Work Material

When tests were run upon a variety of work materials both with and without cutting fluids, results were similar to those already presented for SAE 3245 steel except when a large built-up edge (BUE) was present on the drill lips. Fig. 9 is a torque plot similar to Fig. 4(a) for a large variety of workpiece materials when drilled with standard $^1/_2$-in. drills. A slope of 0.8 for the torque-feed curves ($M \sim f^{0.8}$) is in good agreement with all data except when a large BUE was present as when cutting soft cast-aluminum alloys without coolant. The thrust data for these materials were also similar to that for SAE 3245 steel except where a large BUE was present.

Conclusions

In summary it may be stated that the torque M, and thrust T, required by a twist drill when drilling most steels having a Brinell hardness of less than 250 may be computed from the following general equations

$$\frac{M}{d^3 H_B} = 0.082 \frac{f^{0.8}}{d^{1.2}} \left[\frac{1 - \left(\frac{c}{d}\right)^2}{\left(1 + \frac{c}{d}\right)^{0.2}} + 3.2 \left(\frac{c}{d}\right)^{1.8} \right] \ldots\ldots\ldots [41]$$

$$\frac{T}{d^2 H_B} = 0.15 \frac{f^{0.8}}{d^{1.2}} \left[\frac{1 - \frac{c}{d}}{\left(1 + \frac{c}{d}\right)^{0.2}} + 2.2 \left(\frac{c}{d}\right)^{0.8} \right] + 0.068 \left(\frac{c}{d}\right)^2 \ldots\ldots [42]$$

where all dimensions are expressed in lb-in. units.

For standard drills, c/d can be taken as a constant equal to about 0.180 and these equations simplify approximately to

$$\frac{M}{d^3 H_B} = 0.087 \frac{f^{0.8}}{d^{1.2}} \ldots\ldots\ldots\ldots\ldots [36]$$

$$\frac{T}{d^2 H_B} = 0.195 \frac{f^{0.8}}{d^{1.2}} + 0.0022 \ldots\ldots\ldots\ldots [37]$$

or rearranged to give M and T directly

$$M = 0.087 H_B f^{0.8} d^{1.8} \ldots\ldots\ldots\ldots\ldots [43]$$

$$T = 0.195 H_B f^{0.8} d^{0.8} + 0.0022 H_B d^2 \ldots\ldots\ldots [44]$$

Equation [43] for torque is in general agreement with those presented by other investigators (3). However, their equations have related thrust to $f^{0.8}d^{0.8}$, $f^{0.6}d$, and $f^{0.8}d$. The first of these was obviously derived from the torque equation without regard to chisel-edge extrusion. The other two were based upon experimental observations. If Equation [44] is plotted on log-log paper against both feed and diameter it will be found that it can be well approximated in the normal range of feeds by an empirical equation of the form

$$T = K_{17} f^{0.63} d = K_{18} H_B f^{0.63} d \ldots\ldots\ldots\ldots [45]$$

Equation [45] can be useful in predicting the performance of standard drills under ordinary conditions.

For materials other than steels of medium hardness, Equations [42] and [43] appear to hold in form but the coefficients of the terms are different.

At first glance, Equations [41] and [42] do not appear to be dimensionally homogeneous. However, the coefficients 0.082 and 0.15 are dimensional constants, each being proportional to $s^{0.4}$ where s is the mean spacing of imperfections present in the work metal. When 0.082 and 0.15 are replaced by $K_{19}5^{0.4}$ and $K_{20}5^{0.4}$, these two equations do become dimensionally homogeneous.

As a result of the three-dimensional nature of drilling operations, the over-all specific cutting energy $\bar{u}$ is found to vary with the product of feed and diameter, fd, rather than the feed alone as in turning. This applies only if the ratio of chisel edge length to diameter c/d is constant. A more complex, but generally similar, product is involved when c/d is variable. This difference between drilling and turning has several important aspects, some of which have been discussed here.

Drill helix angles in the normal range, 15 to 40 deg, have only a small influence on torque and thrust so long as no chip-ejection difficulties are encountered.

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Discussion

M. Kronenberg.[5] The formulas presented by the authors for torque and thrust in drilling are quoted from an early publication of the writer[6] with the comment that this equation obviously was derived from torque equations without regard to chisel-edge extrusion. They are partly right and partly wrong in their assumption. It is correct to say that the chisel-edge extrusion was not considered in the derivation of the writer's torque formula and that is as it should be, because of the fact that torque is not or only very little affected by the extrusion. It is the thrust, rather, that is affected thereby. Hence extrusion should not be considered.

They are wrong in their assumption that the formula was derived from torque equations; it was rather derived from the writer's formula for turning force as presented in the paper quoted by the authors.[6]

Equation [43] which the authors derive is identical with the writer's formula of about 25 years ago. That formula was

$$M = \text{const}\, f^{0.803} d^{1.803}$$

Equation [43] of the paper reads

$$M = \text{const}\, f^{0.8} d^{1.8}$$

[5] Consulting Engineer, Cincinnati, Ohio. Mem. ASME.

[6] Reference 3(b) of the paper.

It may be of interest to readers also to learn of an exchange of letters between Prof. O. W. Boston and the writer which took place nearly a quarter of a century ago and was concerned with just these problems of torque and thrust in drilling. Prof. O. W. Boston's letter is as follows:

"Subject: Your paper 'Drilling Investigations and How to Put Them Into Practice'

"Some time ago the ASME referred to me the above paper for review. You had previously told me that you had sent it into the Society and I understand it has been reviewed by Mr. Spencer, the present chairman of the Metal Cutting Committee, as well as Editors of *American Machinist, Machinery,* and *Automotive Industries.*

"I have enjoyed looking through the paper and . . . am pleased with your investigations and how they agree with my own practical experiments. I found some steels to give $f^{0.803}$ exactly, but others fall below, so for steels I took an average of $f^{0.78}$. In extensive planing and turning tests, I also have found $f^{0.78}$ to hold remarkably well. For SAE 3150 steel I find $f^{0.78}$ but for cold-rolled steel I find $f^{0.67}$. This is brought out in a paper I have just submitted for the annual meeting in Buffalo of the American Society for Steel Treating. . .

"I have also a paper before the ASME dealing with 'Performance of Cutting Fluids When Cutting Various Metals.' This deals with drilling and for the steels $f^{0.78}$ is constantly maintained. For other metals it is different."

Since the difference between an exponent of 0.803 and 0.78 is practically very small, we may say that the authors' later research supported the writer's earlier formula very well.

It will be recalled that there were a number of other investigators who took the trouble of deriving formulas for torque and thrust in drilling. Some of these data will be mentioned.

There is Poliakoff, who derived the following formulas in 1909: Torque in steel with a feed exponent of 0.7 and a diameter exponent of 1.8; the same in cast iron. Kurrein-Schlesinger derive a formula with an exponent of 0.84 for the feed and an exponent of 1.48 for the diameter when drilling steel. In the writer's opinion the exponent for the diameter is too small in this latter formula. There is also a publication by Stoewer who ran tests on cast iron and presented data from which the writer concludes that they are proportional to an increase with 0.83 power of the feed and a 2.15 power of the diameter.

The significance of exponents like these lies in the fact that they give information about the change in torque and thrust with changing diameter of the drill and changing feed. As an example, with exponents 0.8 for feed and 1.8 for diameter, the torque increases 74 per cent when the feed is doubled and 250 per cent when the diameter is doubled. The thrust, however, for which the two exponents are more nearly equal is much less affected by a change in diameter of the drill than the torque, namely, about 75 to 80 per cent as it is when the feed is doubled. The difference in per cent change is small when comparing Boston's formula, Kronenberg's formula, and the authors' formulas even though the percentages change also with the materials drilled.

It is therefore not obvious that new results are obtained from the formulas presented by the authors and we may ask whether there is some merit in the paper. And there is merit!

The merit lies in the application of dimensional analysis to drilling operations. Although dimensional analysis has been applied with great success to turning operations as far back as 1939, it is the first time that this convenient method has been used for drilling research. The authors succeeded in this way to prove the dimensional correctness of our earlier formulas. Hence we may say that the exponents 1.8 and 0.8 in the torque formulas for steel are correct, and correspondingly, our earlier formulas for cast iron as well.

The writer wishes to offer two suggestions for possible further research in this field. One is concerned with the term or concept of "energy per unit volume, u" used by the authors and others. It is suggested that this term be replaced by the term "unit cutting force" with which it is identical. The concept of unit cutting force is better understood by the tool engineer and the men in the shop than the term "energy per unit volume." It is also easier to relate it to stress data.

The second suggestion is concerned with another check or step in the direction of dimensional analysis. The authors would add to the merit of their paper by an investigation into the problem whether or not the resultant cutting force may be assumed to act at half the radius of the drill. This is the writer's conclusion from their dimensional analysis, based on the formula

$$M = \frac{ufd^2}{8}$$

It can be shown that this formula holds when the resultant cutting force acts at half the radius of the drill. It seems, however, possible that the force distribution along the cutting edge is different (as Oxford has shown in his chip photos). In this case we would have to revise our torque formulas slightly; namely, increase the exponent of the diameter to about 2 and reduce that of the feed to about 0.65.

As may be concluded from the writer's comments, he considers the paper a thought-provoking contribution to our metal-cutting science and wishes to commend the authors for their effort.

Authors' Closure

The authors are indebted to Dr. Kronenberg for his interesting discussion of the origin of his equation and those of other earlier workers.

The resultant torque force need not act at the midpoint of the radius of a drill and in general it will not. It would follow from the torque expression given by Dr. Kronenberg that the resultant force would act at the midpoint of the radius if u were a material constant independent of drill diameter. However, in this equation u should really be written $\bar{u}$ as defined by Equation [34], where it is evident that in addition to drill diameter and feed, $\bar{u}$ is a function of the material hardness and the ratio (c/d).