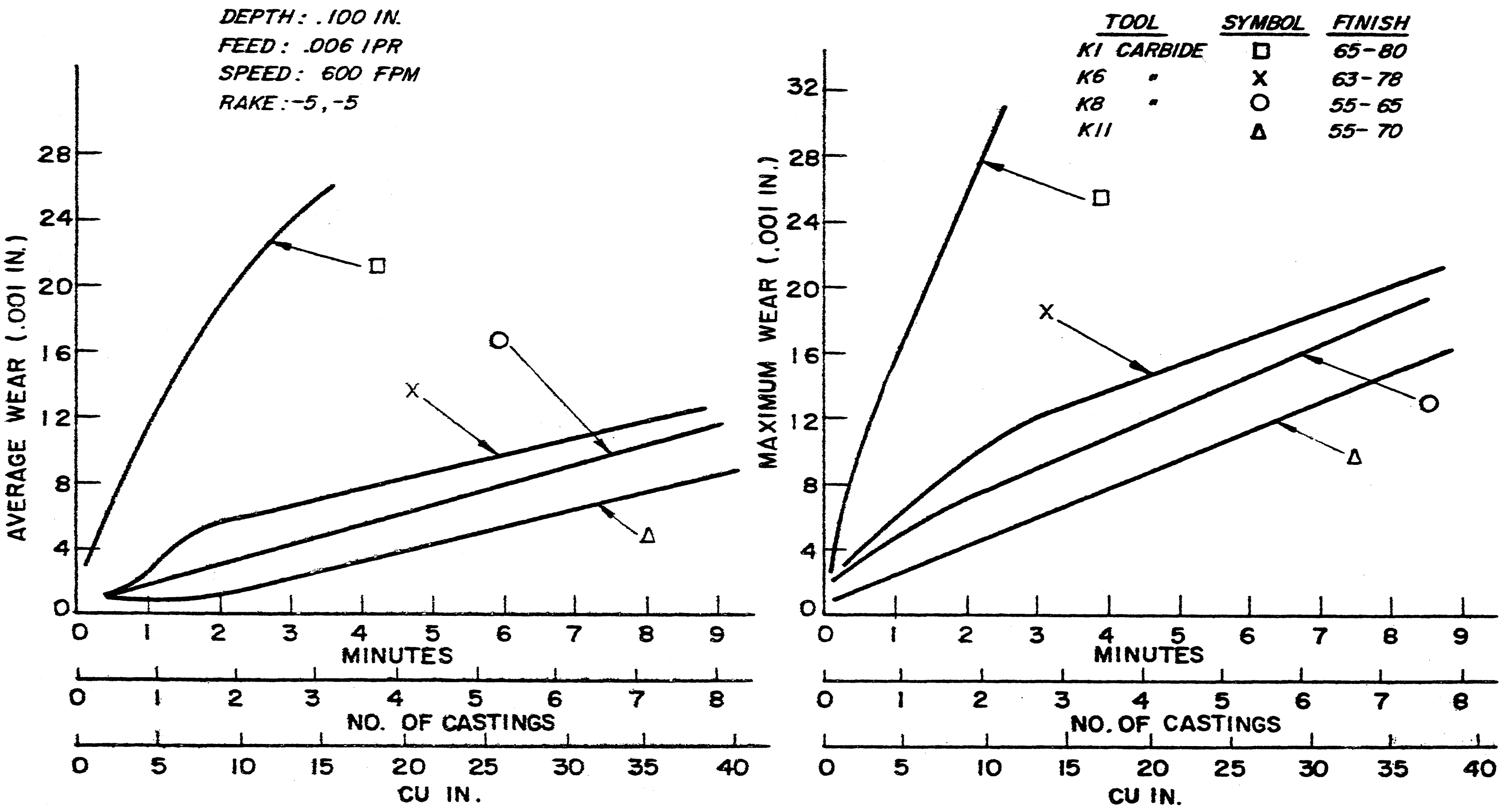


Fig. 7. Effect of tool grade on tool wear.

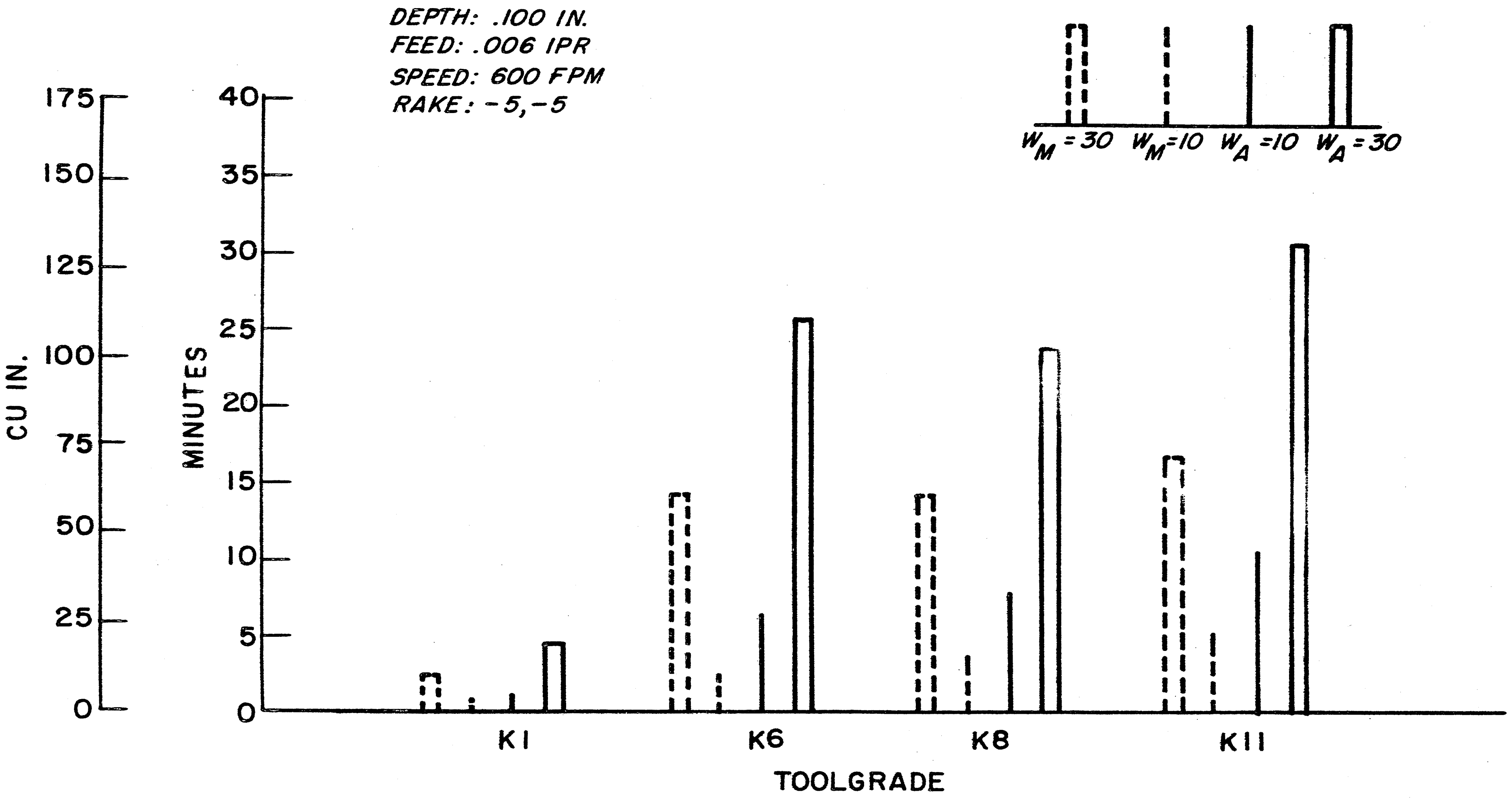


Fig. 8. Effect of tool grade on tool life and metal removal. (Values for .030 in. wear were extrapolated.)

The wear data for the four cast iron grades of carbide are replotted in Fig. 8 to illustrate more simply the effect of the tool grade on both the tool life and the volume of metal that can be machined per tool grind. In comparing these tools on the basis of the amount of metal that can be removed for a 0.030-in. maximum wear land, it is clear that the K1 grade is inferior, being able to remove only 12 cu. in. of metal. The K6 grade, which is the general-purpose tool, and the K8 grade, which is recommended for lighter cuts, have about equal performance inasmuch as both can remove about 60 cu. in. of metal. However, about 73 cu. in. of cast iron can be machined with the harder, K11 grade that is recommended for fine finishing cuts.

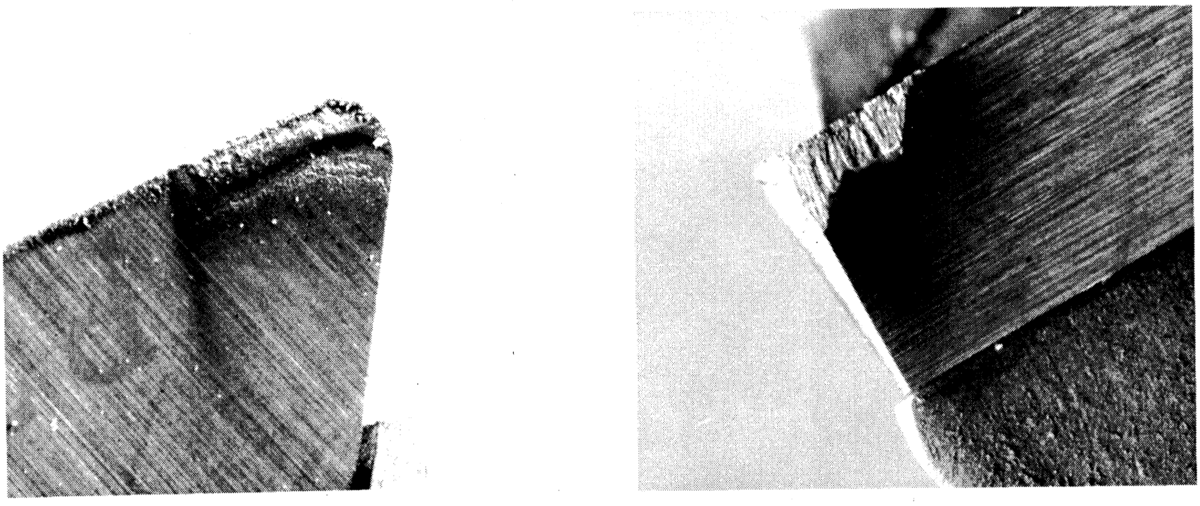
Near the end of this testing program it was decided to ascertain whether a steel-cutting grade of carbide would perform better than the cast iron grade when cutting EPMI. The hardest, most crater-resistant grade, K 7H with positive rake, was selected and one casting was machined at the standard conditions of 600-fpm cutting speed and 0.006-ipr feed. The maximum wear was a modest 0.0025 in. after the first cut. Inasmuch as there were only a few castings left, it was felt desirable not to machine any more castings with a feed of 0.006 ipr, but rather to increase the feed to 0.012 ipr. This was done because it was noticed earlier that when a K6 grade of carbide was used with a feed of 0.006 ipr, all the wear was on the flank and no crater was formed in the top face, as shown in Fig. 9. On the other hand, when the feed was increased to 0.012 ipr, the K6 grade failed by cratering in the top face rather than by flank wear. Inasmuch as the K 7H grade is a crater-resistant type for high-velocity cuts, it was felt worthwhile to see if this grade of carbide would perform better at the higher feed rate.

After machining 2 castings at 600 fpm and 0.012-ipr feed, the wear was only 0.002 in. on the K 7H tool. However, after machining a third casting, the tool failed completely. Consequently, it was decided to reduce the speed to 500 fpm while retaining the higher feed. After machining 8 castings, the maximum wear was only 0.012 in. and the average wear was 0.006 in. Although these data were not plotted in graphical form, the following relationship was established for these conditions:

$$W_m = 8 + .5\,N. \qquad (3)$$

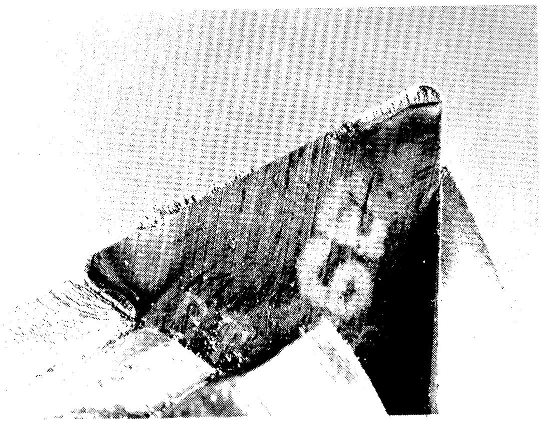
From this relationship, it was determined that 44 castings or 200 cu. in. could be machined for a maximum tool wear of 0.030 in. This substantiates the fact that, for a given tool life, a decrease in cutting speed with a compensating increase in feed will result in a higher rate of metal removal. However, even the K 7H grade obtained a crater when cutting with 0.012-ipr feed.

When a K6 grade of tool was used at 500 fpm and 0.012-ipr feed, after machining 3 castings (14 cu. in.) the flank wear was 0.007 in. and a crater was noticeable. It was impossible to continue this particular test because there were no more castings. However, on the basis of machining 3 castings, it appeared that the K6 grade did not develop a larger crater than did the K 7H tool.



(a) (b)

Figs. 9a and 9b. Photographs of the top and side flank of tool No. 6E-1 (K6, positive rake) after machining 200 cu. in. of base metal from 15 castings at 600 fpm, 0.100-in. depth, and 0.006-ipr feed. Although the maximum flank wear in (b) is 0.043 in., there is no noticeable crater in the top face (a).



(c)

Fig. 9c. Photograph of the top of tool No. 6E-3 (K6, positive rake) after machining 23 cu. in. of surface material (5 castings) at 600 fpm, 0.100-in. depth, and 0.012-ipr feed. Although the flank wear is only 0.007 in., a deep crater is worn in the top face. After machining just one casting, the wear increased to 0.048 in.

F. EFFECT OF FEED ON TOOL PERFORMANCE

The rates of tool wear for feeds of 0.003, 0.006, and 0.012 ipr are plotted in Figs. 10 and 11 for the negative-rake and positive-rake tools, respectively. It should be noted that it is necessary to use separate axes for the tool life in minutes and the tool life in cu. in. of metal machined inasmuch as the cutting time per casting is cut in half when the feed is doubled. It is evident from these two figures that machining EPMI at 600 fpm and 0.012 ipr feed is too severe a machining condition. Much better results would be obtained with a feed of 0.012 ipr if the speed were reduced to 400-500 fpm.

In comparing Figs. 10 and 11 with each other it is apparent that, with the negative-rake tool, the wear increases more rapidly at 0.006-ipr feed than at 0.003-ipr feed, whereas just the opposite is true when cutting with the positive-rake tool. When this was first noticed, it was felt that possibly the negative-rake tool used with a feed of 0.006 ipr was defective, so that the test was repeated. The results with the second tool agreed very closely with those obtained with the first tool.

For the negative-rake tool, the 0.030-in. maximum wear is not a valid criterion of tool performance. The curve for the 0.030-in. average wear in Fig. 12 is much more representative of the relationship between feed and tool performance wherein a slight increase in feed will also increase the cu. in. of metal removed. However, even though the 0.030-in.-maximum-wear curve for cu. in. versus feed has a downward slope, it is not too objectionable. The following table will illustrate this point.

TABLE II

TOOL PERFORMANCE VS. FEED FOR 0.030-IN. MAXIMUM TOOL WEAR

f(ipr)	Total Cu. In.	Actual Cutting Time (min)	Cu. In. per min.
0.003	88	40	2.2
0.006	75	18	4.3
0.012	60	7	8.8

Thus it is apparent that, although 50% more metal may be removed with a 0.003-ipr feed than with a 0.012-ipr feed, it takes 500% more time to accomplish the machining.

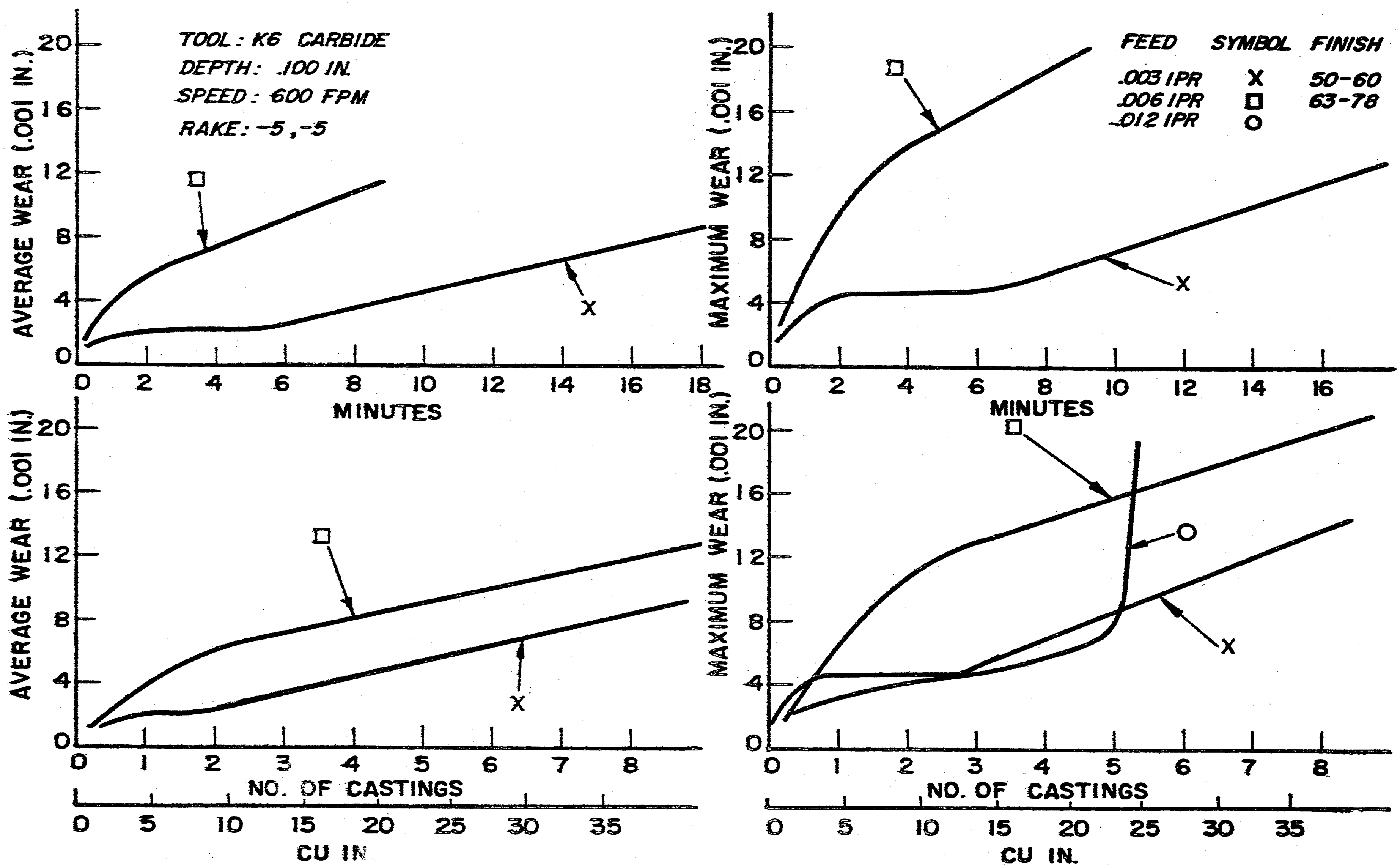


Fig. 10. Effect of feed on tool wear.

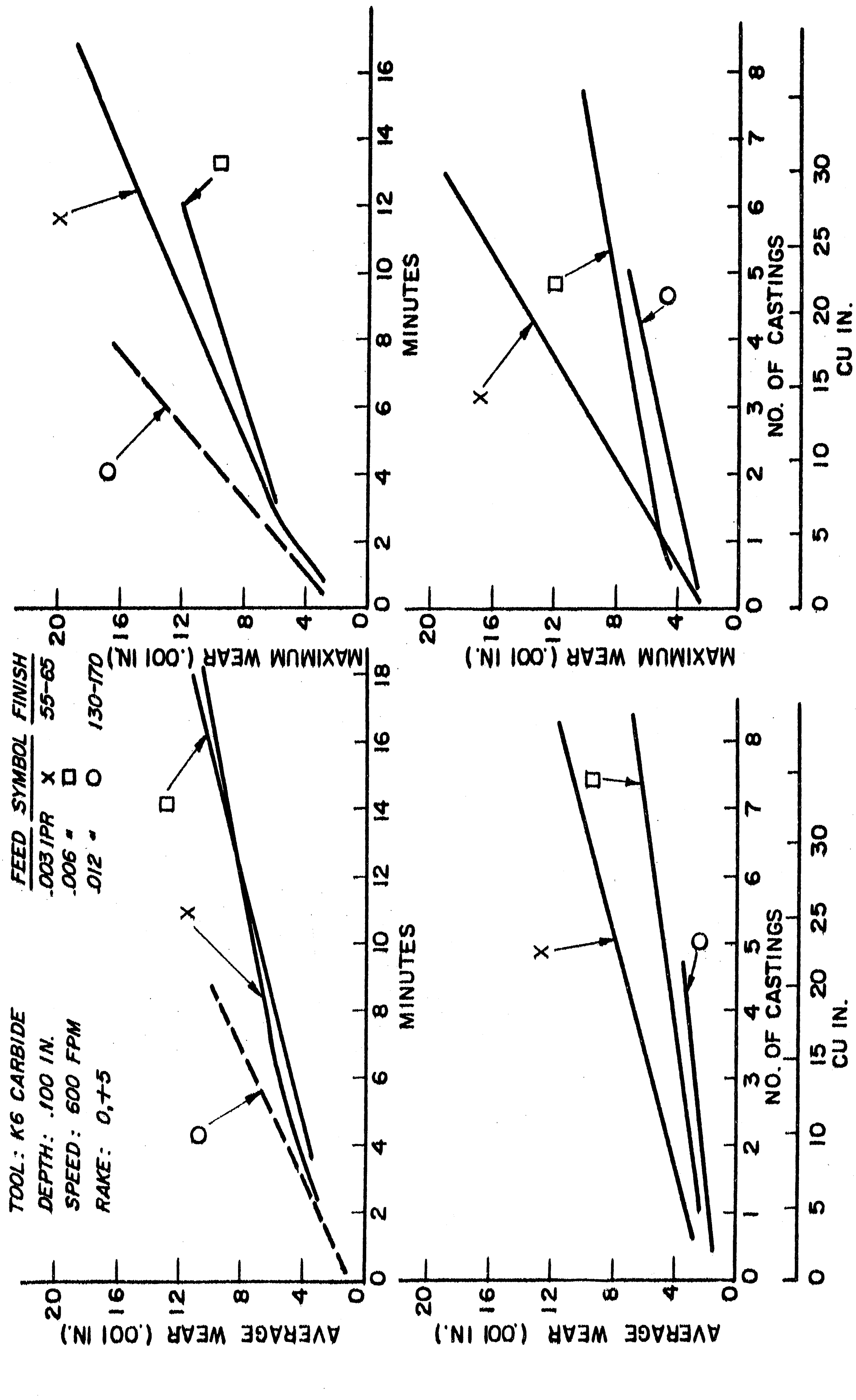


Fig. 11. Effect of feed on tool wear.

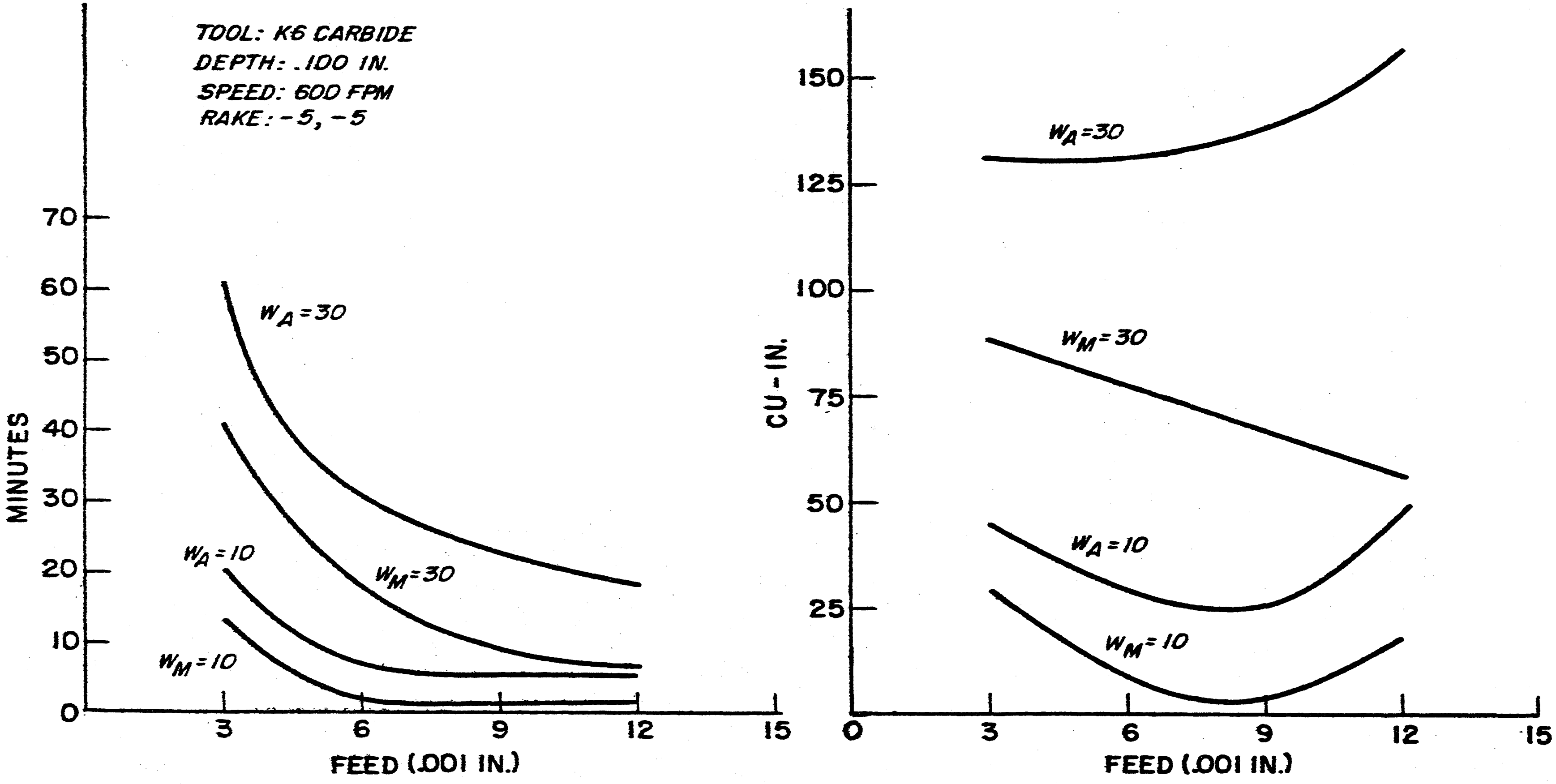


Fig. 12. Effect of feed on tool life and metal removal. (Values for .030-in. wear were extrapolated.)

The graphical data for the metal removal as a function of feed for the positive-rake tool as portrayed in Fig. 13 are more significant than the data obtained for the negative-rake tool. The volume of metal that can be machined for a 0.030-in. maximum wear land increases from 60 to 160 cu. in. when the feed is increased from 0.003 to 0.006 ipr. Although slightly higher feeds would permit even greater volumes of metal removal, feeds of 0.012 ipr or more are too severe when using a cutting speed as high as 600 fpm.

G. EFFECT OF DEPTH OF CUT ON TOOL PERFORMANCE

The rate of tool wear as influenced by the number of castings machined at depths of cut of 0.100, 0.050 and 0.025 in. as shown in Figs. 14, 15, and 16 for both the negative- and positive-rake tools. The data are also plotted in terms of volume of metal machined. It is evident there is an optimum depth of cut when machining EPMI with carbide tools; this is 1/16 in. Figures 17 and 18 illustrate the effect of depth of cut on tool life and metal removal.

H. EFFECT OF CUTTING SPEED ON TOOL PERFORMANCE

The rate at which a carbide tool wears as a function of the cutting speed when machining EPMI is shown in Fig. 19 for a negative-rake tool and in Fig. 20 for a positive-rake tool. As expected, the wear rate increased with an increase in cutting speed; slowly at cutting speeds of 300, 400, and 500 fpm, but quite markedly at 600 fpm. This result is another indication of the appropriateness of the use of 600 fpm as the standard cutting speed for these tests. Although only two castings were machined at speeds of 700 and 800 fpm, it is clearly evident from Fig. 19 that the wear rate is much too high at these speeds.

The performance of the carbide tools as a function of cutting speed is illustrated in Figs. 21 and 22. For the negative-rake tool, there appears to be an optimum speed of about 350 fpm that gives maximum performance in terms of cubic inches of metal machined or minutes of cutting time between tool grinds. It is characteristic of carbide tools to demonstrate an increase in tool life with a decrease in cutting speed down to certain limiting values of cutting speed where the cutting edge of the tool begins to chip and spall, causing premature failures. The following equations represent the cutting-speed, tool-life relationship for .030-in. limiting flank wear:

$$VT^{.15} = 920 \text{ for negative-rake tool.} \qquad (4)$$

$$VT^{.23} = 1300 \text{ for positive-rake tool.} \qquad (5)$$

"V" is the cutting speed in fpm and "T" is the tool life expressed in minutes.

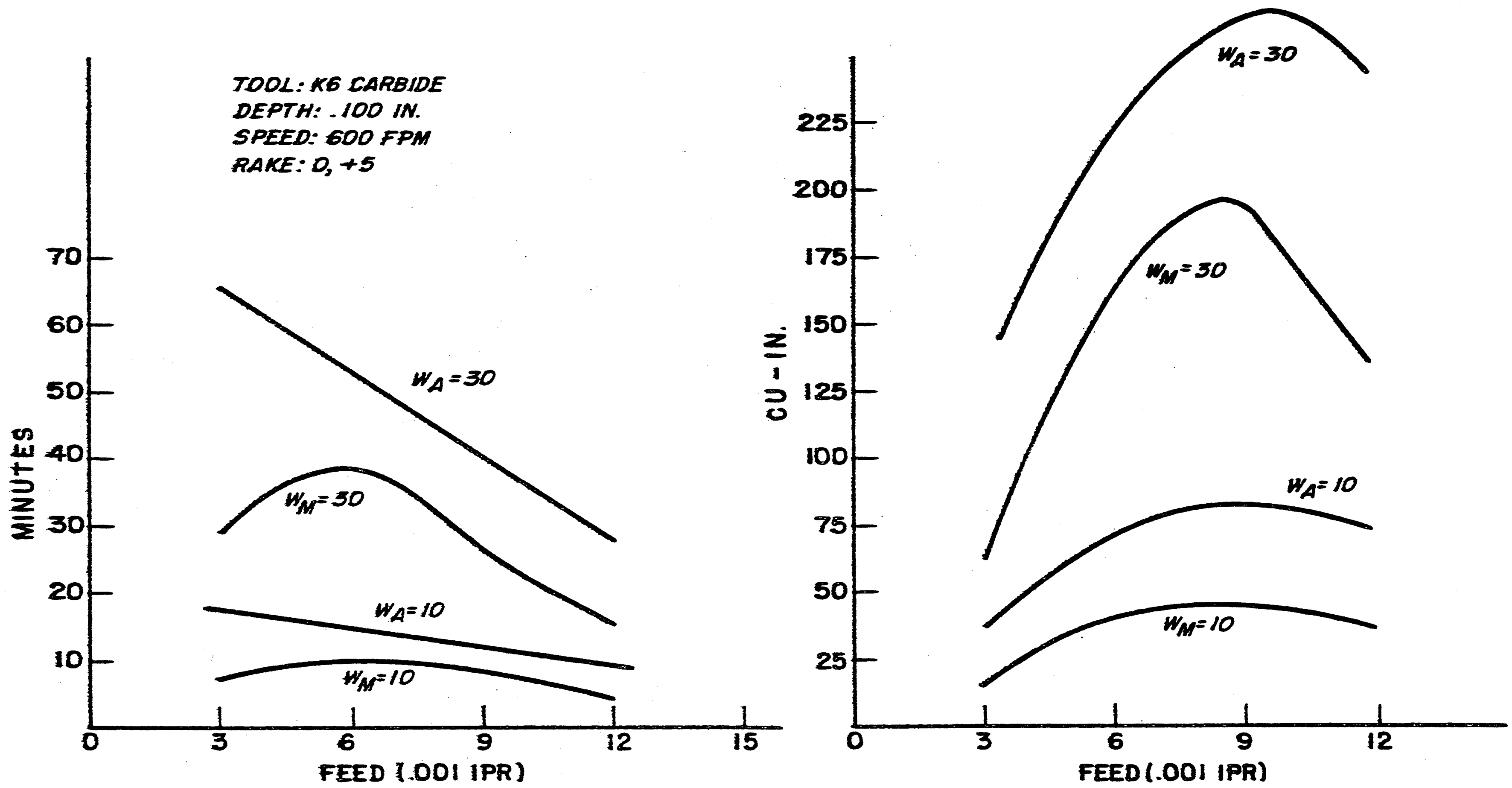


Fig. 13. Effect of feed on tool life and metal removal. (Values for .030-in. wear were extrapolated.)

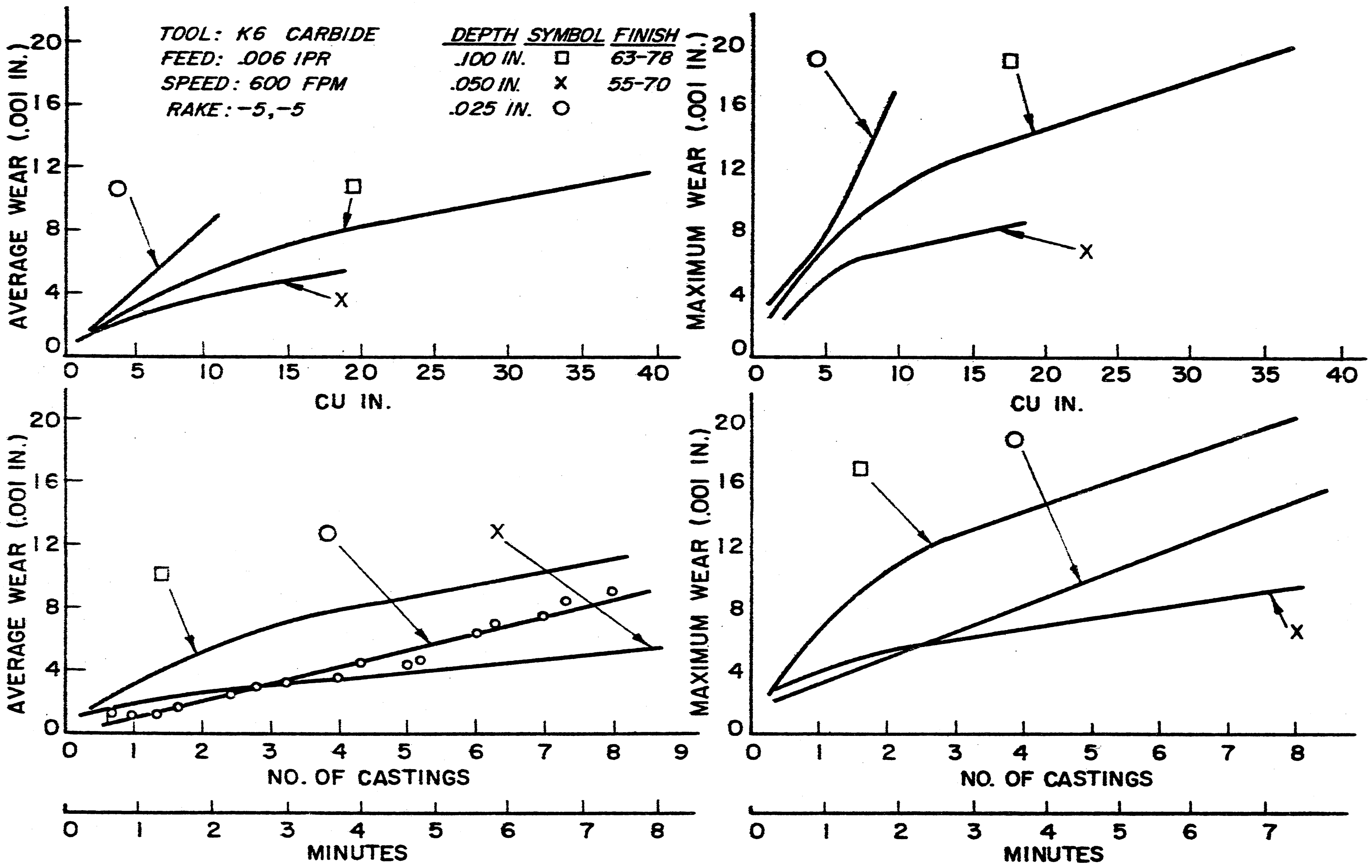


Fig. 14. Effect of depth of cut on tool wear.

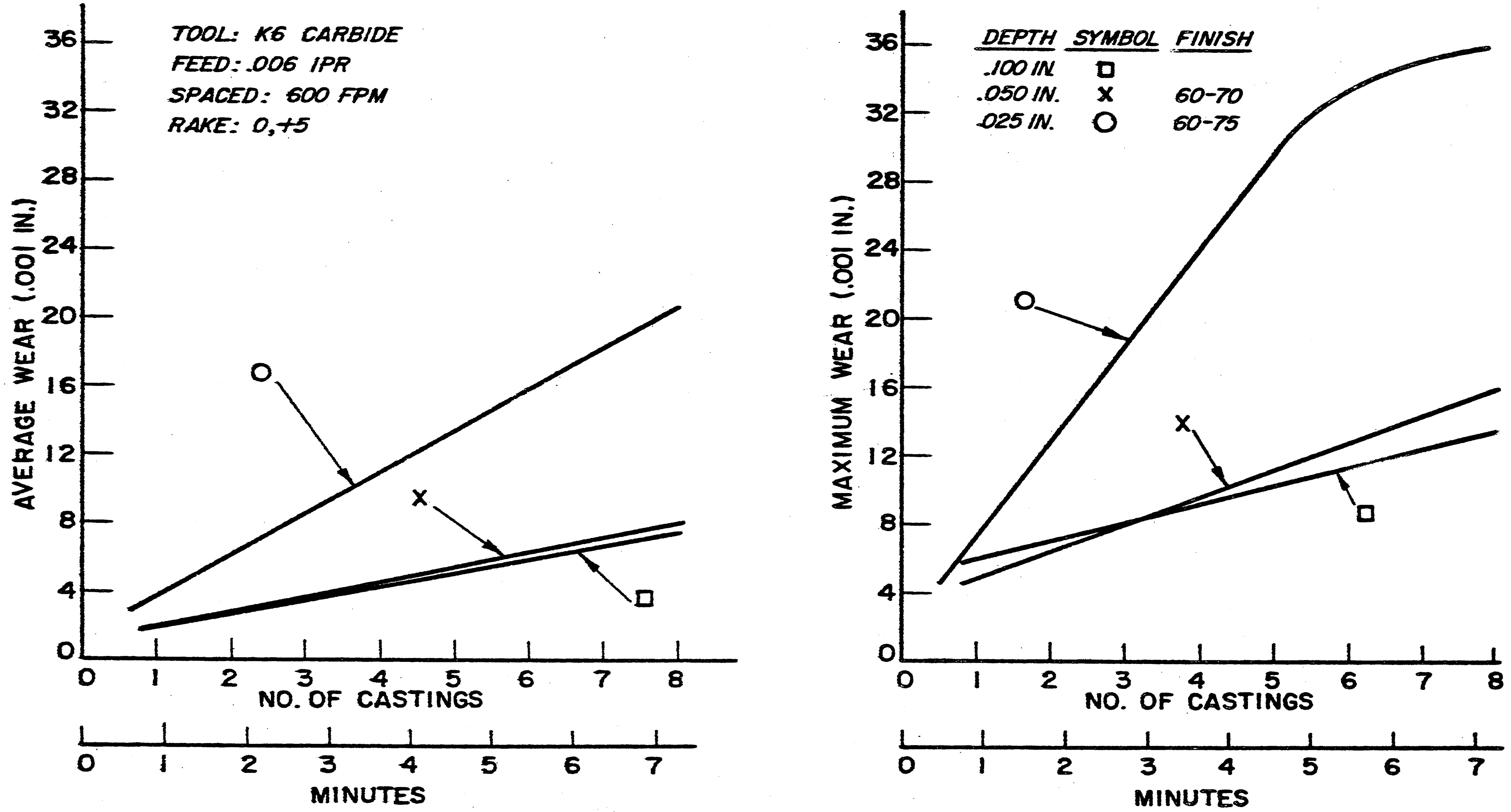


Fig. 15. Effect of depth of cut on tool wear.

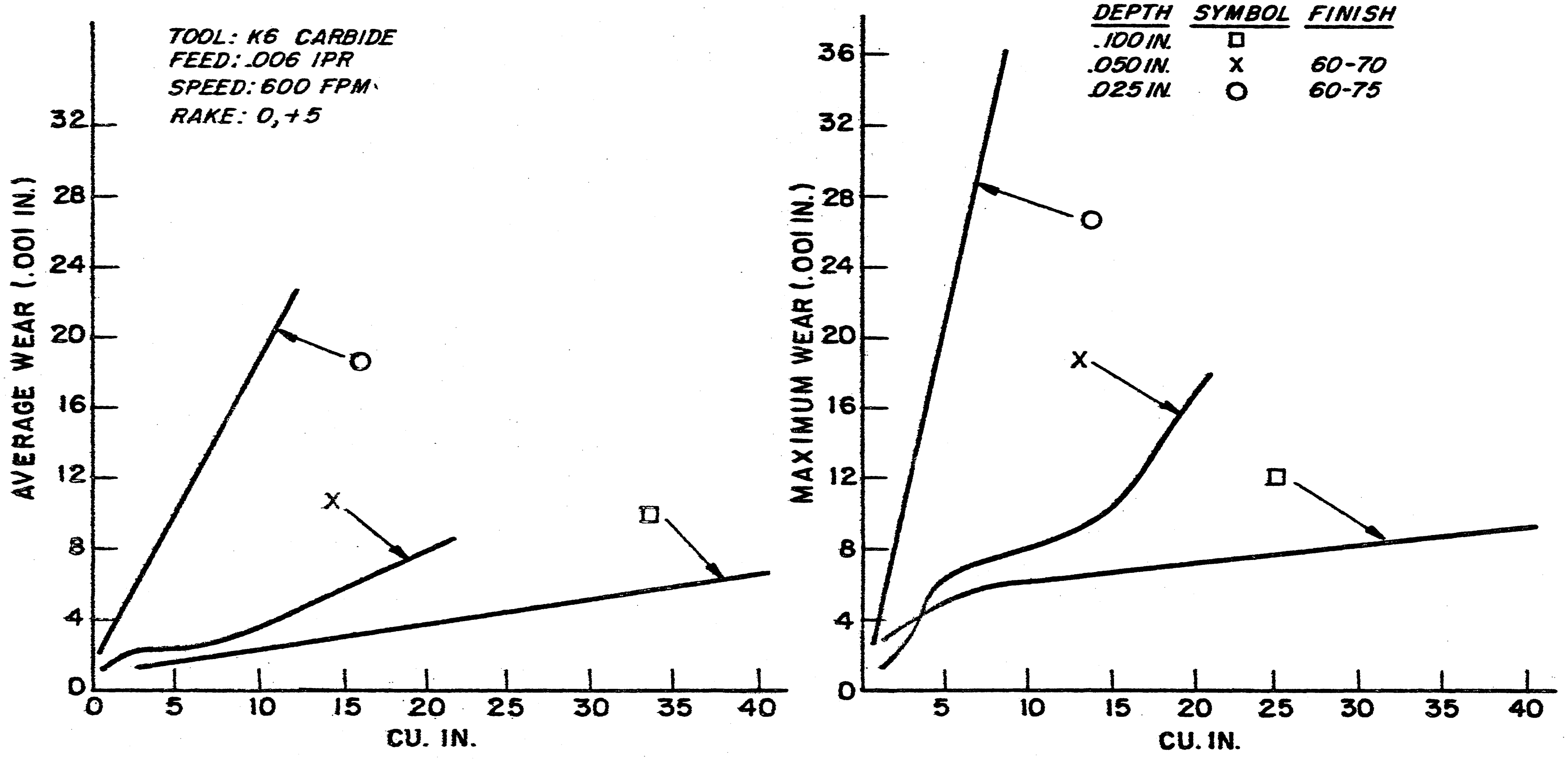


Fig. 16. Effect of depth of cut on tool wear.

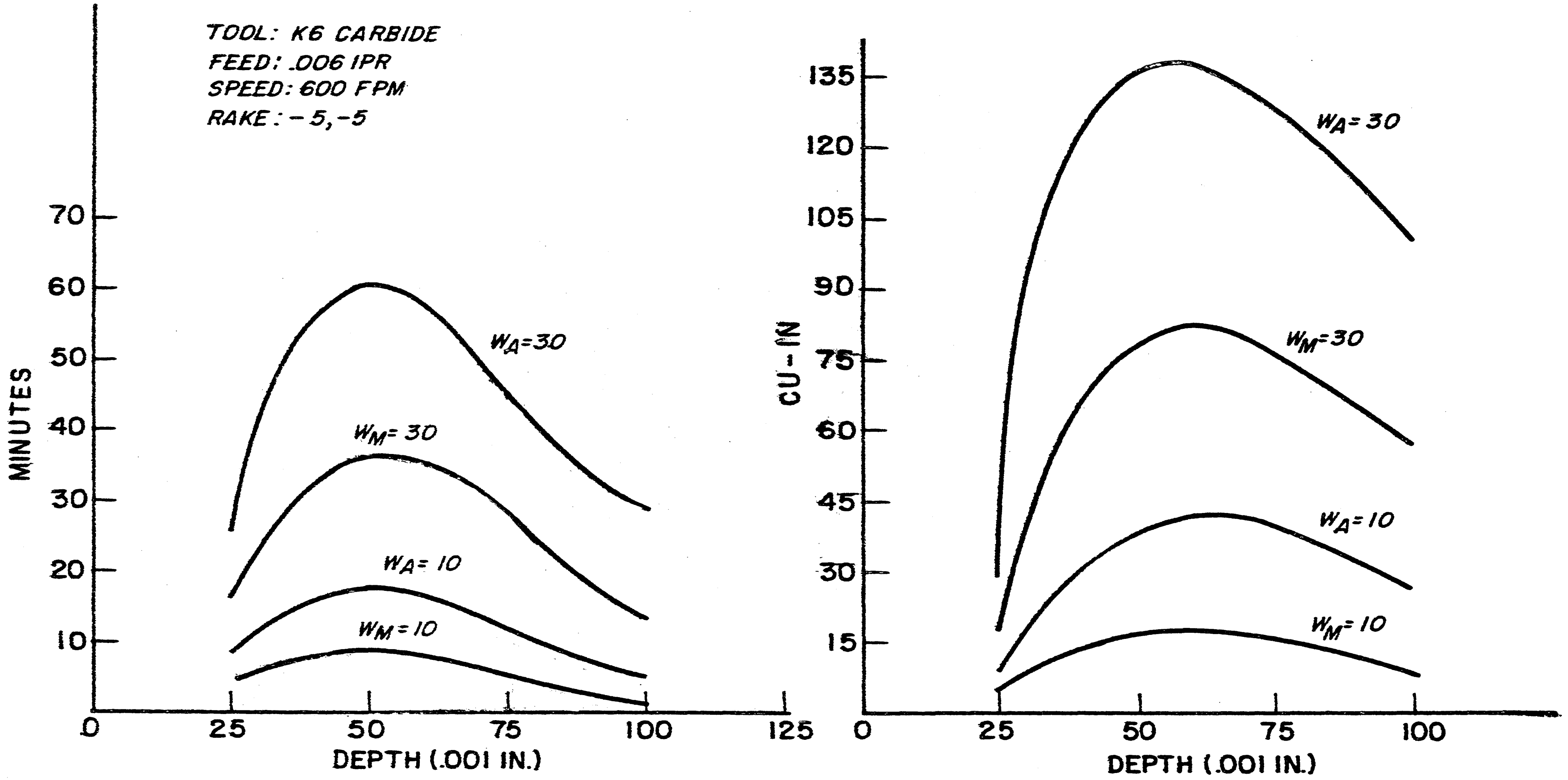


Fig. 17. Effect of depth of cut on tool life and metal removal
(Values for .030-in. wear were extrapolated.)

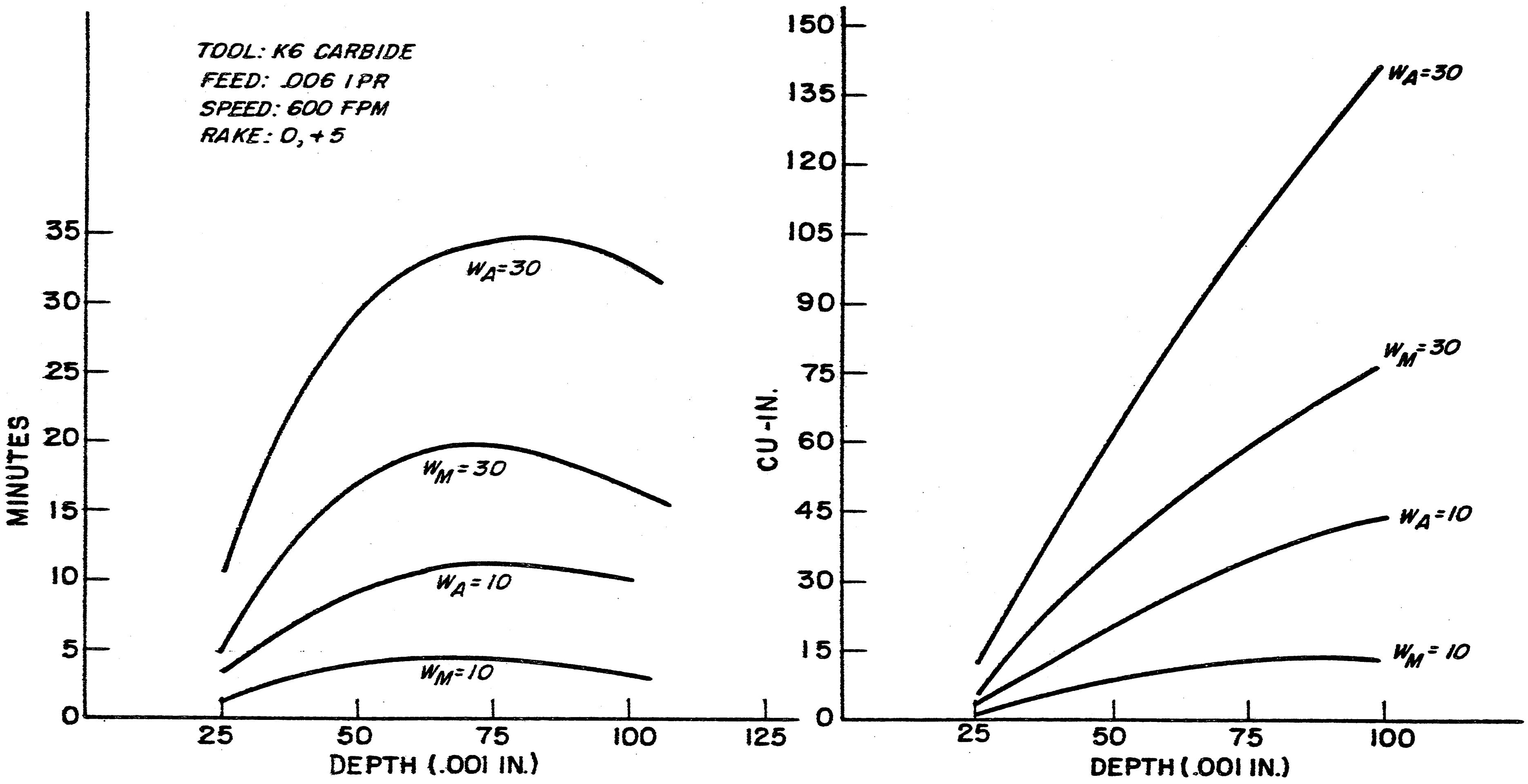


Fig. 18. Effect of depth of cut on tool life and metal removal.
(Values for .30-in. wear were extrapolated.)

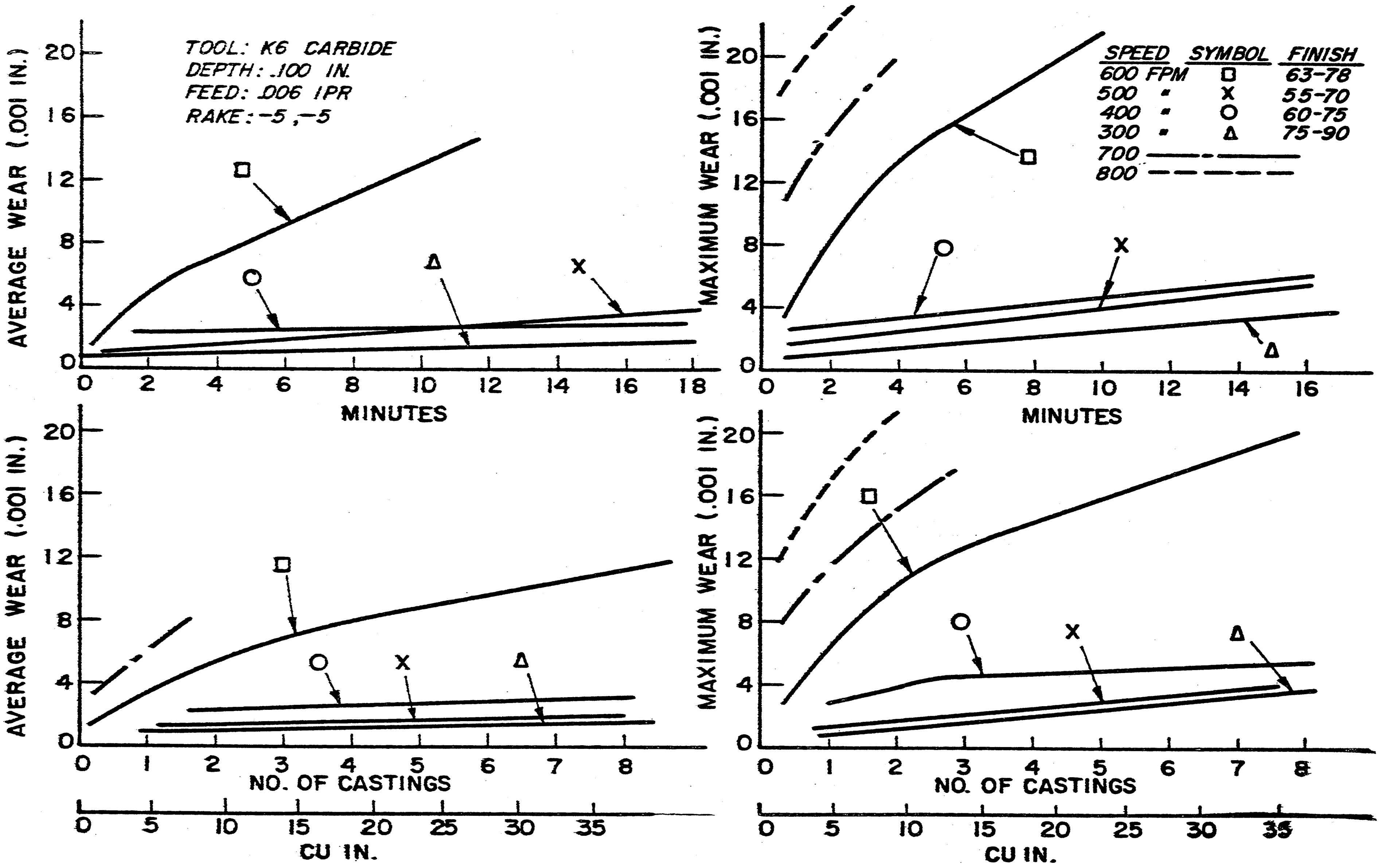


Fig. 19. Effect of speed on tool wear.

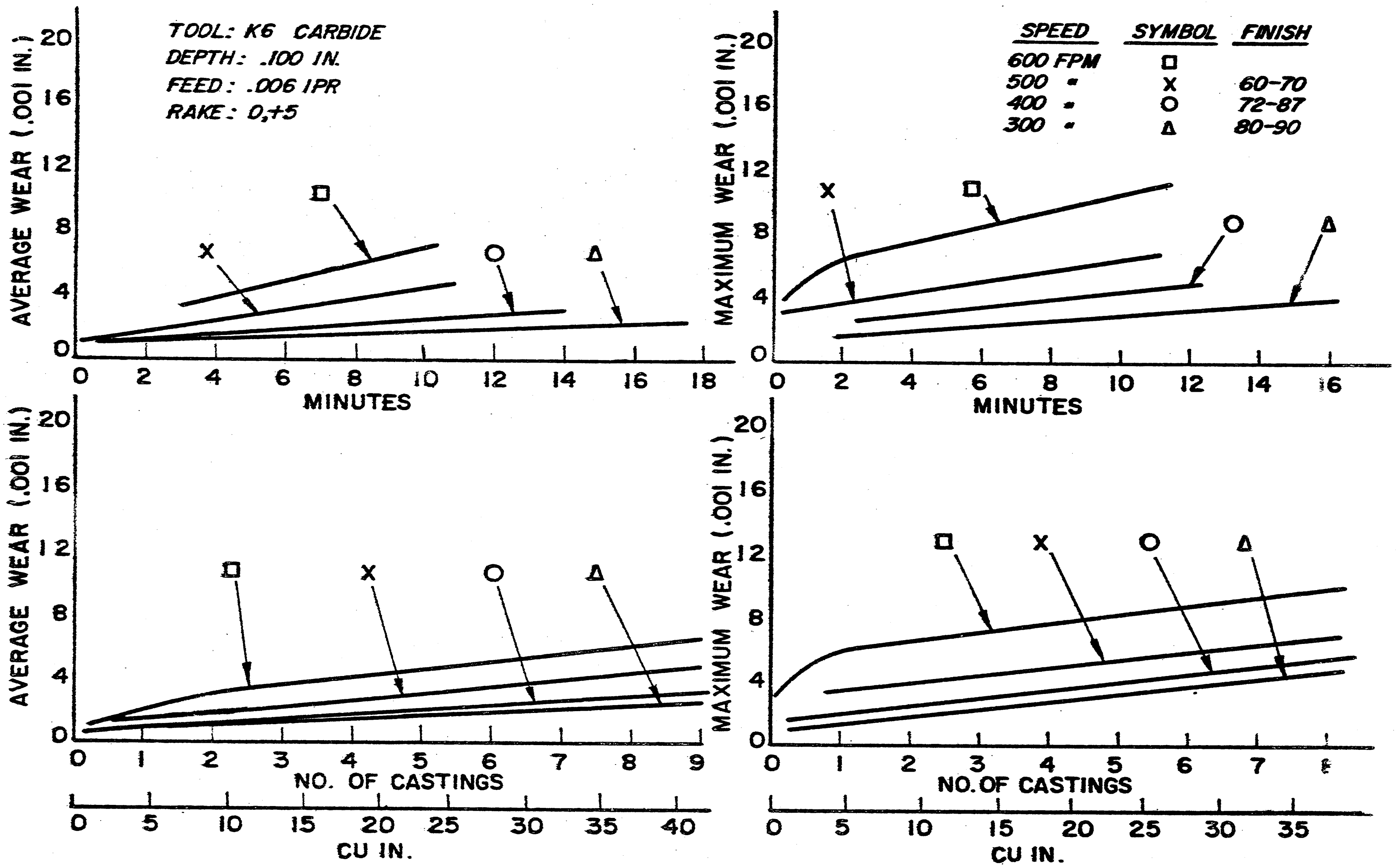


Fig. 20. Effect of speed on tool wear.

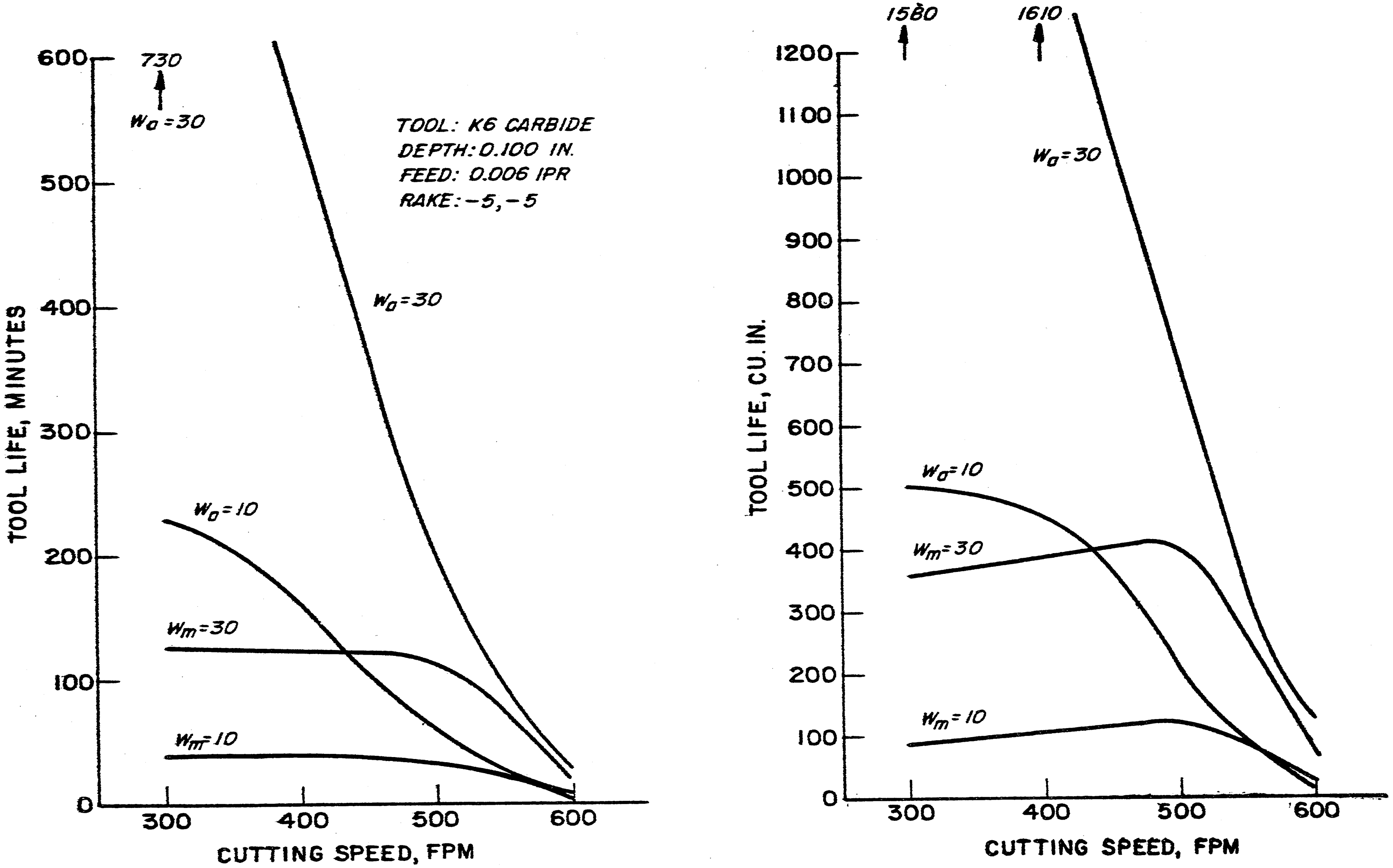


Fig. 21. Effect of speed on tool life and metal removal.

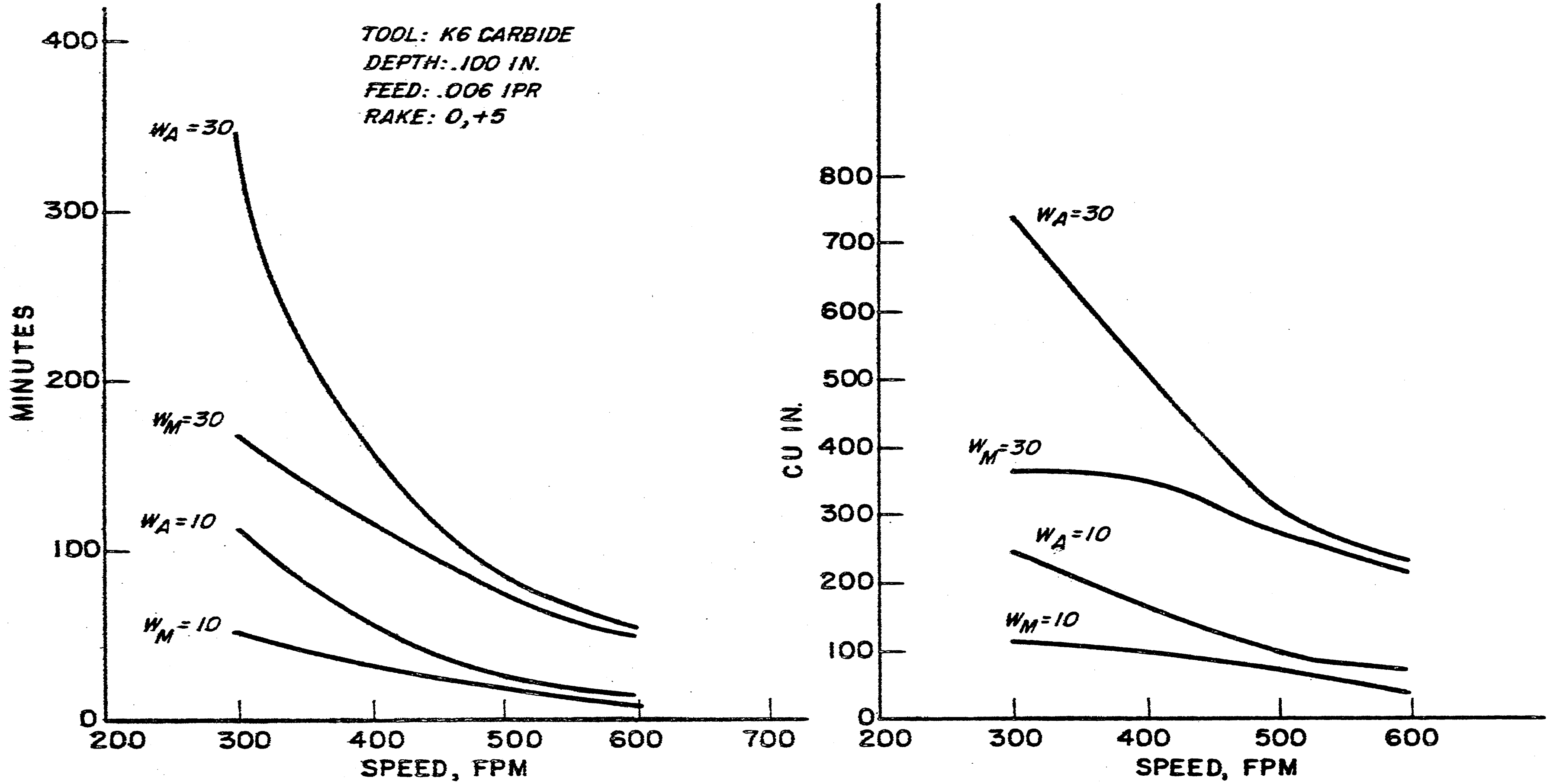


Fig. 22. Effect of speed on tool life and metal removal. (Values for .030 in. wear were extrapolated.)

The high-speed tools tested in this program gave the following results:

$$VT^{.15} = 335 \qquad \text{for surface cuts} \tag{6}$$

$$VT^{.09} = 400 \qquad \text{for interior cuts} \tag{7}$$

Optimum cutting conditions from the cost viewpoint involve tool and machine-operation costs as well as cutting characteristics of the material being machined. The relationships of all these factors are developed in the ASME _Manual on Cutting of Metals_, beginning on page 313.

I. PERFORMANCE OF HIGH-SPEED STEEL TOOLS

Since many of the published data used for comparing the relative machinability of various materials are based on the use of high-speed steel-cutting tools, several EPMI castings were machined with high-speed steel tools in this project and the results are indicated in Figs. 23 through 25. As is customary when conducting machinability tests with high-speed steel tools, the tool life is based on complete failure of the tool point at which time the wear land is so large that the tool ceases to cut and simply rubs against the work.

The machinability of EPMI is most simply presented in Fig. 23 where both the cutting-speed and tool-life axes are logarithmic. This is convenient because they can be represented by straight lines, thus making interpolation and extrapolation easy. The mathematical expression of these tool-life lines takes the general form:

$$VT^{n} = C , \tag{8}$$

where "V" is the cutting speed in fpm, "T" is the tool life in minutes, "n" is the slope of the tool-life line, and "C" is a constant that is numerically equal to the cutting speed that will result in a 1-min tool life. The "n" and "C" values reflect changes in machinability. For example, in Fig. 23 it is evident that the machinability of the base metal is superior to the cast surface metal. The slope for the cast surface (.15) is nearly twice that for the base metal (.09), indicating that the surface is more abrasive.

Figure 24 illustrates the tool performance on ordinary Cartesian coordinates in terms of both minutes of tool life and cubic inches of metal machined per tool grind. The shapes of these curves indicate that small changes in cutting speed in the range of 400 fpm produce only slight changes in the tool life, whereas a small change in cutting speed in the range of 200 fpm produces a great change.

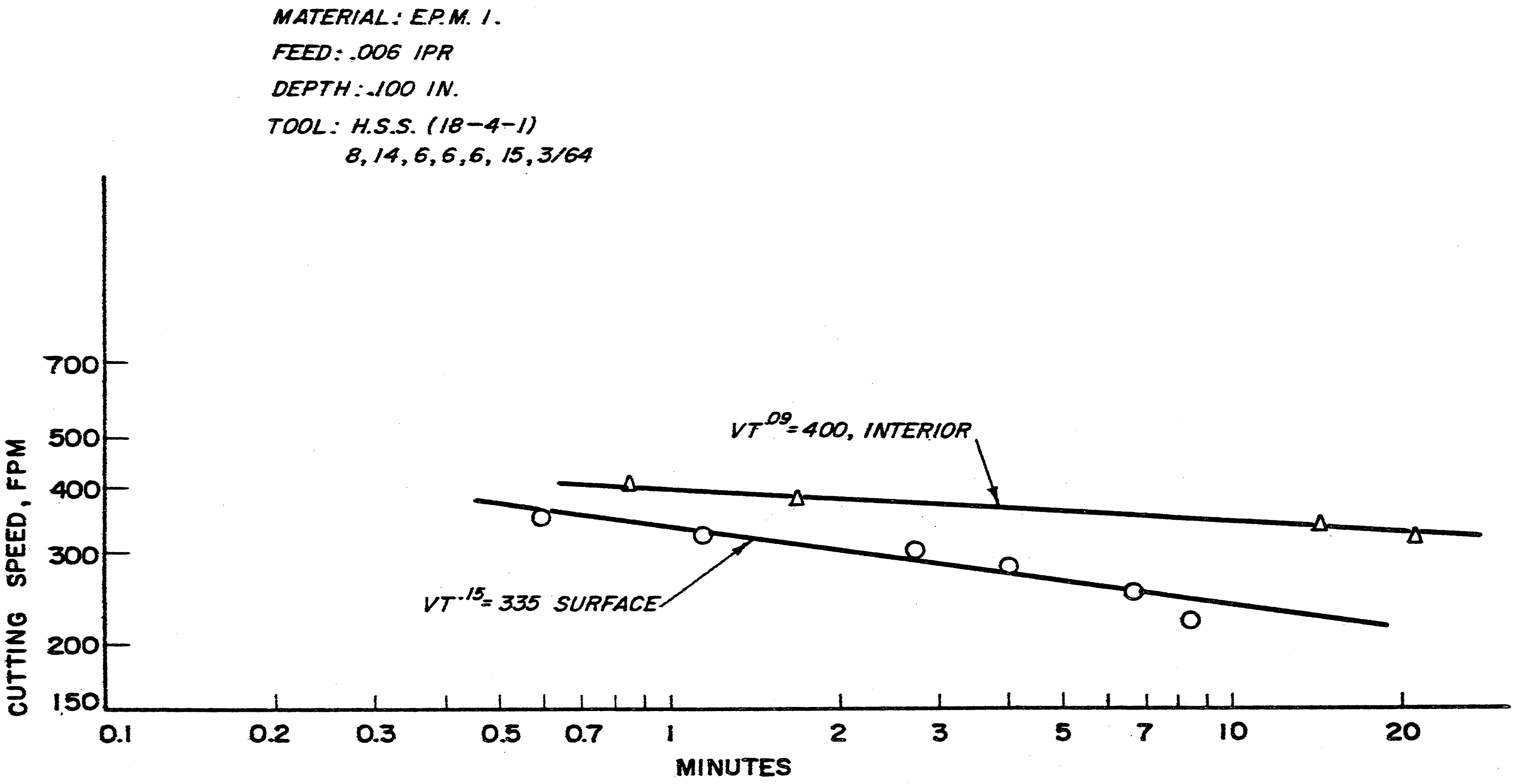


Fig. 23. Machinability of surface and interior metal.

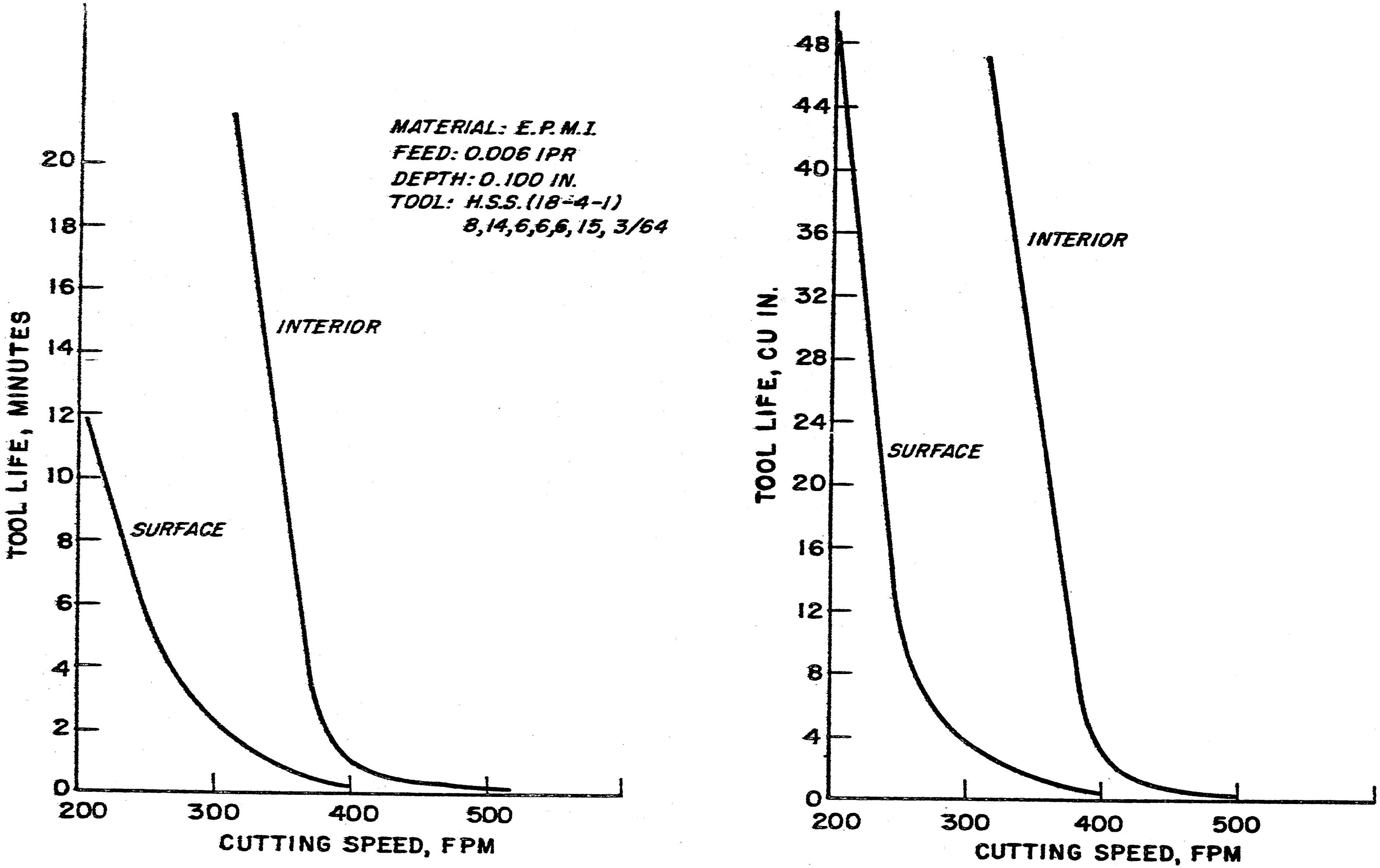


Fig. 24. H.S.S. Tool life for both base metal and surface metal.

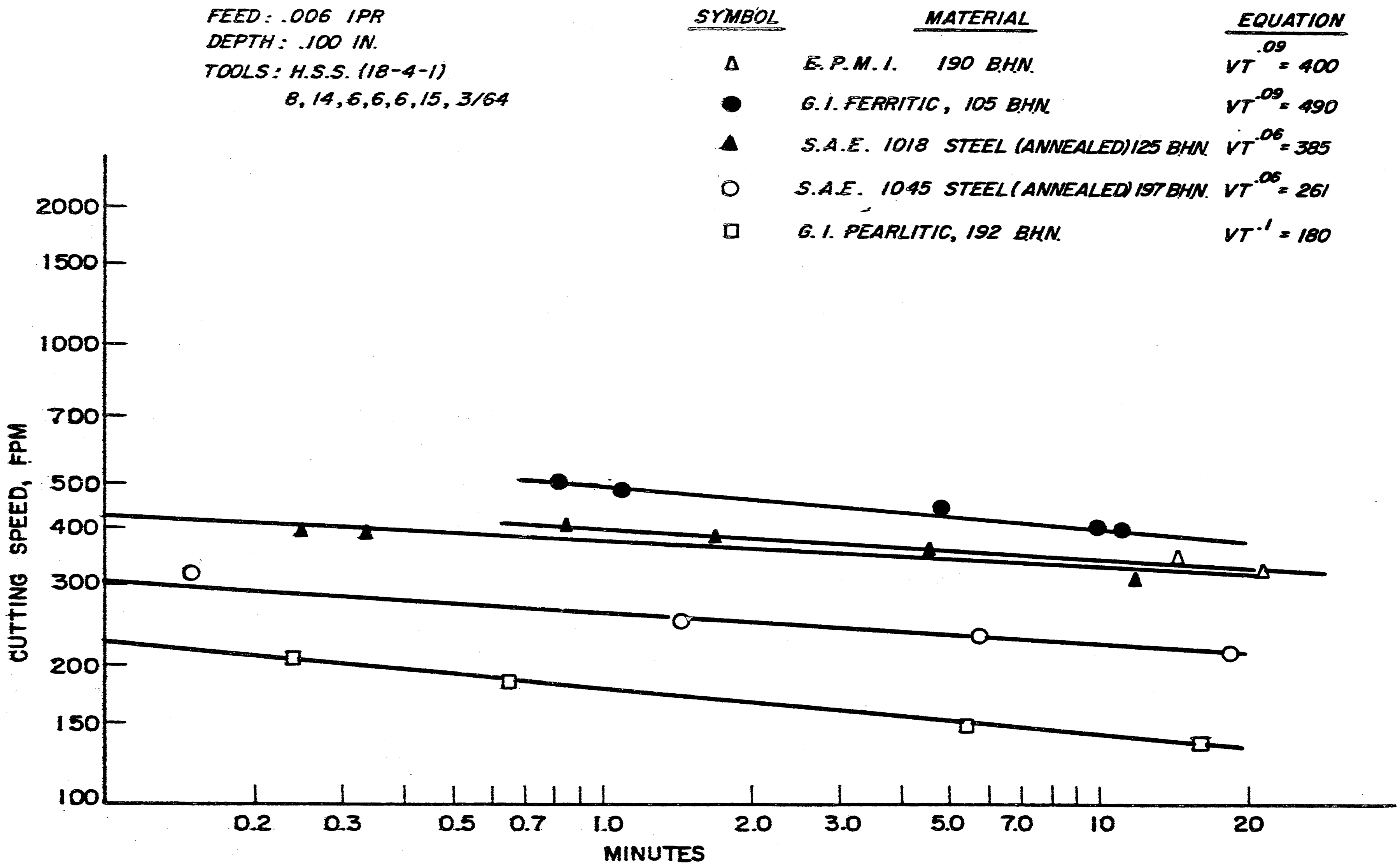


Fig. 25. H.S.S. Tool life curves for some ferrous materials.

Figure 25 illustrates the relative machinability of EPMI with respect to several other common ferrous metals, all based on interior cuts. Although only the EPMI was actually tested under this program, the other materials were tested at The University of Michigan several years ago under similar cutting conditions. From this figure it is apparent that the EPMI of 190 BHN is much more machinable than pearlitic gray iron of 192 BHN and almost as machinable as ferritic gray iron of 105 BHN.

This same relative machinability information is given in Table III in terms of the cutting speed for a 30-min tool life. On this basis, EPMI can be cut at 320 fpm as compared to 130 and 360 fpm for pearlitic and ferritic gray iron, respectively. Also, it is evident that the cast surface of EPMI can be machined at 205 fpm compared to 130 fpm for the interior of pearlitic gray iron of the same hardness.

TABLE III

MACHINABILITY OF SEVERAL FERROUS METALS
WITH H.S.S. CUTTING TOOLS
F + 0.006; d = 0.100 in.

Material	$C = V_1$ for T = 1 min	Exponent	Equation	V_{30} for T = 30 min
EPMI Interior	400	.09	$VT^{.09} = 400$	320
GI Ferritic 105 BHN	490	.09	$VT^{.09} = 490$	360
SAE 1018 Steel annealed 125 BHN	385	0.06	$VT^{.06} = 385$	310
SAE 1045 Steel annealed 197 BHN	261	.06	$VT^{.06} = 261$	210
GI Pearlitic 192 BHN	180	.10	$VT^{.10} = 180$	130
EPMI Surface	335	.15	$VT^{.15} = 335$	205

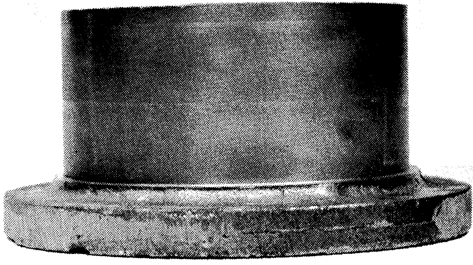
J. SURFACE FINISH

The surface roughness of a casting machined at each of the cutting conditions was evaluated with a profilometer. The results are recorded in Table IV. The last column indicates the average surface roughness, expressed in microinches. With carbide tools and a feed of 0.006, the average surface roughness is 63. This is only slightly improved with a 0.003-ipr feed, whereas with a 0.012-ipr feed the roughness increases to 150-200. With H.S.S. tools, the average surface finish is 125-190 rms. The actual surface finish of a casting cut at the standard condition is shown in Fig. 26a. The surface of a casting cut with a 0.025-in. depth is shown in Fig. 26b. It is evident that such a shallow cut is not sufficient to remove all surface defects.

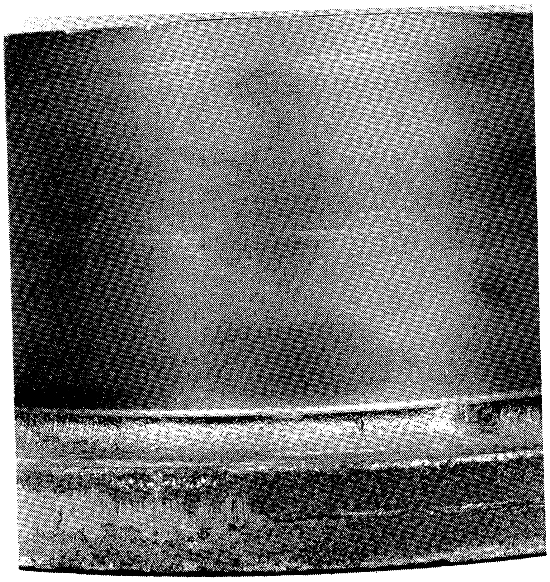
TABLE IV

SURFACE FINISH (CARBIDE TOOLS)

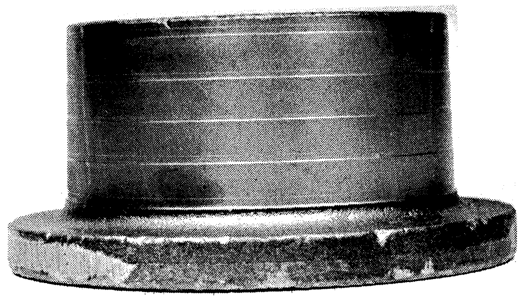
Cast No.	Rake	Grade	Speed	Feed	Depth	Observations			Average
						1st	2nd	3rd	
16	-5-5	K6	600	.006	.100	65-75	60-75	65-80	63-78
52	-5-5	K1	600	.006	.100	65-75	65-75	65-85	65-80
55	-5-5	K8	600	.006	.100	50-65	55-65	55-65	55-65
68	-5-5	K11	600	.006	.100	55-65	55-65	55-75	55-70
79	-5-5	K6	600	.003	.100	50-60	50-60	50-60	50-60
90	-5-5	K6	600	.006	.050	55-65	55-70	55-73	55-70
107	-5-5	K6	500	.006	.100	55-68	55-70	60-70	55-70
119	-5-5	K6	400	.006	.100	60-75	60-70	65-75	60-75
127	-5-5	K6	300	.006	.100	75-90	75-85	75-85	75-90
128	-5-5	K6	200	.006	.100	67-82	67-80	60-75	65-80
75	0+5	K6	600	.003	.100	55-65	50-65	55-65	55-65
137	0+5	K6	600	.012	.100	130-165	130-175	130-162	130-170
144	0+5	K6	600	.006	.050	60-70	60-72	55-75	60-70
150	0+5	K6	600	.006	.025	70-80	60-70	60-75	60-75
157	0+5	K6	500	.006	.100	55-65	60-75	60-75	60-70
169	0+5	K6	400	.006	.100	70-85	75-90	75-85	72-87
177	0+5	K6	300	.006	.100	80-100	80-90	80-90	80-90
179	0+5	K6	200	.006	.100	90-105	90-105	80-105	85-105
206	0+5	K7	600	.012	.100	110-140	120-140	120-140	120-140
213	0+5	K7	500	.012	.100	190-215	200-220	200-230	195-220
222	-5-5	K6	600	.012	.100	95-110	95-110	95-120	95-115
	0+5	K7	600	.006	.100	55-75	55-75	55-70	55-75
					(H.S.S. Tools)				
194	8,14		300	.006	.100	145-165	165-180	185-195	150-190
195	8,14		350 and 400	.006	.100	Not possible to measure due to short length and digging in of tool			
196	8,14		325	.006	.100	125-135	120-135	120-135	120-135
197	8,14		280	.006	.100	180-200	170-190	160-180	170-190
200	8,14		250	.006	.100	130-145	120-140	135-150	125-145
202	8,14		220	.006	.100	130-150	125-150	130-145	130-150



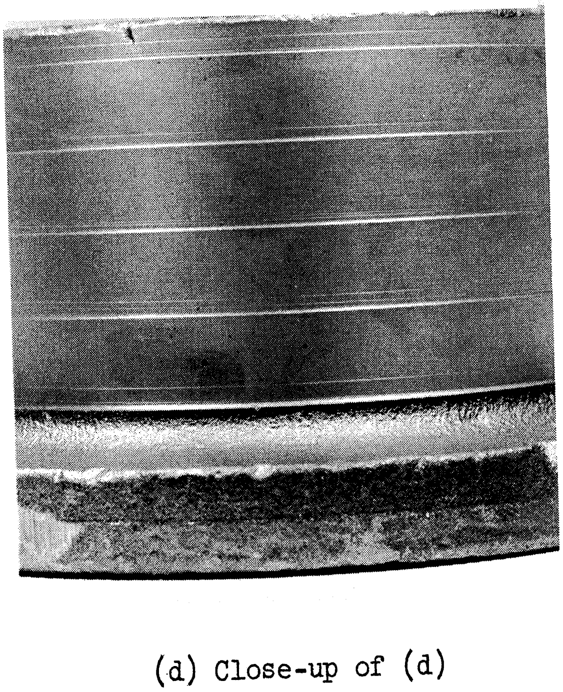
(a) Casting machined at 600 fpm, 0.100 in. depth and 0.006-ipr feed. Surface finish is 63 rms.



(b) Close-up of (a)



(c) Casting machined at 600 fpm, 0.025 in. depth and 0.006-ipr feed. Surface finish is 63 rms. However, many small surface defects are present.



(d) Close-up of (d)

Fig. 26. Photographs of castings showing surface finish obtained.

APPENDIX

INDEX OF CASTINGS

Rake	Grade	Speed	Feed	Depth	Range	No. Saved
-5-5	K6	600	.006	.100	7-38	17
-5-5	K6	600	.003	.100	76-83	79
-5-5	K6	600	.012	.100	84-87	87
-5-5	K6	600	.006	.050	88-95	90
-5-5	K6	600	.006	.025	96-103	101
-5-5	K6	500	.006	.100	104-111	105
-5-5	K6	400	.006	.100	112-119	119
-5-5	K6	300	.006	.100	120-127	127
-5-5	K6	200	.006	.100	128-129	128
0,5	K6	600	.006	.100	40-50	43
0,5	K6	600	.003	.100	70-75 131-132	
0,5	K6	600	.012	.100	133-137	137
0,5	K6	600	.006	.050	138-145	145
0,5	K6	600	.006	.025	146-153	150
0,5	K6	500	.006	.100	154-161	157
0,5	K6	400	.006	.100	162-169	169
0,5	K6	300	.006	.100	170-177	177
0,5	K6	200	.006	.100	178-179	179
-5-5	K1	600	.006	.100	51-53	52
-5-5	K8	600	.006	.100	54-61	59
-5-5	K11	600	.006	.100	62-69	68