compared with the drilling thrust to permit the equations based on the approximate Expression [81] to be used, a lower limit for the critical load will be calculated on the assumption that the drill will not buckle before a uniform column of the same length having a second moment of area equal to the minimum second moment of area of the drill. On inserting the appropriate values in Equation [79] the lower limit for the critical load is found to be 950 lb. As the ratio of drilling thrust to the lower limit is only 0.21, Equation [92] or [93] can be used to calculate the lower limit for the relationship between the displacement \( q_k \) at the top of the hole and the slope \( s \) of the hole. Substituting the given values of fluted length, hole depth, misalignment error, and clearance in Equation [92] for a slender drill, the following equations to the limit lines for the 1\( /\)4-in-diam drill are obtained

\[
\begin{align*}
\sigma(0.001 \text{ in/ft}) &= 6.58 q_k + 9.1 \quad (q_k \text{ in units of 0.001 in})
\end{align*}
\]

By similar substitution of the appropriate values in Equation [93] for a more rigid drill, the equations for the 1\( /\)4-in-diam drill were found to be

\[
\begin{align*}
\sigma(0.001 \text{ in/ft}) &= 5.26 q_k + 2.0 - 7.5 \quad (q_k \text{ in units of 0.001 in})
\end{align*}
\]

**Discussion**

R. G. Kennedy.* It is always refreshing to have new light shed on the many factors affecting drill performance. Both drill users and manufacturers will benefit from the author's work in this field.

The author is to be complimented on his drill dynamometer data, recordings of which are shown in his Figs. 8 and 17. His tests show that increase of torque is a more sensitive indicator of drill failure than is an increase in thrust. In general we have found this to be true. The wide fluctuations in torque, observed when the drill is breaking through the bottom of the test billet, as depicted in Fig. 17(a), clearly reveal the stresses placed on a drill in through-hole drilling. These records emphasize the destructive vibrations commonly occurring during break-through, and furnish an explanation of the reason drill life is so much shorter when drilling through holes rather than blind holes.

We were much interested in the author's ingenious method of depicting point displacement at the onset of drilling as shown in his Fig. 23.

The relation between hole displacement and slope, as shown in Fig. 25, comprises new information of value to drill users.

The author has demonstrated remarkably well the effect of difference in lip height or "relative lip-height error" on the size of holes drilled and their alignment. The fact that a poorly pointed drill, having lips of different height, produces larger sized holes than a correctly pointed drill is revealed in Fig. 22(b). This subject has been explored in a limited manner in our own laboratory. A chart (Fig. 33) of our data is hereby offered in the hope that it will supplement the author's data of Fig. 22(b). In our work we did not explore lip-height errors larger than 0.010 in. However, we did collect data from tests in both soft steel and hard cast iron.

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* The Cleveland Twist Drill Company, Cleveland, Ohio.
run with four different sizes of drills. Our tests showed that a relative lip-height error of 0.010 in. results in a greater amount of oversize of holes when drilling with smaller sized drills than when drilling with larger sizes, at least in the drill sizes we used, which were \(\frac{1}{4}\) in., \(\frac{3}{8}\) in., \(\frac{5}{16}\) in., and 1 in.

The author is to be congratulated for the quantitative evaluation he has made of many important factors affecting drill performance. The writer also offers the hope that he will submit the results of future work in this field for publication in our country.

R. S. HAHN. This discussion deals with the section on vibrational forces which is based upon an analysis of regenerative chatter in drilling. In this analysis the author derives the equation

\[ m\ddot{x} + c\dot{x} + kx = -r(x - x_0) \]

where the argument of \(x_0\) is retarded by the time interval \(t\). This equation is essentially identical to that derived by the author.

The author's method of analysis is preferable to that of the author since it gives information regarding the frequencies of chatter which the author uses to compute the undamped augmented natural frequency \(\Omega\) and the “work constant” \(r\). However, this procedure should be used with care since the experimental measurement of frequency requires a finite amplitude; i.e., the self-excited vibration has grown and reached a limit cycle where its amplitude is usually halted because of nonlinearities which the original differential equation does not contemplate.

The author's condition for unconditional stability Equation [65] is identical to the writer's.\(^1\) The regions of conditional stability shown in Fig. 20 are also in agreement.\(^1\) The example computed by the writer (Fig. 7)\(^1\) corresponds exactly to the situation represented in Fig. 20 for \(r = 0.1, \beta/\rho = 2.5\).

In addition to the conditions for “unconditional stability” and “conditional stability” Equation [62] of the paper gives the condition for “unconditional instability” (for zero damping).

In connection with Fig. 20 for the case where \(r = 0\) it is not clear what meaning the ordinate \(\beta/\rho\) has since the denominator is zero.

The abscissa of Fig. 20 may be interpreted in general as the number of cycles of vibration between consecutively adjacent cutting edges. For example, in single-point turning, it would be the number of cycles for one work revolution. With a two-lipped drill, it is the number of cycles occurring in a half revolution. For a tool with 4 cutting edges

\[ n = \frac{f}{2N} \] (cycles per tooth interval)

The author's analysis is well done and as he points out, applies to many types of operations, such as turning, boring, drilling, counterboring, and even dressing internal-grinding wheels.

C. J. OXFORD, Jr. The author is to be commended for this fine paper describing the Production Engineering Research Association experimental program to obtain basic data on drilling. The work covers many important factors influencing drill performance, and the paper is a valuable addition to the literature on drilling. The writer regrets that the author did not describe some of the work in greater detail, but realizes that several papers would be required to do this adequately.

As is always the case with good work of this type, more new questions are raised than old questions answered. The writer hopes that the PERA will continue its work on drilling to follow up the many leads uncovered in the present program.

The writer is pleased to see the author has recognized that wide variations in drill performance are normal and has used statistical techniques in evaluating the results of life tests. This procedure is especially necessary if small performance variations are sought, and here it may be necessary to use a very large number of drills in the tests. This point is often overlooked by drill users who attempt to conduct tests under production conditions.

The writer has found that drill-life test data tend to be normally distributed about the average, but that the standard deviation range is relatively wide, of the order of ±30 to 40 per cent. By careful selection of drills and workpiece materials it is possible to reduce these ranges somewhat. This was done by Wolfe, Kinman, and Lennard\(^2\) in their evaluation of cutting fluids by drilling test. Such selected drills gave reasonably satisfactory results in evaluating cutting fluids. However, this procedure is certainly not proper in the testing of drills where one wishes to take into account the normal variations encountered in production-drilling operations.

The author's use of a portal-frame drilling machine to minimize machine deflection and vibration is to be commended. Because of this, the tests more nearly reflect performance of the twist drills rather than the twist drills in combination with a particular drilling machine. It is unfortunate that the portal-frame construction is not more widely used. One manufacturer of drilling machines in this country attempted to introduce a machine of portal-frame construction, but was compelled to drop it because his customers would not accept the loss of versatility and accessibility which is inherent to this type of design.

In describing his dynamometers the author gives data as to the full-load torsional and vertical deflections, but neglects to indicate the capacities of the unit. It would be of interest to know the vertical and torsional spring constants.

The writer would like to inquire whether the author has observed any effect of the dynamometer upon drill life. Certainly, when the workpiece is mounted upon the dynamometer it is not as rigidly mounted as if it were clamped directly to the machine and. In tests of \(\frac{1}{2}\)-in. end mills with the workpiece mounted upon a dynamometer having a spring constant of about 250,000 lb per in. the writer has observed a reduction of life of about 40 per cent as compared to the case where the workpiece was mounted rigidly on the machine table. Of course, in drilling, the tool forces are more nearly balanced than in the case of end mills, and this effect may be less.

The author's device for measuring relief angle at any radius on the drill point by optical sectioning is very good. This apparatus simplifies this type of measurement and probably possesses greater accuracy than the usual indirect method.

The variation in design of nominally similar \(\frac{1}{4}\)-in. drills supplied by various British manufacturers is of interest. Actually, it appears that some of the manufacturers furnished a heavy-duty drill while others furnished a drill of substantially standard design. In this country the standard drill designs used by most manufacturers are quite similar, but most manufacturers also carry a line of heavy-duty drills. The heavy-duty drills are usually made with heavy webs to provide greater torsional stiffness when drilling tough materials. The heavy-duty designs of different manufacturers differ considerably.

The drills used by the author in his test program are somewhat unusual in that they have straight parallel webs. The straight

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\(^3\) Research Engineer, National Twist Drill & Tool Company, Rochester, Mich. Mem. ASME.

web construction has the obvious advantage of not requiring thinning during resharpening, but there may be a considerable loss of stiffness which could affect drill life in varying degrees, depending upon the drill and flute length. The writer feels that the difficulties encountered in web thinning are more than offset by the increased life obtained with drills having tapered webs. However, the accurate thinning of heavy drill webs is a real problem in some shops. The author does not touch upon the effect of drill length upon drill life. In the writer's laboratory it is always observed that shortening a \( \frac{1}{6} \)-in. taper-shank drill about \( \frac{1}{2} \) in. from its original length will increase the average drill life by 10 to 15 per cent when drilling a chrome-nickel-alloy steel having a hardness of about 220 Brin. In the case of some of the very tough alloys the increase in life with drill shortening can be even more dramatic. The accompanying Fig. 34 shows the case of drilling S-816 cobalt-base high-temperature alloy. This particular alloy has extreme work-hardening tendencies. In the figure it will be noted that a new letter "F" (0.257) drill, with a \( \frac{2}{3} \)-in. flute length, has a relative life of one corresponding to the drilling of two holes through \( \frac{1}{16} \)-in. bars. As the drill was shortened during successive regrooves the life increased gradually at first, and then when the flute length was finally shortened to \( \frac{1}{3} \)-in. the drill life increased more than 80 times. With normal work materials the increase in life is not as great but it is always observed.

It is further noted that the drills were made of a tungsten high-speed steel, apparently in accordance with usual British and European practice. In this country, all or nearly all manufacturers are now making their standard drills of molybdenum high-speed steel. While the lower cost and the strategic value of the molybdenum high-speed steels in the United States is certainly a factor, the main reason for the change from tungsten to molybdenum high-speed steel has been improved drill performance.

The author's analysis of the nominal relief angle as produced by conical-point grinding is a valuable addition to the literature. He shows that misalignment of the drill point with the sharpening cone generator will modify the theoretical relief angle. It should be noted that deliberate misalignment sometimes can be used to modify drill relief angles for particular applications.

The writer must take issue with the author's definition of drill rake angle. The author uses the plane containing the cutting edge which is parallel to the drill axis as the zero rake plane. The rake angle is then measured in a plane perpendicular to the drill cutting edge. This angle is the same as the face rake angle defined by the writer in an analysis of twist-drill geometry presented several years ago.\(^{11}\) The face rake angle is not an angle of fundamental importance in metal cutting. Its only merit is that it is an angle which is readily measured and visualized on the twist drill. The normal rake angle, which is measured with reference to the finished surface produced by the drill point is a basic angle. The author has correctly defined the normal rake angle in his Appendix 4. The normal rake angle always has a lower value than the face rake angle and on a twist drill is usually quite negative at small radii. Another important rake angle is the effective rake angle which is a measure of the angle through which the chip is deflected in cutting. This angle is partly a function of the properties of the work material. The accompanying Fig. 35 shows the relationship between face rake angle and normal rake angle; Fig. 36 shows the variation of face rake angle, normal rake angle, and effective rake angle for various radii on a \( \frac{1}{4} \)-in. drill.

It has not yet been established completely which rake angle is of major importance in determining drill performance. Stabler\(^{12}\) claims that metal-cut-
ting forces are principally determined by the normal rake angle, but Shaw\textsuperscript{13} has shown that both the normal rake angle and the inclination angle (which influences the effective rake angle) are important in oblique cutting.

In Fig. 36 it can be seen that all of these rake angles tend to approach each other at larger radii and here they are principally functions of the drill helix angle. The values of all of these rake angles are reasonably close together for the outer half of the drill lips. This portion of the drill removes 75 per cent of the metal and hence dissipates most of the cutting energy. The problem is further complicated by the continuity of the chips across the drill lips which affects the direction of chip flow.

The writer is in full agreement with the author in his view that short-duration accelerated-life tests are of little value because the wear mechanism may change completely in accelerated tests. This factor has been overlooked often by tool users who attempt to conduct tests by accelerating the rate of metal removal by four or five times over the contemplated shop practice.

The author is correct in stating that many factors must be considered in determining the end of drill life. As yet no single criterion which will apply in all cases has been discovered. The writer has found that in drilling high-strength steels and other materials where considerable flank wear is encountered, the thrust force appears to be a good indicator of dulling. However, on ordinary materials, the wear pattern seems to depend considerably upon the combination of speed and feed used to give a particular penetration rate.

In the writer's laboratory it has also been found that the titanium alloys have unique drilling characteristics. In determining torque and thrust versus feed characteristics, enough drill wear may occur during a test to make the results obtained dependent upon the order in which the tests are run. With these materials it is essential that the first point be rechecked at the end of a test to be sure that no appreciable change in the drill has taken place.

The author states that none of the web-thinning methods he investigated appeared to be worth using on thin-web drills. This is probably true for routine drilling operations but the writer feels that web thinning of such drills is justified for drilling deep holes in tough materials and where the drills are used in portable drilling equipment. For this purpose a style of thinning which is related to the author’s method B is most effective. This is called a split (crankshaft) point and it is usually ground approximately as shown in Fig. 37. Here, the effective length of the chisel edge is reduced to nearly zero because the thinning cuts form additional cutting edges which extend to the center of the drill. With this style of thinning the torque is reduced very little but the thrust can be reduced to very nearly the theoretical minimum. Figs. 38(a) and 38(b) show how the drill torque and thrust are partitioned between the lips and the web for various lengths of drill chisel edge. These plots are based upon a recent analysis of the

torque and thrust in drilling presented by M. C. Shaw and
the writer.11

As the author mentions, the split point sometimes gives dif-
ficulty in that the intersection of the two cutting edges is not
adequately supported. This can be helpful in two ways: (1) The
included angle of the drill point can be increased and this is usu-
ally done when drilling tough materials. (2) The new cutting
edges can be ground so that they are swung more toward the main
lips of the drill and this reduces the relief angle behind the new
cutting edges and gives more support to the edges. This has
been found particularly effective in the drilling of high-strength
steels.

The author claims that his method C reduced drill thrust by 25
to 40 per cent when drilling cast iron and steel. The writer at-
ttempted to check this, but was unable to discover a thrust re-
duction of more than 10 to 15 per cent when drilling two types of
steel. The fact that there is any reduction in thrust with this
thinning method is probably due to the fact that it permits easier
escape of the chips and extrusion products formed by the drill
chisel edge.

The experiments which determined the difference between the
actual and theoretical paths of the drill are particularly enlighten-
ing. These clearly show that machine deflection can far exceed
the nominal feed per revolution and can cause a large and damag-
ing increase in feed during the break-through. This situation is
unfortunately very little appreciated by drill users and by some
drilling-machine manufacturers. It further points out that a
twist drill can take a surprising amount of abuse and still give a
good account of itself.

In connection with the investigation of chatter, was any evi-
dence of high-frequency vibration involving the tool itself rather
than the complete system encountered? There is some indication
that this does happen when drilling certain materials.

The tests relating hole size to relative lip height and point
eccentricity clearly point out the need for accurate drill sharpen-
ing and thinning. As the work material becomes harder, accurate
sharpening and thinning are essential to satisfactory drill per-
formance.

It would be interesting to have a brief description or a sketch
showing the method of using capacitive gages to make records of
point displacement while drilling. The records produced by this
apparatus clearly show the unstable nature of the drill point
during entry into the workpiece.

The tests on the use of jig bushings are very interesting. They
clearly show that the common radial-drill-press practice of allow-
ing the drill bushing to pull the drill head into approximate align-
ment with the desired hole location can give very poor holes.
It should be noted that alignment with short bushings can be
improved considerably through the use of double-margin drills.
Double-margin construction is shown in the accompanying Fig.
39. Here an additional margin is provided at the trailing edge
each drill land with the result that initial guiding is greatly
improved.

The writer again wishes to compliment the author and his staff
at the PERA on a well-designed comprehensive investigation of
drilling. It is to be hoped that the experimental work and the
analysis of data will be continued and reported in future papers.

Author's Closure

The author is very appreciative of the interest shown in the
paper and the valuable comments made by contributors to the
discussion.

Mr. Kennedy's charts of hole oversize against relative lip
height are of considerable interest and exhibit characteristics
which were not revealed by the author's experiments. A puzzling

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11 "On the Drilling of Metals, 2—The Torque and Thrust in Drill-
ing," by M. C. Shaw and C. J. Oxford, Jr., Trans. ASME, vol. 79,
1957, pp. 139–148.
feature of the graphs shown in Fig. 33 is that in two cases the hole oversize for a relative lip height of 0.005 in. is considerably less than that which might be expected from considerations of equilibrium at the drill point. There are many factors other than relative lip height which could affect hole oversize and one might expect therefore to find values which were greater than those given by Equation [71] in Appendix 6 rather than smaller. The results in Fig. 33 suggest that it would be worthwhile to carry out more extensive investigations into the effects of the various factors on hole size.

Dr. Hahn's comment on the apparent obscurity of $\delta/p$ in Fig. 20 when $p = 0$ was accepted, but in this instance the author had sacrificed explicitness of statement for the sake of brevity. It was intended to represent the limiting case when $\rho$ is approaching zero and is very small. The analysis of self-regenerative vibration given in the paper was based on essentially the same equation as that first discussed by Dr. Hahn some years ago in his paper on chatter in precision grinding operations. In that paper he derived the condition for unrestricted stability expressed by Formula [65]. Certain additional results are presented in the author's analysis, notably the instability zones and the equation relating the chatter frequency to the parameters of the system. The instability zones provide a general view of the phenomenon of regenerative chatter, while the frequency equation enables the basic parameters of an actual vibrating system to be determined by simple observation of a range of chatter frequencies.

Dr. Hahn's remarks on effects due to nonlinearities in the system are very relevant, since such effects were observed in the author's tests and indeed commonly serve to limit the amplitude of the vibrations occurring in an unstable vibrating system. It is interesting to note that the method described in the paper for determining the basic parameters of the system is applicable in most practical cases of this type. The parameters $\Omega$, $\delta$, and $\rho$ may still be determined by observing the chatter frequencies even though nonlinear effects are present and the frequencies observed correspond to vibrations having a finite nonconstant amplitude. The type of vibration which can be dealt with may be described as essentially sinusoidal in character in the sense that it may be represented with good accuracy over any complete period by a sine wave, although the amplitude of the sine wave used to represent it varies from period to period. The chatter vibrations occurring in the chatter bands shown in Fig. 21 fell into this category, as do many chatter vibrations—at least in their initial stages. Vibrations having a markedly nonsinusoidal character commonly supervene only when the amplitude of the chatter vibration exceeds the feed, so that impact takes place between tool and work.

Equation [43] is applicable in the case of a nonlinear system undergoing vibrations which are essentially sinusoidal in character provided that the coefficients in the equation are suitably interpreted. The quantities $m$, $c$, $k$, and $r$ are no longer to be treated as constants, but as functions of $a$, the amplitude of the chatter vibration. For clarity Equation [43] may be revised to make explicit this dependence on amplitude, thus

$$m(a)x + c(a)x + k(a)x = -r(a)(x - x_1), \ldots \ldots [43a]$$

An "essentially sinusoidal" solution of Equation [43a] is obtained by substituting

$$x = a \sin \omega t, \ldots \ldots \ldots \ldots [68a]$$

where $a$ is a function of $t$ such that $\dot{a}$ is a quantity small enough to be neglected over the period $2\pi/\omega$ of the chatter vibration. After substitution of Equation [68a] in Equation [43a] and some slight simplification

$$-m(a)x^2 + \frac{\dot{a}}{a} c(a)x + k(a)x + r(a) - r(a) \cos \omega t \sin \omega t \\
+ \left[ 2 \frac{\dot{a}}{a} m(a)x + c(a)x + r(a) \sin \omega t \right] \cos \omega t = 0$$

The coefficients of $\sin \omega t$ and $\cos \omega t$ must both be equal to zero for this equation to be satisfied, hence

$$-m(a)x^2 + \frac{\dot{a}}{a} c(a)x + K(a) - r(a) \cos \omega t = 0$$

$$2 \frac{\dot{a}}{a} m(a)x + c(a)x + r(a) \sin \omega t = 0$$

where $K(a)$ has been written for $[k(a) + r(a)]$.

New parameters $\Omega(a)$, $\delta(a)$, $\rho(a)$, and $\Delta(a)$ are now introduced, where

$$\Omega(a) = \frac{K(a)}{m(a)}$$

$$\delta(a) = \frac{\pi c(a)}{\sqrt{m(a)K(a)}}$$

$$\rho(a) = \frac{r(a)}{K(a)}$$

$$\Delta(a) = \frac{2\pi \dot{a}}{\Omega(a) a}$$

The parameters $\Omega(a)$, $\delta(a)$, and $\rho(a)$ are obvious generalizations of the parameters $\Omega$, $\delta$, and $\rho$ which appear in the paper, and it is readily shown that if $a$ and $a + \dot{a}$ are the amplitudes for corresponding points in consecutive chatter cycles then $\dot{a}/a = \Delta(a)$ approximately; i.e., $\Delta(a)$ approximates to the logarithmic increment of the chatter. Rewriting the pair of equations in terms of the new parameters, the following relationships are obtained, after some simplification

$$\left( \frac{v}{2\pi} \right)^2 = \left( \frac{\Omega(a)}{2\pi} \right)^2 \left( 1 + \frac{1}{2\pi} \Delta \delta - \rho \cos \theta \right)$$

$$\frac{v}{\Omega(a)} (\Delta + \delta) = -\pi \rho \sin \theta$$

In these equations $\theta$ has been written for $\omega t$, and for ease of writing the dependence of the quantities $\Omega$, $\delta$, $\rho$, and $\Delta$ on the amplitude $a$ has not been indicated explicitly as hitherto.

From the first equation it may be seen that in practical cases $v = \Omega(a)$ to a first approximation; hence, by substitution in the second equation, $\Delta + \delta = -\rho \pi \sin \theta$ approximately; it follows that the inequality $\Delta + \delta < \rho \pi \sin \theta$ holds approximately. From this inequality it follows that the inequality

$$\frac{1}{2\pi^2} \Delta \delta < \frac{1}{8} \rho^2$$

is also approximately true. Finally, then, since $(\rho^2/8)$ is normally a small second-order quantity in practical cases, the term $(1/2\pi^2)\Delta \delta$ may commonly be neglected, so that the two equations may be simplified to give

$$\left( \frac{v}{2\pi} \right)^2 = \left( \frac{\Omega(a)}{2\pi} \right)^2 (1 - \rho \cos \theta), \ldots \ldots [50a]$$

$$\frac{\Delta + \delta}{\rho} = -\sqrt{\frac{\pi \sin \theta}{(1 - \rho \cos \theta)}}, \ldots \ldots [50a]$$

The close formal similarity between these equations and the corresponding Equations [59] and [59] of the paper is at once apparent. In particular, Equations [59a] and [59a] are identical.
in form and do not include the damping parameter $\delta$. It follows that the method described in the paper for determining the basic parameters of a vibrating system is unaffected by nonlinearity in the system, providing the amplitude $a$ of the chatter vibration is small enough for the parameters $\Omega(a)$ and $\rho(a)$ not to differ substantially from the parameters $\Omega_0$ and $\rho_0$, which appear in the paper. This is the situation which was indicated in the author's tests. The amplitude of the chatter vibration assumed a fairly small limiting value and no appreciable dependence of $\Omega_0$ or $\rho_0$ on this limiting amplitude was detected.

With a slight modification, the method for determining the basic parameters of the vibrating system may still be applied even when the dependence of $\Omega(a)$ and $\rho(a)$ on the amplitude of the chatter vibration is appreciable. The square of the chatter frequency is plotted against $\cos \theta$ as before, only in this case, since $\Omega(a)$ and $\rho(a)$ are no longer constants, Equation [59e] shows that a curve is obtained which deviates from the straight line of Equation [59]. However, the ends of the curve will lie on the straight line since at the ends the amplitude $a$ of the chatter vibration is small. Thus, if a suitable regression curve is fitted to data obtained in a case such as this, the desired straight line corresponding to Equation [59] of the paper is obtained by joining the ends of the curve. Having obtained this straight line, the rest of the method described in the paper is unaffected by the nonlinearity of the system.

The scatter of drill life reported by Mr. Oxford agrees very well with that observed during drilling tests in steel and cast iron carried out at PERA. These showed that the average coefficient of variation of drill life in steel was about 35 per cent, of which only a comparatively small amount could be attributed to the variability of test drills. The distribution of drill-life values in cast iron was marked asymmetrical and it would be misleading therefore to quote a coefficient of variation, but in general the scatter of drill life in this material was about twice that occurring in steel.

The capacity of the large drilling dynamometer shown in Fig. 3(a) can be varied by changing the steel diaphragms in the load-measuring elements; thrust loads up to 2 tons and torques up to 100 lb-ft may be measured readily. The spring constants of the dynamometer when fitted with the diaphragms used in the majority of the tests were 300,000 lb/in. for thrust and 19 lb-ft/in. for torque. The maximum capacity of the small drilling dynamometer shown in Fig. 3(b) is 20-lb thrust and 0.09 lb-ft torque, and the respective spring constants are 10,000 lb/in. and 0.03 lb-ft/min of arc.

The author has not carried out comparative drill-life tests with and without a dynamometer, but feels that the stiffness of the dynamometer is high enough compared with the stiffnesses of the drill and machine to ensure that the dynamometer effect will be relatively small. For example, the vertical deflection of the dynamometer table was roughly only $1/4$, the vertical deflection of the drill caused by the elastic twisting of shafts in the drill-feed mechanism, and the torsional deflection of the dynamometer was less than 1 per cent of that of a standard $1/4$-in-diam drill. It is appreciated that reference only to stiffness in a dynamic system could be misleading, but it is thought that the figures given indicate the general order of the dynamometer characteristics as compared with those of the drilling setup.

The author is not convinced that the conventional tapered web can always be justified in terms of drill life. It is argued that the tapered web increases the torsional and flexural rigidity of the drill and thereby improves drill life, but the extent of this improvement will depend on how sensitive drill life is to changes in rigidity of the drill. Tests by the author in cast iron and medium-carbon steels with standard length $1/4$-in-diam drills did not reveal a significant improvement in drill life as the fluted length of the drill was reduced from 4 to 3 in., and it would appear therefore that under these conditions an increase of approximately 25 per cent in the torsional rigidity of the drill was of little consequence. If, therefore, standard length drills were made with a parallel web for say, two thirds of the fluted length it does not appear likely that drill life in normal engineering materials would be impaired seriously, and the elimination of the possibility of incorrect or poorly executed point thinning might well result in substantially improved drill life in practice. When tough, work-hardening materials are drilled, however, the drill performance seems to be much more sensitive to changes in rigidity and the tapered web may then become essential. Mr. Oxford's results showing the effect on drill life of the length of the drill when drilling S-816 high-temperature alloy (Fig. 34) point very clearly to the marked effect of drill rigidity during drilling operations on this type of work material.

The greater sensitivity of drill life to changes in drill rigidity when drilling certain materials may well be due to the occurrence of high-frequency torsional vibrations involving only the drill. It has been shown by Arnold that self-induced vibrations of the tool may occur if the material being machined has a negative cutting force/cutting speed characteristic. This type of vibration is quite different in origin from the self-regenerative vibration discussed in the paper and further equipment would have been required to detect it. However, the author has often noted audible signs of drill vibrations during the drilling of certain materials, and the squeal that is frequently heard when a drill is near failure certainly points to torsional vibration. It is hoped that it will shortly be possible to investigate the problem of drill vibration in greater detail.

The author agrees that the rake specified in Appendix 3 is not a fundamental metal-cutting angle, but is of the opinion that the advantages of ready measurement and visualization mentioned by Mr. Oxford are of major importance in a practical workshop nomenclature. Even if our knowledge of metal cutting was sufficiently advanced to enable a fundamental rake to be defined clearly, it is doubtful whether the definition of such an angle could be applied readily in the workshop. Workshop personnel are principally concerned with the facility with which a tool can be specified, ground, and measured as a separate entity, and the definitions given in Appendix 3 have been prepared with these essential workshop requirements in mind. The author feels that

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the onus is on the research worker to translate metal-cutting fundamentals into terms which are familiar to workshop personnel, and which are best suited to the practical requirements of workshop specification and tool servicing.

As pointed out by Mr. Oxford the split or crankshaft point has considerable advantages for the drilling of deep holes in tough materials. In this type of drilling operation the structural properties of the drill mainly set the limits of drill performance. The thick web which is necessary for maximum rigidity must be thinned at the point with the primary object of reducing the drilling thrust, and the split point described by Mr. Oxford fulfills this purpose very well. Provided the thinning is done accurately, the type of point produced also should facilitate the starting of the drill.

The reduction in thrust achieved with the method C type of point thinning is almost certainly due in part to the fact that it permits the material removed at the chisel edge to escape readily into the flutes; this also may account for the improved drill life shown in Fig. 12(a). The author notes that Mr. Oxford obtained a rather smaller reduction in thrust than that quoted in the paper. The behavior of the twist drill is governed by a very large number of factors and even small changes in these factors can have a pronounced effect on drilling forces and drill life. Without a detailed comparison of the conditions of the author's tests and those of Mr. Oxford's, it is not possible to determine the causes of the observed difference in the results.

A diagram of the equipment used to record the point displacements of the drill is shown in Fig. 40 of this closure. Two insulated condenser plates A were positioned close to a concentric sleeve B, located on the lands of the drill. The changes in capacitance across the sleeve and the two plates as the drill deflected were converted to voltage changes, amplified and presented on the X and Y-plates of an oscilloscope fitted with a high-speed cine-recording camera. A contactor C was arranged to trigger a pulse on the trace once per revolution of the drill and thus to mark the position of the outer corners along the trace. By photographing the movements of the spot on the face of the cathode-ray tube as the drill entered the workpiece D, a continuous polar record could be obtained of the transverse deflections of the drill point.

The double margin drill described by Mr. Oxford would appear to have considerable advantages where greater accuracy of the hole is required, and the author hopes to be able to include drills of this type in future tests.