the feed was varied from 0.0125 in. to 0.050 in. per revolution, while the depth of cut was kept constant at 0.200 in. Three cutting fluids, dry, *EmF* 1:50, and *SM* were used. See Figs. 9 to 15, inclusive, and Fig. 18.

This depth of cut of 0.200 in. was selected as, in previous tests in which depth was varied, it was found that cutting fluids are more effective with large depths of cut than with small depths of cut. The results of the experimental data of these tests are represented as straight lines on log-log paper in Fig. 9. The tool-life cutting-speed line is shown for each cutting fluid for the light feed of 0.0125 in. at the top. As usual, the line for dry cutting is lowest, giving a V_{40} of 79 fpm. The line for *SB* is higher but of a steeper slope and has a V_{40} of 93 fpm. The line for the emulsion *EmF* 1:50 is highest, producing a V_{40} of about 99 fpm. The increase in cutting speed of the emulsion over dry cutting is 25 per cent. The three lines for the feed of 0.025 in. are somewhat lower, producing a cutting speed V_{40} of 46 fpm for dry cutting, 61 fpm for the *SB* oil, and 63 fpm for the *EmF* 1:50 emulsion. The increase in cutting speed of the emulsion over dry cutting for this feed is 37 per cent. Only the line for dry cutting is shown for the maximum feed of 0.050 in., for which V_{40} is 28 fpm.

The tool-life cutting-speed lines for the emulsion *EmF* 1:50 do not have such a steep slope as those for the *SB* oil. This indicates that, for longer tool-life values, the emulsion would be superior to the *SB* oil for these sizes of cut.

The lines for dry cutting of Fig. 9 are shown alone in Fig. 10 for each feed of 0.0125, 0.025, and 0.050 in. per revolution. Increasing the rate of feed lowers considerably the tool-life cutting-speed line. The slope of the line, as represented by n in the equation $VT^n = C$, is increased from 0.106 for the light cut to 0.140 for the heaviest cut. The values of C, which correspond with the cutting speeds for a 1-min tool life, are decreased from 117 to 46.7, or 60 per cent, while the feed is being increased by 300 per cent. The cutting speed V_{40} for a 40-min tool life is decreased from 79 fpm to 28 fpm as the feed is increased from 0.0125 in. to 0.050 in. V_{40} is increased from 28 to 46 fpm, or 64 per cent, as the feed is reduced from 0.050 in., to 0.025 in., or 50 per cent. It is increased from 46 to 79 fpm, or 46 per cent, as the feed is reduced further from 0.025 in. to 0.0125 in., or 50 per cent. It is increased from 28 to 79 fpm, or 182 per cent, as the feed is reduced from 0.050 in. to 0.0125 in., or 75 per cent, or an increase of feed to four times, reduces the speed to $^1/_{3.5}$ of that for the light feed.

It was difficult to obtain the exact time of total failure of the tools when the feed was 0.050 in. because a preliminary failure would often be obtained early in the run, but the tool still would cut, getting progressively duller, until the operator's judgment set the time of total failure. The preliminary failures introduced excessive loads on the tools, causing them to be broken off, particularly when using the oil or emulsion.

The relation between cutting speed and variable feed for dry cutting is shown on log-log coordinates in Fig. 11, for three values of tool life, namely, 1, 10, and 100 min. Straight lines are formed, the slopes of which increase slightly as the tool life is increased. These slopes, as represented by the exponent of the feed in the equation $V = C/f^x$, are shown on the figure. Since the tangent of the slope of these curves, that is, the exponent of the variable feed, is less than one, the most efficient cutting speed to remove this material is obtained for the large values of feed. It is seen that the exponents of feed are 0.67 for a 1-min tool life, 0.73 for a 10-min tool life, and 0.78 for a 100-min tool life. The 100-min tool life is the steepest. From this, it follows that a lower exponent is obtained for a lower value of tool life. Therefore, for dry cutting, the most efficient metal removal would be obtained for the largest values of feed when operating at relatively high speeds or short tool life. In Fig. 11, the most efficient metal removal theoretically will be obtained at the point *A*. For practical reasons, the tool life should be longer than 1 min. The exact time must be correlated with the time for tool replacement and so on.

When using the *SB* oil and varying the rate of feed, it was not possible to use a feed of 0.050 in. and a depth of 0.200 in. because of excessive loads on the tool after the preliminary failure. These loads would cause the $^3/_8$-in. square tools to break off, thereby interrupting the tests. The tool-life cutting-speed lines for feeds of 0.0125 and 0.025 in. per revolution are shown on log-log coordinates in Fig. 12. The slope of these lines is less for the heavier feed. This is just the opposite from dry cutting, Fig. 10, and indicates that the use of the *SB* oil would be more desirable for the heavier cuts at a long tool life. For a tool life of 1 min, the cutting speed is reduced from 152 to 90 fpm, or 41 per cent, by increasing the feed from 0.0125 in. to 0.025 in., whereas for a tool life of 100 min, the same change in feed reduces the cutting speed from 82 fpm to 56 fpm, or 31.5 per cent.

Discussion

M. Kronenberg.[7] There has been much discussion as to the question when a tool is to be considered dull. Ripper and Burley measured the wear on the face of the tool and considered a blunting of $^1/_{16}$ in. as a criterion. Schlesinger, on the other hand, found as a scientific criterion the sudden rise in the two horizontal components of the cutting pressure, which is not always accompanied by an increase in the main (tangential) component of the cutting force. This behavior may be explained by the fact that the heat which is generated by friction between both tool face and chip and tool flank and work is mainly responsible for the wear of the tool. If the friction due to dulling increases, the horizontal components of the pressure increase too before the vertical component increases. The authors noticed that the breaking down of a part of the cutting edge did not change the quality of the machined surface and did not cause an appreciable increase in power consumption. Thus they allowed the tools to run until total failure which was indicated by the increase of power consumption. It does not seem to be advantageous to run tests until total failure due to the fact that in practice a total breakdown is uneconomical on account of the high cost for regrinding. A rapid change in the horizontal components usually reveals the instant of dulling; viz., between a partial breakdown of the edge and the total failure, provided that a time-recording device is used for measuring the horizontal cutting components.

The writer agrees with the statement that an increase in cutting speed by 22 per cent is possible in the case where the shape of chip cross section is changed from 1:2 to 1:8. Fig. 19 shows the same results for S.A.E. 1035 for various areas of chip and a tool life of 60 minutes. It will be seen however later on that for practical purposes this increase is of minor importance as to the most efficient metal removal on a lathe.

The finding that a shape factor of 1:8 for the area of chip is a desirable proportion of cut agrees with actual practice, where the ratio of feed to depth of cut (= shape factor) varies approximately between the limits of 1:2 and 1:20 and usually only between 1:5 and 1:10.

Formulas for the cutting speed V, in which the feed and depth of cut are given separately are usually presented in the form:

$$V = Cd^{-x} f^{-y}$$

[7] Research Department, Cincinnati Milling Machine Company, Cincinnati, O.

which can be transformed into

$$V = \frac{C}{A^{1/2\,(y\,+\,x)}\;S^{1/2\,(y\,-\,x)}}$$

where

A = Area of cut = $f \cdot d$
S = Shape factor = $\frac{f}{d}$
f = Feed per revolution
d = Depth of cut
x,y = exponents of d and f, respectively
C = Material constant for a definite tool life

This transformation indicates very clearly that the area A of the chip is of considerably greater effect on the cutting speed than the shape S, since the exponent of A is composed of the sum of y and x, while the exponent of S derives from the difference $y - x$.

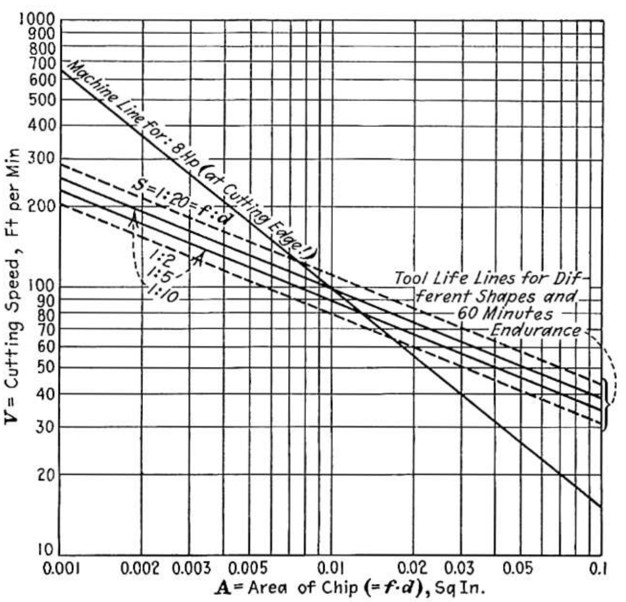

FIG. 19 CUTTING SPEEDS FOR VARIOUS AREAS OF CHIP; EFFECT OF SHAPE OF CHIP CROSS SECTION

(Example for high-speed-steel tool, [18-4-2]; S.A.E. 1035; 20-deg true rake angle; cutting fluid used. f = feed rate, in. per rev; d = depth of cut, in.; $S = f:d$ = shape of chip cross section; $A = f \times d$ = area of chip cross section.)

If as an example, the shape of chip cross section is changed in the ratio 1:4 (viz., from 1:2 to 1:8) then the cutting speed may be increased by 23 per cent, while a change of 1:4 in chip cross section (viz., from 0.004 sq in. to 0.001 sq in.) permits an increase of cutting speed by 270 per cent for the same tool life.

As to the exponent n of the cutting-speed–tool-life relationship, no definite connection with either the chip cross section, the shape factor, or the cutting fluid can be seen from the paper. It is known that the values for n vary approximately between 0.1 and 0.17 and usually between 0.12 and 0.16. The ideal condition would be an exponent $n = 0$, meaning that the tool life would be infinite; since this is out of the question the aim must be to reduce n as much as possible by cooling fluids, etc. On the other hand, care must be taken not to lay too much importance on the change of n within the limits mentioned above. A value of n of 0.12 as against 0.16 results in an increase of the cutting speed (all other conditions unchanged) of approximately only 21 per cent, while a change in the chip cross section has considerably more effect as will be shown. Furthermore the accurate determination of n is difficult. Fig. 3 of the paper indicates this. An exponent $n = 0.111$ occurs twice although no reason is to be seen why this value should be true only for $d = 0.035$ and $d = 0.200$, while the n values of the other lines are different. In the writer's opinion the four exponents shown could be averaged and the lines be made parallel. This averaging would hardly be noticeable on the diagram as it calls only for a minute turning of the lines through 1 deg or less. Thus the value of n averaged from Table 5 of the paper would be 0.127 for dry cutting as against 0.11 for *EmF* 1:50. This indicates a definite improvement, which becomes still more evident if the V_{100} values on this basis are taken into consideration and compared for the same chip cross section and shape. Then it will be seen that the improvement in cutting speed due to *EmF* 1:50 ranges between 15 per cent (for small chip cross sections) and 39 per cent for greater ones.

The most effective combination of the various variables involved in cutting with single-point tools will be explained by

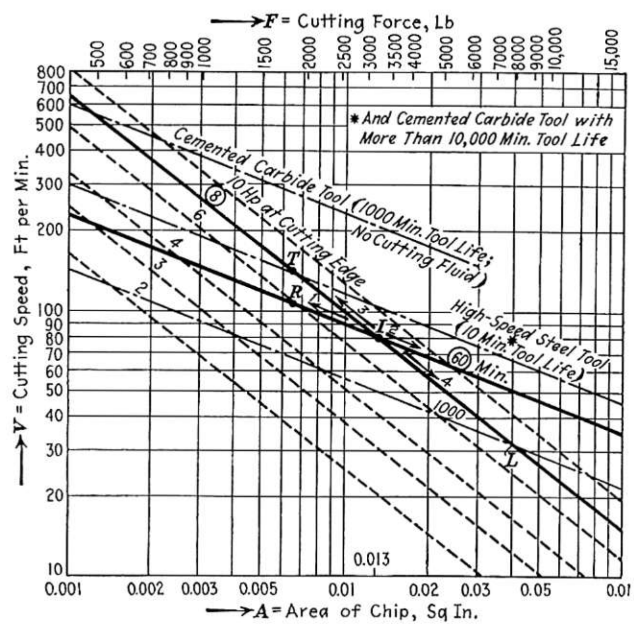

FIG. 20 DETERMINATION OF MOST EFFECTIVE COMBINATION OF CUTTING VARIABLES

(Example for high-speed-steel tool, [18-4-2]; S.A.E. 1035; 20-deg true rake angle; cutting fluid used.)

Fig. 20.[8] It will be seen that two different relationships exist between cutting speed V and chip cross section A as indicated by the lines with smaller slope (lines of constant tool life) and with greater slope respectively (lines of constant horsepower). The lines intersect, for example, in point I where a high-speed-steel tool of 60-min endurance and a machine of 8 horsepower are assumed. Increasing the cutting speed (along arrow 1) by decreasing the chip cross section in such a manner that the kind of tool and tool life is kept constant is not advisable, due to the fact that the productivity is decreased. (The combination at point I gives 12.5 cu in. per min metal removal at point R only 8.2 cubic inches per minute).

Following the tool line in direction of arrow 2 results in an increase in the chip section and a decrease in speed for a constant tool and tool life. Here the 10-horsepower line is approached, indicating an overloading of the machine.

[8] "Science and Practice in Metal Cutting" by Dr. E. Bickel, *American Machinist*, October 1934, page 693. This article is based mainly on investigations made by the writer.

Further combinations of the variables are possible by following the machine line (along arrow 3). Here we increase the cutting speed and decrease area A, but we leave the tool line of 60-min endurance. Thus the tool must be changed and a cemented carbide tool be taken. The production at point T would be 11.2 cu in. per min and the pressure 1800 lb (see scale at top). In spite of the diminution of chip volume per minute, it is often desirable to use small chip cross sections and high speeds due to the decrease of cutting force and consequently less deflection and higher accuracy (no built-up edge).

This will obviously be at some sacrifice in productivity but still considerably more advantageous than in the case of following arrow 1 (tool-life line) where the chip volume was reduced to 8.2 cu in. per min.

Following the machine line in the direction of arrow 4 leads for example to point L, where the productivity is 15.3 cu in. per min and the tool life 1000 min. Thus it seems that the use of a low cutting speed in combination with a big chip results in both a better endurance and a higher productivity. However, it must be borne in mind that the cutting force increases to 8000 lb in this example. This procedure (along arrow 4) is only advisable if roughing cuts are to be taken on stable work pieces.

In conclusion it must be said, that the selection of and changes in the cutting speed should be made in accordance with the machine line (arrows 3 and 4, respectively) and the tool should be adapted to the respective speeds. The machine line is often still unknown, although it is the best guide as to the most efficient metal removal.

Authors' Closure

Dr. Kronenberg has presented charts, the purpose of which is so to generalize the information as to make it applicable for shop use. This was not the primary object of the paper. The authors have emphasized cutting fluids particularly, which are not considered in Dr. Kronenberg's discussion.

The authors, on many occasions, have correlated cutting forces with tool wear and tool failure. They have found and have published data[9] in which the three components of the cutting force are shown to be maximum when a newly ground tool starts to cut, are gradually reduced as the tool is cupped on the face, but are increased perceptibly as soon as the newly formed cutting edge between the cup and the flank of the tool is broken off. The occurrence at this instant has been called preliminary failure by the authors, as the tool will run an additional length of time, ranging up to 60 or 70 per cent, before complete tool breakdown occurs.

By modifying the side-cutting-edge angle and nose radius for a given size of cut, preliminary failure may occur. It will be evident by a burnished ring on the shoulder of the metal being cut but in no way will it affect the size or roughness of the machined surface. The cutting-speed–tool-life line for the preliminary failure, as well as for the ultimate failure, has been determined. Sometimes the line for the preliminary failure plotted on log-log paper is parallel to, but just below, that for the ultimate failure. More often, however, this line has a slope greater than that for the total-failure line. This point is discussed to show that, by determining the time of total failure, using the increase-in-force method, a time of tool failure differing from that of the ultimate tool failure is obtained, which has no consistent relation to the latter in different sets of tests.

When high-speed-steel tools fail in machining cast iron, failure occurs by abrasion on the flank. For some tool shapes this wear is below the side cutting edge. It is gradual in its development. The cutting force will start to increase and become maximum at the time of complete tool failure, at which time there is the first evidence of change in diameter and surface quality on the machined surface. When the wear occurs under the end cutting edge, the diameter of the work gradually increases and it is hardly possible to determine a definite time of tool failure. It would be difficult to obtain consistent values of a certain definite amount of wear by the force method when turning cast iron for these reasons.

Many experimenters have tried to correlate the time of tool failure when taking light cuts with the cutting force. No satisfactory data were published until French and Digges replaced the cutting-force idea with their trailer tool. The authors have used the trailer tool, but have found, even for the 0.0125-in. depth × 0.0125-in. feed in cutting steel, that there is a very definite time of tool failure, as observed by the sudden burnishing of the work shoulder, at which time the diameter and quality of the machined surface is first affected.

The authors believe that the chip-shape factor is of more importance than indicated by Dr. Kronenberg. It is believed that, in the development of curves for guidance in general machining, this chip-shape factor should provide for ratios of feed to depth in excess of 1:5 and 1:10. This is indicated in Fig. 18. It is shown in Figs. 4, 6, and 8 that the chip-shape factor has a greater effect for ratios larger than 1:8. For high ratios, such as 1:16, the formula expressing a relation between V and d no longer holds, as shown by Fig. 3. This would mean that, for large ratios, the depth factor S would become of equal effectiveness to that of area A, as expressed in Dr. Kronenberg's second equation, inasmuch as the value of x becomes zero.

Dr. Kronenberg points out that, as the shape of the chip cross-sectional area is changed from 1:2 to 1:8 (keeping the area of cut constant), the cutting speed is increased 23 per cent, as shown in Fig. 1. He further states that a change in chip cross-sectional area from 0.004 to 0.001 sq in. (giving one quarter the area of cut) permits an increase in cutting speed of 270 per cent for the same tool life. This latter example actually shows a loss in production by reducing the size of cut.

Dr. Kronenberg's Figs. 19 and 20 are very interesting and valuable from a practical viewpoint. It is unfortunate that the material, tools, and cuts are so different from those of the paper. The authors have no way of comparing their data with those of Dr. Kronenberg, shown in Fig. 19, inasmuch as the materials are different and the areas of cut hardly overlap. In Fig. 20 Dr. Kronenberg has used an S.A.E.-1035 steel, presumably annealed, which in general calls for a machinability rating of about 68 per cent, as compared with that of 100 per cent for the S.A.E.-1112 cold-finished screw stock. The machinability rating of the S.A.E.-2340 steel annealed as generally accepted, and used by the authors, is around 56 per cent or only 12 per cent below that of the S.A.E.-1035 steel.

By referring to Fig. 2, the cutting speed for a 60-min tool life for an area of cut of 0.0125 in. by 0.100 in. (equals 0.00125 sq in.) is shown to be about 95 fpm for the emulsion. Fig. 20 shows, for the S.A.E.-1035 steel, that the cutting speed for a 60-min tool life for the same area of cut is about 210 fpm, which is 120 per cent higher than that for the S.A.E.-2340 steel. Dr. Kronenberg used 18–4–2–type high-speed steel, which might increase the cutting speed by 10 per cent over the 18–4–1 type of steel, but even so his values do not seem to agree favorably with those of the steel used in the paper.

The authors greatly appreciate Dr. Kronenberg's contribution and the many oral questions and discussions which brought out numerous interesting phases of the research and added greatly to its practical understanding.

[9] "Metals Handbook," American Society for Metals, Cleveland, Ohio, 1936 edition, p. 752.