

peak temperature would be reduced to 45 per cent of what it would be for steady-state cutting. This is at least of the same magnitude as that determined experimentally and shown in Fig. 7.

*Effect of Vibrations on Abrasive Wheels.* Data on grinding ratio plus the observed improvements in surface finish point to altered condition of the grinding wheel as another result of the ultrasonic vibration. Probably any such effects can be ascribed directly to the magnitude of acceleration which for the conditions of most of these tests was approximately 5000 times the acceleration of gravity or 5000  $g$ . It is quite impossible to predict these results quantitatively without knowledge of the properties of both the work material and grinding wheel at such high accelerations. It is not entirely unexpected that the grinding wheel would break down more rapidly or even that individual abrasive grains themselves might be fractured rather than torn from the wheel. Studies of grinding ratio have confirmed varying degrees of more rapid wheel breakdown, particularly just after redressing.

In ordinary grinding practice, the surface roughness frequently is greater immediately after dressing than sometime later when the wheel has reached equilibrium. In this case, however, the greater wheel breakdown accompanying vibration also is accompanied by improved surface finish. This would appear to be due to two things:

- 1 Fewer and smaller built-up edges.
- 2 Continuous, uniform redressing resulting from fragmentation of individual abrasive grains.

Both of these are logical results of the high accelerations achieved at ultrasonic frequencies.

#### CONCLUSION

There is little doubt that high-frequency vibrations can produce desirable results in grinding. However, much more work needs to be done to clarify the mechanism of its effectiveness. Considerably more than that needs to be done to learn how to apply it to industrial grinding. It is fascinating to consider that, even now, we may be deriving the benefits of ultrasonic vibrations in industrial grinding without knowing it.

#### ACKNOWLEDGMENT

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#### Discussion

W. R. BACKER<sup>3</sup> AND HANS ERNST.<sup>4</sup> This paper presents some interesting data on the utility of controlled vibration in the metal-cutting process. Several of the reported effects of vibration on the grinding operation, such as the improved finish and reduced workpiece damage due to heating, lend positive support to commercial application of this principle. Others, including more rapid wheel wear and the technical difficulties of inducing the vibrations, in controlled direction and at useful energy levels, may detract from the value of its commercial use.

The test results presented are of a survey nature, and it is hoped that further work is in progress. The tests on surface finish show little advantage on 1020 steel compared to the harder materials. The question arises as to whether the process is significantly advantageous on softer workpieces. There is also a question on the vibrational amplitude obtained in the tests. If

the amplitude measurements were made prior to grinding, the amplitude obtained during the actual cut may have been considerably reduced, because the transducer then had to oppose the over-all rigidity of the wheel-work-machine system. Further data on vibrational amplitude and frequency effects are also desirable.

The effect of vibration on grinding ratio is very interesting, and the author's explanation of the higher wheel wear is plausible. The improved finish and lower temperatures may likewise be associated with this "redressing" of the wheel by the vibratory force. An interesting test would be the comparison of the results obtained with vibration, to those when grinding with a "softer" wheel giving comparable grinding ratio. It is well known that a softer grinding wheel (one with more friable grits or weaker bonds) usually provides a freer cutting action, with less heating and consequent damage of a hard workpiece, because of the more rapid breakdown of the wheel by shattering or breaking out of the grits as they become dull.

Corroborative evidence that rapid radial motion between wheel and work (radial vibration) may cause more rapid wheel breakdown was given by an experience in the writer's laboratories during the development of grinding-machine spindle bearings. With an improved type of bearing which provided a more constant axis of rotation (and therefore a more constant position of wheel relative to work) it was found necessary to use grinding wheels one to two grades softer than previously used with conventional bearings, in order to provide comparable grinding conditions.

In applying high-frequency vibration to practical grinding operations, numerous problems will arise. In addition to the problem of higher wheel wear (and consequent higher wheel costs) already mentioned, there is the problem of providing a transducer of sufficient power to excite a full-sized workpiece; the power requirement would be reduced, however, if further tests show that vibration in the direction of the wheel axis is equally effective. The vibration frequency must be considerably higher than the resonant frequency of any significant elastic system in the machine, to prevent marring the workpiece. Preferably, it should be above the sonic range (say, about 20,000 cycles per sec) in order to avoid objectionable noise.

On the positive side, corroborative evidence that high-frequency vibration may advantageously affect a metal-cutting process is given by our experience some years ago with vibration applied to other forms of metal-cutting tools. In a series of experiments in 1934, in which a longitudinal vibration with a frequency of 1500 cps and amplitude of about 0.005 in. was applied to a

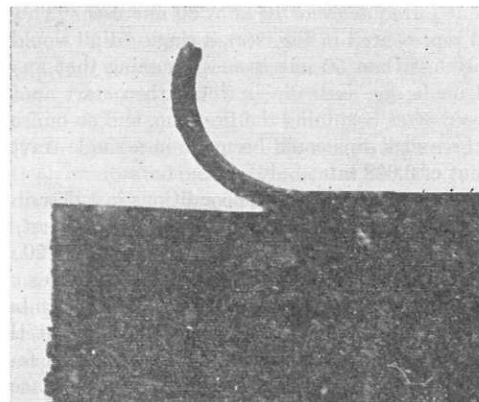


FIG. 10 CHIP FORMED BY MANUAL PRESSURE OF WORKPIECE AGAINST VIBRATING CUTTING TOOL  
(Material: Hard bronze; width of cut,  $\frac{1}{8}$  in.; depth of cut, 0.040 in.; cutting ratio, 1.0.)

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planer-type tool, it was found that a heavy chip could be formed by merely pressing a workpiece against the tool by hand, an obvious impossibility without the vibration. From the accompanying illustration, Fig. 10, it will be seen that the cutting ratio (as shown by the chip-length ratio and the chip-thickness ratio) was approximately equal to unity, thus indicating that the effective friction between chip and tool face was extremely low. Later studies with vibrations at ultrasonic frequency have similarly shown an appreciable increase in cutting ratio.

We hope that the author will continue his work in this interesting and potentially useful field.

R. S. HAHN.<sup>5</sup> The author has certainly discovered some very interesting and important effects. The work of the author may have industrial application on one hand, and on the other may help in understanding the basic details of every-day grinding operations.

The results obtained by the author may be further explained by focusing attention on the important part the clearance surface (i.e., the surface on the grits generated by the dresser diamond) of the grit plays in the grinding process. It is possible to explain the soft or hard action for the vibrated and nonvibrated conditions, and the attendant change in grinding ratio, burn, and finish on happenings at the clearance surface.

The author shows in Fig. 9(b) the velocity of a grit relative to the work. Although the actual normal velocity may be relatively small, on the "going into the work" stroke very appreciable effective negative clearance angles occur (in this case  $\tan^{-1} 1/20$ ). On the "going out of the work" stroke the effective clearance angles are naturally positive; i.e., during one half of the cycle there is interference on the heel of the grits and during the other half there is clearance.

The action observed can be explained by supposing that during the in-stroke when interference occurs on the "heel" of the grit, the heel spalls or flakes off either as a result of stress or of highly localized temperature, or both. It is known that wheel wear during certain precision-grinding operations often amounts to something around 0.001 in. Thus whole grits cannot be tearing loose. The writer has also observed<sup>6</sup> that wheels dressed at a small diamond lead actually become "sharper" as they are used after dressing. This again suggests a breaking down of the heel of the grits, thus relieving the interference.

As a result of the foregoing it is natural to expect the grinding ratio to be lower (i.e., more wheel wear and a softer action). Furthermore, since the dimension of the rubbing area of the grit in the direction of motion will be reduced by spalling off of the heel, the temperature developed will be less according to the moving source theory.<sup>7</sup>

The tests described by the author were performed on a surface grinder where it is conventional to prescribe a certain down feed (wheel depth of cut) and then to take passes of the table simultaneously with increments of cross-feed. Under these conditions heavy forces are induced near the leading edge of the wheel with lesser ones near the trailing edge. If the wheel is free-cutting by virtue of a comparatively small amount of interference on the heel of the grits, the nonlinear distribution of induced force across the wheel width will differ from the distribution for a hard acting wheel or under nonvibrating conditions. The surface roughness is likely to depend on these force distributions. In the case of a free cutting action (soft) it seems reasonable to expect a lower

surface roughness since the finishing grits at the trailing side of the wheel will be under less force. It would be interesting to compare the roughness for cases where the wheel cuts its full width in one pass of the table.

R. O. LANE.<sup>8</sup> The writer would caution future investigators to consider carefully the following: 1 The different types of abrasives available from all leading companies.

2 The structure or structures of grinding wheels used in the test.

3 Variations in types of bonding of the abrasive particles.

4 Degree of uniformity of any or all wheels used in all investigation.

It is possible to have erroneous results from improper wheel selection on a given metal being investigated in lieu of the so-called correct or proper wheel selected.

The author is to be complimented on the presentation of a very fine paper.

L. P. TARASOV.<sup>9</sup> This excellent pioneering study shows clearly that high-frequency vibrations can reduce the heat generated in grinding. This has been found to be accompanied by a reduction in the grinding ratio, which is the same as an increase in wheel wear. It has long been known that a change to a softer wheel (containing less bond) will generally also reduce both the heat and the grinding ratio, and the question naturally arises as to how much of the effect of vibration on the generation of heat was due to the drop in grinding ratio.

The observed effects of vibration are very pronounced with respect to heat generation, much more so than might be expected from the simultaneous changes in grinding ratio. Hence it is probably correct to assume that vibration can affect heat generation independently of grinding ratio, but it would be desirable to verify this experimentally. This could be done by repeating the experiment without vibration and using a sufficiently softer wheel so that the grinding ratio would be the same as for the harder wheel used with vibration. A comparison of heat effects would then show the direct effect of vibration.

The entirely different appearance of the cracks in the two specimens in Fig. 8 of the paper shows that there was some difference in the effect of grinding, with and without vibration, but it is doubtful that this can be ascribed to vibration on the basis of the evidence presented. Practically nothing is known about the detailed mechanism of formation of such cracks, but both crack patterns shown are typical of those often seen in nonvibrated badly cracked specimens. Only a few cracks are present in the upper or vibrated specimen but they are much wider than those in the other one. The crack width is some measure of the stress that was relieved elsewhere in the surface when the crack was formed. Just as much stress may have been relieved by the formation of the very few wide cracks in the upper piece as by the numerous narrow cracks in the lower one, and no light is thrown on the relative magnitude of the stresses prior to cracking. Hence no conclusions can rightfully be drawn from a comparison of these two crack patterns other than that the stresses were in some way different. The crack width, for example, might be determined by the nature of the stress gradient perpendicular to the surface, but this is only a speculation. A far more detailed understanding of the relationships between surface cracks and stresses will be necessary before the former can be used even as rough measuring sticks for the latter.

It might also be mentioned that the observed necking or plastic flow is not surprising in view of the marked softening of the steel

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<sup>6</sup> "The Effect of Wheel-Work Conformity in Precision Grinding," by R. S. Hahn, Trans. ASME, vol. 77, 1955, pp. 1325-1329, Fig. 5.

<sup>7</sup> "The Relation Between Grinding Conditions and Thermal Damage in the Workpiece," by R. S. Hahn, published in this issue, pp. 807-812.

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to a depth of several thousandths of an inch, as judged from the severity of the burn pattern. The deformation occurred in steel that may easily have been softened to Rockwell C50.

The writer would like to suggest that a simple way of determining relative heat effects such as are of interest here is to measure the depth of grinding burn; i.e., the depth to which overtempering caused by grinding heat can be detected in hardened steel after suitable sectioning and etching. It is just as quantitative as the thermocouple method, which measures the average temperature in a layer located a considerable distance below the ground surface.

#### AUTHOR'S CLOSURE

Thanks are due to all those who have contributed discussions of this paper. Their contributions represent serious thought, and the many suggestions are definitely useful in interpreting observations whose causes are not yet clearly defined. The closure will take up the several questions in the order that they were raised by the discussers.

First the comments by Mr. Backer and Mr. Ernst. It should be emphasized that this paper was not in any sense intended to promote commercial application of high-frequency vibrations in industrial grinding, although some applications would seem to be feasible. Instead, it was believed that the observations made in this study help to explain many of the phenomena well known to precision-grinder operators under the general heading of "grinding by ear." The author agrees with the discussers that attempts at commercial application where such vibrations do not occur naturally to significant extent will be met with complex problems of both a technical and economic nature. Such problems might very well prevent practical use in some areas.

It was pointed out by Mr. Backer that there might have been a substantial attenuation of amplitude of vibration during actual cutting. The amplitude of the work was not monitored during these tests, but it is doubtful that there was any significant attenuation since it will be recalled that the accelerations were of the magnitude of 5000 "g's," or in other words, 5000 times the acceleration of gravity. Consequently, the forces developed by the transducer are also very large, about 500 lb in this case, so it would not be expected that grinding forces, which are also relatively low, would have any appreciable effect. Rather, it is to be expected that power limitations would assert themselves before any difficulties from limited force capacity would arise. Even so, there could be rather little power demand from the transducer in the grinding area except where there was a large coefficient of friction to convert this energy into heat. The earlier investigation reported by the discussers as illustrated in Fig. 10 would appear to confirm the assumption that the amplitude would not be attenuated appreciably by the act of grinding.

Attention also was called to the fact that softer wheels break down more rapidly, resulting in a sharper average condition for the abrasive, and that this can be expected to reduce cutting temperatures. That observation is also most certainly true and it is difficult to say as to how much the temperature reduction observed in this test was due to sharper abrasive and how much was due to shorter exposure to the peak temperature created where vibration was superimposed.

Mr. Backer referred to the difficulties that may be encountered in attempted commercial application of high-frequency vibrations to grinding. Certainly the number and complexity of problems will increase with the complexity of the grinding operation. It can be expected that considerable development effort will be required before extensive use can be made, if at all. Despite the magnitude of the development problems, it is believed that commercial application to such operations as the grinding of carbide tools can be made almost immediately with little development effort. Other and more complex operations may come in due time.

Dr. Hahn has called attention to what might prove to be a very important aspect of this problem. He points out that the relative motion between the work and the wheel caused by the vibration creates interference on the approach between the work and the heel or flank of the abrasive grain since diamond dressing is known to produce substantial areas of zero relief. It is quite possible that this interference, coupled with the high accelerations, does remove such interfering material, thus accomplishing two desirable effects; one, a resharping of the abrasive grain, and the other, a reduction in the amount of rubbing and associated heating.

Mr. Lane reminds us that this investigation covered a very limited range of bonded abrasive properties and grinding conditions. This fact leaves doubt as to the extent to which high-frequency vibrations would bring about desirable results over the broad ranges of these variables. It can be expected that such investigations as are desired for commercial purposes will eventually be made, and one would expect further clarification of the mechanism from tests conducted at substantially different conditions.

The author was pleased to learn that Dr. Tarasov has arrived at substantially the same conclusion—that vibration does have an independent effect in reducing the temperature, but, as he pointed out, this conclusion can be further confirmed by tests with softer wheels which will give about the same grinding ratio as a harder wheel with superimposed vibration.

It is regrettable that the photographs of the cracked specimens as shown in Fig. 8 are poor. Dr. Tarasov got the impression that the cracks in the vibrated specimen were much wider than in the nonvibrated specimen. As a matter of fact, the exact opposite is true, and what appears to be a wide crack in the upper half of Fig. 8 is in reality a shadow created by angular lighting and noticeable localized necking or plastic flow in the vicinity of the crack. It is the belief of the author that it was a coincidence that the residual stress level in the vibrated specimen was almost identically that of the yield or fracture stress of this material. A somewhat higher stress level presumably would not have resulted in sufficient time for a substantial amount of plastic yielding to take place. The author believes that this interpretation is confirmed by the fact that the cracks in the nonvibrated specimen occurred almost instantly during grinding, whereas none of the cracks in the vibrated specimen showed up until quite some time later; there was one small short crack within an hour and the rest of the cracks developed within the next 24 hours. The author wishes to thank Dr. Tarasov for his helpful suggestions as to additional techniques which can be used to refine the information that can be obtained from an investigation of this type.