5 The grinding forces and specific energy are independent of the hardness of the workpiece.

6 A grinding coefficient which in formulation resembles the coefficient of friction may be defined as the ratio of the horizontal force to vertical force. It appears that when a grinding wheel is cutting freely the grinding coefficient is greater than the corresponding coefficient of friction.

7 The dressing techniques employed showed that the diamond pyramid was superior to the conventional diamond as follows:

(*a*) Lower grinding-force components resulted
(*b*) More consistent values were obtained
(*c*) Grinding burn occurred less easily

8 The depth of the cold-worked layer in a ground surface is approximately half the depth of cut.

9 The extent of the residual tensile stress which results from grinding extends undiminished far below the cold-worked layer and hence the cause of the stress is not due to the cold-worked layer.

Acknowledgment

The authors are indebted to the Timken Roller Bearing Company for their generous support of this project. Valued discussion with Drs. E. Rowland and J. Wulff and the advice and assistance of Prof. J. T. Norton and Mr. J. Morales in connection with the x-ray measurements are gratefully acknowledged.

Discussion

B. T. Chao[4] and K. J. Trigger.[5] The grinding dynamometer described in the paper has an ingenious arrangement to eliminate the interaction between the horizontal and vertical components of grinding forces. It also has the advantage that the vertical component of the forces can be recorded correctly irrespective of the grinding position along and across the I-beam. The authors are to be congratulated for their accomplishments in designing this simple and useful instrument in the field of metal-cutting research.

The authors found that a variation from Rockwell C 18 to Rockwell C 65 in the hardness of the work material had only a negligible effect upon grinding forces. This result is not unexpected in the light of single-point cutting experience. The effect of the workpiece hardness upon tool forces at various cutting speeds for NE 9445 steel has been reported by the writers.[6] For this particular steel, it was found that the tool forces were actually slightly less when the hardness was higher. The increase in dynamic shear stress due to quenching and tempering to a high hardness level was more than compensated for by the decrease in tool-chip friction and the chip thickness. However, owing to the proportionately greater decrease in tool-chip contact area, the cutting temperature was higher. This, together with the abrasiveness of the microconstituents of the harder material, is the cause of the greatly reduced tool life.

In the synopsis, the authors state: "Specific energy is found to be the best criterion for interpreting grinding data." The writers would like to point out that this does not mean that the success of a grinding operation can be evaluated in terms of specific energy alone. Among other things, surface finish, temperature rise of the workpiece, dimensional accuracy, amount of wheel wear per unit volume of metal removed, and so forth, are at least equally important in grinding performance as the specific energy consumption.

In Fig. 4(*a*) of the paper the grinding-force trace shows a steady rise when a long specimen is ground. The authors attribute this phenomenon to the fact that a heat wave extending in front of the wheel causes an expansion of the specimen. However, the temperature gradient ahead of the grinding zone is extremely steep, and, with a downfeed of 0.001 in., it should make little difference whether the length of the specimen is $^1/_2$ in. or 3 in. in so far as its effect on volumetric expansion is concerned. The instrument reading due to a vertical load is independent of the point of application along the length of the I beam as shown in Figs. 2 and 3. However, the spring constant or rigidity of the dynamometer does change with the grinding position. This change can be estimated with reasonable accuracy if detailed dimensions and Young's modulus of the materials making up the various parts are known. The variation observed in the grinding-force trace may be due partly to this change in deflection as the point of load application is shifted. It should be recalled that such a change in spring constant of the system cannot be detected by dead-weight calibration.

L. P. Tarasov.[7] The fundamental study of the grinding process which has been undertaken in the Metal Cutting Research Laboratory at the Massachusetts Institute of Technology, and the first results of which are so ably described in this and other papers, will be of very great interest to those in the metal-cutting field who would like to have a better understanding of what happens when grinding chips are formed. Practically all of the information available about the process has been concerned either with the art of grinding or with its results, and very little could be said about the mechanism of grinding except speculatively.

Some of the reasons for this condition have been pointed out by the authors of this paper, such as the very high cutting speeds and very small chip dimensions associated with grinding, and the random geometry of the cutting points. Another reason that the study of the grinding process is bound to be complicated is that the geometry of the cutting points not only varies considerably from one grit to another but also varies continually and unpredictably for each individual grit as a result of wear, which is partly by fracture and partly by attrition. The relative importance of the two types of wear is a function of the grinding conditions. When the purpose of grinding is to remove stock and not to get the highest possible finish, wear by fracture is beneficial in that it restores the sharpness of the grit, while wear by attrition is detrimental since it makes the cutting element dull. When the grinding forces acting on a given grit become sufficiently high to fracture the bond posts holding it in place, the grit is thrown out of the wheel face and other grits are enabled to start cutting. Thus the definite geometrical factors like rake angles, which are so important in the theoretical studies of single-point cutting operations cannot be given numerical values in grinding, except perhaps eventually on a statistical basis.

The equality of force on the up and down cuts observed by the authors is not necessarily observed under other grinding conditions. For example, we have sometimes found considerable differences in power consumption for opposite directions of table travel in surface grinding when the table speed was much higher (60 fpm) than that used by the authors. Power consumption is proportional to the horizontal-force component and hence can be considered a measure of it in this instance, provided a slight correction involving the ratio of work to wheel speed is made. Even with this correction, we have found the power consumption to be as much as 20 per cent greater for the upcut than for the downcut. Under such circumstances, it is clear that the grinding action is not the same in the two directions.

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[6] "Cutting Temperatures and Metal-Cutting Phenomena," by B. T. Chao and K. J. Trigger, Trans. ASME, vol. 73, August, 1951, pp. 777–793.
[7] Research and Development Department, Norton Company, Worcester, Mass.

Although the authors were able to get the wheel satisfactorily dressed when the diamond was permitted to feed across the wheel in several final passes with no downfeed, this practice cannot be recommended generally since all too frequently it leaves the surface of the wheel in a dull condition. We have also found it desirable to dress the wheel prior to each change in grinding conditions, since the results obtained without re-dressing are sometimes influenced considerably by the previous history of the wheel. The grinding conditions used by the authors may have been such that their results were not affected by their dressing practice, but this will not necessarily be true for other grinding conditions. In order to attain satisfactory reproducibility, which was the reason the authors did not re-dress the wheel whenever grinding conditions were changed, we have always found it necessary to do a certain amount of grinding before the test run is started. This practice insures that the results of a given test run are not affected by the previous test runs.

The writer has successfully used a diamond in the shape of an obtuse 12-sided pyramid for several years but the use of a Vickers diamond pyramid for dressing the wheel is novel, and the excellent results obtained by this technique suggest a thorough study of the mechanism involved in dressing. The factors affecting the wear of dressing diamonds have been investigated by Whittaker,[8] but the writer does not know of any study of the effect of diamond geometry upon the mechanism of dressing. A study of the forces involved in diamond dressing under various conditions, and of the relationship between these forces and the resulting conditions of the wheel face, would be an important step in extending our limited understanding of the dressing process.

The authors' statement that the pronounced discoloration of the work surface was an indication that excessive heat was generated is certainly correct, but it may be appropriate to point out for the benefit of those with only a limited knowledge of grinding burn that the absence of discoloration does not imply that the surface was not heated excessively. Work can be very badly overheated in grinding without any trace of discoloration remaining on the finished surface if the grinding conditions are such that the wheel is able to clean off the discoloration almost as soon as it appears. If the leading edge of the wheel in cross-feed grinding takes a heavy cut so that the work is heated severely to a depth of several thousandths of an inch, the trailing portion subsequently may remove a layer a fraction of a thousandth deep, thus eliminating all evidence of the prior discoloration and, at the same time, leaving practically all of the heat-affected layer of metal.

The conclusions derived by the authors from their results apply to their particular surface grinding conditions, but they do not necessarily apply to conditions representative of commercial practice even though light cuts may be taken. The important difference is that much higher table speeds, perhaps 30 to 60 fpm, are common in production as compared to the 4 fpm used by the authors in most of their experiments. With table speed as the only variable, experience shows that grinding conditions are likely to be much more severe at very low than at high table speeds. From the standpoint of localized heat effects, the authors' grinding conditions were severe rather than relatively mild, as is pointed out by the writer in his discussion of a paper by J. O. Outwater and M. C. Shaw.[9]

We have found that under commercial surface-grinding conditions, the grinding energy of a large number of hardened tool steels, and hence their horizontal-force component, varies over a wide range; moreover, there is considerable variation of energy and horizontal force with Rockwell hardness for a particular steel. These differences have been found whether the depth of cut is light, moderate, or heavy, provided the table speed is high. The reason that we have observed such differences is presumably that the thickness of the grinding chips at high table speeds exceeds some critical value below which these differences are likely to be absent, as is discussed by Backer, Marshall, and Shaw.[10] It would be highly interesting to obtain force data under the authors' conditions for a variety of tool steels.

The proportionality observed by the authors between grinding forces and the work width was found for plunge-cut grinding where the wheel was in contact with the whole width of the work. In cross-feed grinding, the work is ground primarily with the leading edge of the wheel, which becomes rounded, as grinding progresses, to an extent depending upon the grinding conditions. We have observed that an increase in the unit cross-feed does not increase the horizontal force proportionately, as happens when the work width is increased.

The great value of this paper lies not in its agreement or lack of agreement with results obtained under conditions representative of commercial practice but rather in the detailed picture it presents of the effects of certain factors upon grinding forces under specially selected grinding conditions that make it possible to get simple answers. Now that the foundations have been laid, it should be easier to extend the studies to conditions more closely simulating normal practice, where the results and their interpretation may well be more complicated.

NOTE: The combined Authors' Closure to the discussions on the following papers appears on pages 83–86 of this issue of the Transactions: (*A*) "Forces in Dry Surface Grinding"; (*B*) "The Size Effect in Metal Cutting"; (*C*) "Surface Temperatures in Grinding." In the closure the papers will be referred to as (*A*), (*B*), (*C*).

[8] "Substitution of Lower-Quality Industrial Diamonds in Diamond Dresser Tools," by H. Whittaker, Trans. ASME, vol. 68, 1946, pp. 35–45.

[9] "Surface Temperatures in Grinding," by J. O. Outwater and M. C. Shaw, published in this issue of the Transactions; discussion, pp. 83.

[10] "The Size Effect in Metal Cutting," by W. R. Backer, E. R. Marshall, and M. C. Shaw, published in this issue of the Transactions, pp. 61–72.