ENGINEERING RESEARCH INSTITUTE
UNIVERSITY OF MICHIGAN
ANN ARBOR

A PRELIMINARY INVESTIGATION OF THE EFFECTS OF VIBRATIONS IN GRINDING

L. V. COLWELL

J. R. FREDERICK

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The initial objective of this project was to investigate the influence of vibrations on the grinding process. As a method of approach it was decided to induce vibrations artificially between the work piece and grinding wheel by means of an ultrasonic transducer. The original program was set up and outlined with the expectation that performance characteristics affected by vibration would be generally unfavorable. However, the initial results were so spectacularly favorable that the original outline of tests was abandoned in favor of a broad exploration of the scope of these effects. Grinding conditions and, in particular, materials being ground were varied over broad ranges for the purpose of determining whether the favorable effects of vibration would persist.

The favorable effects of the induced vibrations did persist, so the entire period of this preliminary investigation was devoted to substantially qualitative tests. Quantitative data were obtained only where necessary to confirm the existence of a desirable result. In brief, the laboratory data obtained to date indicate that properly controlled vibrations in grinding can achieve the following desirable results:

1. Reduce surface roughness of the ground surface by as much as 50%.
2. Reduce the temperature of the work surface.
3. Reduce the incidence of burning of the work surface.
4. Reduce residual tensile stresses in the ground surface.
5. Eliminate thermal cracks resulting from grinding carbide tools.
6. Reduce "loading" of abrasive wheels.

7. Reduce "glazing" of abrasive wheels.

8. Successful crush-dressing of resin bonded abrasive wheels (only partially confirmed).

It appears that the only sacrifice necessary to achieving the results listed above is a loss in the grinding ratio, that is, the ratio of the volume of metal cut to the volume of abrasive worn from the abrasive wheel. This aspect of performance has not been completely investigated but it would appear that the sacrifice in volume ratio is not very substantial particularly when it is offset by the more frequent dressings required where the favorable vibrations are not present.

Although the spectacular results of this investigation were obtained through the use of artificially induced vibrations, they nevertheless indicate that naturally occurring vibrations have far greater affect upon performance in industrial grinding practice than was realized earlier.

THE LABORATORY SETUP

Grinding Machine

A Thompson 8 x 24 reciprocating surface grinder was selected for the tests because it was known to be one of the more rigid types. The table is driven by an hydraulic cylinder with the speed being controlled by metering. The actual table speed was indicated by an electronic counter.

During the early stages of the investigation a study was made of the natural vibrations and deflections of the grinder. It was determined that the maximum deflection between the grinding wheel and the work table at very heavy loads did not exceed 0.0003 inch. The deflection caused by unbalance of the grinding wheel and the spindle motor was of the magnitude of 0.0001 inch.

Vibrating Equipment

Figure 1 shows the schematic arrangement of the laboratory setup for studying the effects of artificially induced vibrations in grinding. The work specimen is mounted on a device known as a transducer, which, in turn, is mounted on a vibrating beam or plate supported at its nodal points. The transducer consists of an armature built up with 0.005 inch pure nickel laminations. The armature is wound with an electrical coil which is driven by relatively simple electrical apparatus that is available commerically. Consequently, this apparatus will not be described in this report.

The alternating current in the electrical coil causes the nickel laminations to lengthen and contract alternately in the direction parallel to the magnetic field. This causes relative motion between the top and the bottom of the transducer. The flat steel plate is supported on points or knife edges in such a manner that the plate and the transducer will vibrate freely at the same frequency as the exciting current. Thus the steel plate or vibrating beam tends to reinforce or amplify the vibration of the work piece. By this means it was possible to obtain amplitudes of vibration up to about 0.0007 inch at frequencies in the range of 10,000 to 18,000 cps.

Figure 2 is a picture showing a closeup of the transducer in position on the table of the grinder relative to the grinding wheel. A copper tube or cooling coil is shown in place around the transducer. This was used to spray coolant on the transducer to dissipate the excess heat from the magnetic field. The picture shows a thermocouple imbedded in a special specimen that was used to study the effects of vibration on temperature of the work surface. Results of these tests are detailed later in the report.

Figure 3 is a picture of the surface grinder with all the test apparatus and instruments used at various times during the investigation. The electrical apparatus required to operate the transducer is shown to the left of the grinder, while the various instruments used to observe or record the results are shown to the right of the grinder. These include a recording wattmeter, a chopper-amplifier for thermocouple indications and an oscilloscope for monitoring and occasionally recording various electrical phenomena.

VIBRATION CHARACTERISTICS

Simple vibrations of the type used for this study are sinusoidal and can be described completely in terms of amplitude and frequency. From these quantities it is possible to determine displacement, velocity, and acceleration for any instant.

The frequency is expressed in two ways:

(a) Frequency = f = cycles per second

(b) Circular frequency = ω = radians per second
and $\omega = 2\pi f$.

The amplitude is the maximum displacement from the free position and one half the total range of the vibration. The displacement, velocity, and acceleration are expressed by equations as follows:

$$\text{Displacement} = a \sin \omega t,$$

$$\text{Velocity} = \omega a \cos \omega t,$$

$$\text{Acceleration} = -\omega^2 a \sin \omega t,$$

where "a" = amplitude in inches or other units of length and

"t" = elapsed time in seconds.

Usually only the maximum values are of interest so that:

$$\text{Max. Displacement} = a \text{ (Inches)}$$

$$\text{Max. Velocity} = \omega a \text{ (Inches/Second)}$$

$$\text{Max. Acceleration} = \omega^2 a \text{ (Inches/Second/Second)}$$

During this investigation, the frequency was varied from about 10,000 cycles per second up to 18,000 cps. The amplitude was varied from a maximum of about 0.0005 inch down to about 0.0001 inch.

For the purpose of comparing the vibration characteristics with the geometry of the grinding cut, the induced vibration is assumed to have a range of 0.001 inch and a constant frequency of 10,000 cps. At these conditions the significant characteristics are as follows:

$$\text{Max. Displacement} = 0.0005 \text{ inch}$$

$$\text{Max. Velocity} = 2\pi \times 10{,}000 \times .0005 = 31.4 \text{ ips.}$$

$$\text{Max. Acceleration} = 62{,}800^2 \times 0.0005 = 1{,}971{,}900 \text{ in./sec}^2$$

$$= 5000 \text{ g apx.}$$

$$\text{Period} = 100 \text{ microseconds}$$

Acceleration is often compared to the acceleration of gravity as in the case of an airplane pulling out of a dive. If the load on the wings is five times the normal weight of the plane, the acceleration is said to be 5 g's. In this case, the acceleration is 5000 g's. The period is the time required for the vibration to go through one complete cycle and return to the original position. This is only 100 millionths of a second yet it will be shown that in relation to grinding, significant motions take place in substantially less time.

The geometry of the grinding cut is quite important to the effectiveness of induced vibrations. The theoretical chip that might be removed by a single abrasive grain is shown in longitudinal section in Fig. 4a. The length of the chip is designated by "l"; the average thickness midway of the length is designated by "t" and the forward movement of the work by "x".

The length of chip "l" or arc of contact, as it is sometimes called, is dependent only on the wheel diameter and the depth of cut, as follows:

$$l = \sqrt{D\ d} \text{ inches,}$$

where D = wheel diameter in inches and

d = depth of cut in inches.

Table I shows the theoretical length of contact for the 12-inch diameter wheels used in this study for depths of cut ranging from 0.0002 to 0.008 inch. The third column in the table shows the corresponding time of contact of an individual abrasive grain with the work for the wheel speed of 6000 fpm; it varies from 41 to 258 millionths of a second.

TABLE I

"Theoretical Length of Contact" - l

(Between Abrasive Wheel and Work)

(d) Depth of Cut - Inches	(l) Length of Contact - Inches	Time of Contact - Microseconds
0.0002	0.049	41
0.0005	0.077	64
0.0010	0.109	91
0.0020	0.154	128
0.0040	0.219	182
0.0080	0.310	258

Length of Contact $l = \sqrt{D\ d}$

Wheel Diameter D = 12 inches

THE TEST PROCEDURE

The grinding procedure was uniform throughout the entire investigation except in a few special cases. The following steps were carried out in the performance of each grinding test:

1. Dress abrasive wheel with a diamond.

2. Precut the test specimen by making 5 successive passes at a depth of 0.001 inch, cross feed of 0.050 inch. (The work specimen was vibrated during the precut only when it was to be vibrated during the subsequent test.)

3. Conduct test by grinding 5 successive layers at the test condition.

Exceptions to the above procedure are noted when they occur; the principal deviations were associated with the temperature and residual-stress studies. So called "out grinding" was used for all tests. In other words, the wheel was cross-fed only at one end of the table stroke, so that the wheel and work motions were opposite during the cutting stroke of the table.

The theoretical chip thickness "t" as designated in Fig. 4a is determined by the formula:

$$t = \frac{4v}{VCr} \quad \frac{d}{D} \quad \text{inches,}$$

where:

D = wheel diameter in inches,
d = depth of cut in inches,
v = work speed in feet per minute,
V = wheel speed in fpm,
C = number of abrasive grains per square inch of wheel surface, and
r = ratio of the width to the depth of the grinding scratch.

The above formula is derived from the previous formula for chip length, and the assumption that the metal removed is distributed uniformly over the total number of abrasive grains contacting the surface. Calculated values of chip thickness for a 0.0005-inch depth of cut and a range of work speeds are shown in the last column of Table II.

TABLE II

Depth of Cut = 0.0005 inch

Theoretical Thickness of Chip - "t"

		Chip Thickness - Microinches	
Work Speed - fpm	Parallel to Work Speed[1]	Minimum[2]	Probable[3]
20	62	.9	55
40	124	1.7	82
60	186	2.5	96
80	248	3.4	110

1 = $v/V\sqrt{C}$
2 = $2\,v\sqrt{d}/V\sqrt{DC}$
3 = $2\sqrt{v\sqrt{d}}/\sqrt{VCr\sqrt{D}}$

where V = wheel speed in inches/sec = 1200,
v = work speed in inches/sec,
d = depth of cut in inches = .0005,
D = wheel diameter in inches = 12,
C = grain/square inch = 3000, and
r = ratio of mean width to depth of scratch = 10.

The second column gives the thickness parallel to the work motion as designated by "x" in Fig. 4a. The third column is the absolute minimum assuming a rectangular distribution of abrasive grains; these latter values have only academic interest. The values in Table II are based on the following operating conditions:

Wheel speed = 6000 fpm
Depth of Cut = 0.0005 inch
Grains/square inch = 3000 (estimated for 60 grit wheel)
Ratio of width to depth of grinding scratch = 10 (estimated)

Fig. 4b shows the velocity of an abrasive grain relative to the work piece during vibration; the nonvibrated or conventional motion is shown as a straight line for reference. This curve is drawn to scale to show that there are no drastic changes in direction. The maximum vibratory velocity is only one-fortieth that of the grinding wheel. A similar curve for displacement drawn to true scale would be even flatter, since the vibratory motion travels only 0.001 in. while an abrasive grain travels 120 times as far. These conditions apply to a wheel speed of 6000 fpm and a 10 kc vibration with an amplitude of 0.0005 inch. Thus it would appear that the effectiveness of the vibration is not due to change in direction of motion.

There appears to be a clue to the effectiveness of vibration in a comparison of the amplitude of the vibration with the theoretical chip thickness. Such a comparison is made graphically in Fig. 4c where the motion of an abrasive grain relative to the work is exaggerated vertically. The range of vibration is shown as 0.001 inch and the chip thickness as 0.0001 inch. This is the chip thickness that would be obtained at a 0.0005-inch-deep cut with a work speed of 80 fpm during conventional grinding. The contact time during conventional grinding would be 64 microseconds but only 20.5 microseconds during vibration. At 0.008 inch depth of cut, the contact time for conventional grinding is 258 microseconds and only 29.6 microseconds for vibrational contact at the same work speed despite the fact that the chip thickness is doubled.

Thus, in the first instance the vibrational contact time is about 1/3 conventional, while at the deeper cut the ratio is reduced to about 1/9 although there are repeated contacts during the same pass over the work. It might be concluded that the vibration is relatively more effective at deeper cuts. Using the same reasoning, it may also be concluded that vibration will be more effective at the lower work speeds, at least to the extent that the beneficial effects arise from shorter contact time. Other causes also appear to be effective, as will be pointed out under the "Test Results."

THE TEST RESULTS

In view of the broad scope of the investigation and the diverse nature of the tests, it is better to present the results in chronological order of their appearance. This approach is desirable because the outline of each successive series of tests was based on results of the previous series.

Series 1 (Preliminary)

In the first series of tests two different vitrified grinding wheels and two different work materials were studied over a range of depth of cut. The grinding wheels were Carborundum DA60F9V20 and DA60J9V20. The first work material was hardened AISI 52100 steel, a typical bearing steel, and the second material was ordinary cold-rolled steel designated in this report as 1020 steel. Each of the two grinding wheels was used on each of the two work materials at depths of cut of 0.0002, 0.0005, and 0.002 inch. The surfaces were ground at each of the test combinations, both vibrated and nonvibrated. The nonvibrated condition is referred to in the report as convetnional grinding.

All tests were run dry with a table speed of 40 fpm. During grinding, samples were collected of the swarf, or grinding dust, from each of the test combinations. The swarf was collected in small beakers mounted about eight inches from the grinding zone. A stainless-steel funnel directed the airborne stream at the beaker. After grinding, the test specimen was removed from the transducer and examined under a binocular microscope. Notations were made as to the presence and relative intensity of surface oxides as evidence of so-called "burning." Following this analysis the surface roughness was measured with a Profilometer. Roughness measurements were made both parallel to and across the grinder marks. The surface roughness data, along with remarks concerning burning and unusual wheel breakdown, are given in Table IV, V, and VI for depths of cut of 0.002, 0.0005, and 0.0002 inch, respectively. The Profilometer indication covered a range in each case. This range is shown in parentheses in the table. The single figure outside the parentheses is a weighted average determined visually.

Only the roughness readings made across the grinder marks are considered in analyzing the results, since they were both greater and more sensitive to change than roughness readings made parallel to the grinder marks. The weighted averages of the surface roughness readings across the grinder marks are summarized for the first series of tests in Table III.

It will be noted that in every instance there was either no change or an improvement in surface finish as the result of induced vibration. The greatest improvement was a reduction from 40 microinches to 16 microinches for grinding the 52100 steel with the F-grade wheel. At the other extreme there was no improvement in grinding the 1020 steel with the J-grade wheel.

It will be noted that there is little correlation between surface roughness and depth of cut since the roughest surface occurred at the intermediate depth of 0.0005 inch. It was learned later that this can be due to incidental variations in the properties of the grinding wheel after successive dressings. More will be said about this property in the section dealing with temperature.

Numerous microscopic studies were made of the grinding swarf for the purpose of trying to determine why the vibration produced favorable results. It was noted that in general the grinding swarf appeared to be cooler when the work specimen was vibrated. This was manifest in several ways. First, it was noted visually that the spark stream was generally shorter and of darker color. Secondly, the swarf from vibration contained more orthodox chips; they are considered to be orthodox in that they look like milling chips. Third, the swarf from conventional grinding contained a large percentage of small spheres which could be formed only by molten metal. This was particularly evident when grinding the 52100 steel. An enlarged photograph of the swarf from the 52100 steel ground conventionally at a depth of 0.002 inch is shown in Fig. 5a. Figure 5b is a similar photograph for the "vibrated" swarf. It also contains many spheroids, but they are considerably smaller, as are the orthodox chips.

It is believed that the larger spheres and the larger chips peculiar to the conventional grinding are due to "loading"; that is, the amount of metal represented by a large sphere or chip is more than would ordinarily be removed by an abrasive grain in a single pass across the work. Thus, on the basis of an examination of the grinding swarf it was concluded that vibration not only reduces temperature in the grinding zone but also reduces the incidence of loading. It is this latter effect which is believed to be responsible for the improvement in surface finish.

The grinding swarf contained not only metal but also abrasive and bond. In the first series of tests these were separated by magnetic means for only part of the tests. The results are summarized in Table VII. In every case the rate of wheel breakdown was greater for the vibration. This is expressed in the form of the grinding ratio as shown in the last column. The grinding ratio is the ratio of metal removed to abrasive worn away from the wheel. Usually, this is the ratio of volumes, although in Table VII the ratio is formed by weights. The volume ratio would be somewhat lower due to the lower specific gravity of the abrasive. The grinding ratios in Table VII are unusually low when compared to commercial experience. This is due to the fact that the swarf sample was obtained shortly after redressing the grinding wheel, during which period the wheel wears much more rapidly. Therefore, the only conclusion to be drawn from this analysis is that vibration causes more rapid wheel breakdown, which, of course, results in a greater average sharpness of the exposed abrasive grains.

Series 2

In the second series of tests an attempt was made to develop correlations between performance characteristics, particularly surface roughness and such common grinding variables as depth of cut, table speed, cross feed, and work material. The same type of observations were made as in Series 1. Table VIII summarizes the surface roughness readings obtained from the variable-depth tests. Eight tests were made in this group. The work specimen was ground conventionally and with vibration at each of four depths of cut ranging from 0.0005 to 0.008 inch. It is interesting to note that the surface roughness of the vibrated specimens did not change appreciably over the entire range of cuts, while that of the nonvibrated specimens improved appreciably as the depth of cut increased. Table VIII also indicates that there was some burning of the nonvibrated specimens at all depths of cut equal to or greater than 0.002 inch.

Figure 6 shows the specimens ground at 0.002 inch depth of cut. In the conventionally ground specimen shown at the top are seen dark blotches, which are areas of concentrated oxides. It is believed that these oxides are concentrated in this manner as the result of either or both of two possible causes: (1) local hard or worn spots on the surface of the wheel, (2) loaded regions of the wheel. In either case the oxides are caused during the rubbing and not during the original grinding. In other words, some portion of the wheel other than the leading edge is responsible for this evidence of burning. In any event, it does not occur when the work is vibrated and it did not occur in any of the tests subsequent to this series.

The last column in Table VIII contains the grinding ratios based on volume, as determined from all the swarf available from each test. It will be noted that the grinding ratio tends to decrease with increased depth of cut and that in general it is somewhat less favorable for the vibrated conditions.

Table IX contains data similar to those of Table VIII for the group of tests during which the table speed was varied from 5 fpm up to 80 fpm. Again the surface roughness did not change appreciably for the vibrated specimens over the entire range of table speed. Of greater significance is the fact that none of the vibrated specimens showed evidence of burning or overheating. On the other hand, the conventionally ground specimens were burned most at the lowest table speed and least at the highest speed, thus indicating that thermal damage to the work surface is a sensitive function of time at temperature. It was pointed out in the section on "Vibration Characteristics" that vibration materially reduces the time at temperature at all depths of cut. It follows logically that vibration would have the same effect over a range of work speeds. The validity of this theory appears to be confirmed by the severe burning with conventional grinding at low work speeds.

The grinding ratio is decreased in both conventional and vibrated grinding as the table speed increases. This is evident in the last column of Table IX. It will be noted also that conventional grinding shows a more favorable grinding ratio than vibration at the three higher table speeds, while the opposite is true for the lowest table speed. Further, the relative position for vibration, as compared to conventional grinding, with respect to grinding ratio deteriorates continuously with increased table speed.

The third group of tests in Series 2 was devoted to variable cross feed. These results are summarized in Table X. It will be seen that the improvement in surface finish for vibration, as compared to conventional grinding, becomes less and less as the cross feed is increased from 0.025 to 0.200 inch. On the other hand, the evidence of less burning or thermal damage with vibration persists even at the high cross feeds. The substantially lower grinding ratios shown for the two higher cross feeds are not typical, since the wheel contour had not had time to reach equilibrium.

The fourth group of tests in this series involved a range of work materials including many that are not ordinarily ground. The principal purpose other than for indicating the scope of effectiveness of vibration was to determine whether the vibration could appreciably reduce the loading which occurs so readily with such materials as 2S aluminum and red brass. The results obtained from this group of tests are summarized in Table XI. It will be noted that some of the surface roughness measurements are missing. This is due to the badly torn or smeared surfaces of the aluminum specimens. There is no evidence of improvement in surface finish in the Profilometer readings; on the other hand, there were visual indications of improvement. Microscopic examination of the ground surface and of the grinding swarf definitely confirmed that vibration does reduce wheel loading. This is manifest particularly in fewer large chunks or built-up edges in the grinding swarf. It is also noticeable visually in the wheel surface.

It was observed in Series 1 that the beakers used to collect the grinding swarf could not be re-used because some of the swarf was fused to the sides and bottom of the beaker. It was further observed that the amount of material fused to the beaker appeared to be greater for conventional grinding. As a consequence considerable care was taken in positioning the beakers during Series 2 so that substantial differences in temperature could be indicated reliably in the amount of material fused to the beaker.

Figure 7 shows the two beakers used for collecting swarf from Ti 150A titanium. The beaker on the left was for vibration, the one on the right for conventional. The dark specks on the bottom of the right-hand beaker were originally spheres of molten titanium which have become fused with the glass and are in the form of flat disks. This is another demonstration of the lower level of temperature associated with vibration grinding.

In the preparation of titanium specimens for the fourth group of tests the original stock was surface-ground while being held by steel screws counterbored in a supporting steel plate, so that, as the titanium was ground, the ends of the screws also were ground. The result is shown in Fig. 8. The screw was under the grinding wheel for less than one wheel revolution and contact between the screw and the wheel cleaned titanium products from the wheel surface. This cleaned portion subsequently ground the titanium with less smear and a smoother surface. This is shown in the reflections of the screw holes in the specimen in Fig. 8.

The last group of tests in Series 2 was a grinding-ratio study. Two specimens of 52100 steel were used for these tests, one for vibrated and one for conventional grinding. Fifty-eight test passes were made on each specimen. Four samples of swarf were collected in each case; the first sample involved only one pass across the work, the second sample consisted of the next two passes, the third sample included the next 5 passes, and the fourth sample included the last 50 passes. All eight samples were analyzed by chemical tests after reducing the oxides in a hydrogen atmosphere. In the conventional grinding tests the grinding ratio increased from 5.8 for the first pass up to an average of 39.8 for the last 50 passes. Similarly, in the vibration tests the ratio increased from 2.18 up to 24.35. It is believed that these tests give a better indication of the amount of increased wheel breakdown caused by vibration.

Analysis of Residual Stresses

It was decided to conduct one series of tests for the purpose of determining the difference in residual stress between a conventionally ground specimen and one ground with vibration. Not only are residual stresses of interest per se, but, also, it is known that the magnitude of residual tensile stress is determined by the amount of overheating or temperature level. Consequently, the earlier indications of temperature difference pointed toward a significant difference in residual stress as between conventional and vibrated grinding.

Two specimens were prepared for this study. They were 7/8-inch square by 0.060-inch thick, were made from fully hardened SAE X4340 steel, and were approximately 55 R_c. The specimens were "cycle-welded" to bakelite supports, which, in turn, were mounted on the transducer for grinding. One specimen was ground conventionally and the other with vibration. Both specimens were ground at the following conditions:

Grinding wheel	Carborundum DA60J9V20
Wheel speed	6,000 fpm

Table speed	20 fpm
Depth of cut	0.002 inch per pass (5 test passes)
Cross feed	0.050 inch per stroke
Fluid	Dry grinding

Observations were made of input power, and watchglasses were used to intercept the stream of grinding swarf. The curvature of the underside of the test specimens was determined before and after grinding, so that the change in curvature could be used as a measure of the residual stress.

It was noted that the input power was appreciably less when vibration was used. Similarly the watchglass test indicated lower temperature during vibration. Analysis of the curvature change gave the following results for curvature in the direction of wheel velocity:

Conventional = 38×10^{-4}
Vibrated = 26×10^{-4}

The above figures show that there was approximately 50% greater average tensile stress in the conventionally ground specimen. There was very little stress in the other direction in either specimen.

Temperature Test with Imbedded Thermocouple

Two groups of tests were conducted with thermocouples imbedded in the test specimen, as shown in the closeup of Fig. 2. Tests were run at the same grinding conditions as the previous residual-stress series except that the full width of the 1/2-inch-wide test surface was ground in a single pass with what might be called "plunge" grinding. The test specimens were 7/8 inch square by 0.125 inch thick, with a thermocouple hole 1/16 inch diameter drilled into the middle of the underside. The end of the thermocouple was resistance-welded to the bottom of the thermocouple hole. Initially there was 0.030 inch of metal between the end of the thermocouple and the ground surface.

The first tests were preliminary in nature and were made while using a Speedomax recorder. Observations were made also of input power. All tests made during vibration of the work specimen gave definite repeatable temperature indications. On the other hand, the same tests without vibration resulted in varying temperatures. For example, it will be noted in Fig. 2 that a dark area of oxides exists near the middle of the top surface of the specimen. This occurred repeatedly during conventional grinding but never occurred during vibration. When the oxides occurred immediately above the thermocouple, the recording pen of the Speedomax was unable to keep up with the rate of temperature rise, but even so it indicated a very high temperature of approximately twice that occurring during vibration. On the other hand, when the circle of oxides occurred at some distance from the thermocouple the resulting peak temperature was only slightly higher than during vibration.

If it is assumed that the oxidized area was caused by a local "hard spot" on the grinding wheel, the work speed was such that the oxidized area would be expected to occur only once on the surface. With a longer work surface it would occur repeatedly at substantially constant pitch. Thus it would appear that one reason for the lower temperatures observed with vibration is continuous and uniform breakdown of the wheel surface, thus avoiding abnormal wear and resulting higher temperatures from those portions of a grinding wheel which may be harder than the average.

A second series of temperature tests using imbedded thermocouples was made with an oscilloscope to indicate the temperature change. The temperature curves were recorded with a Polaroid-Land camera with the setup pictured in Fig. 3. The results of these tests followed closely the experience in the preliminary group. A typical temperature-versus-time record is given in Fig. 9. The two curves shown were obtained from consecutive tests, the first by conventional grinding and the second by vibration. During the conventional grinding the thermocouple was 0.014 inch from the ground surface, while during the next pass with vibration it was only 0.011 inch from the surface and 50% more metal was removed. The two temperature curves were recorded on the same negative. The reproduced curves show that the peak temperature for conventional grinding was approximately 475°F at the thermocouple, while the corresponding temperature for vibration was 255°F. It was evident that the hard spot, if this was the cause, did contact the work piece above the thermocouple during the conventional grinding test.

Test of Resinoid Wheel

This group of tests was run for the purpose of comparing the effect of vibration on a resinoid wheel with that obtained for a vitreous-bonded wheel. For this purpose two 52100 full hard specimens were ground at a work speed of 20 fpm, cross feed of 0.050 inch, depth of cut of 0.002 inch, since these same conditions had been used previously with the J-grade vitrified wheel. A Carborundum A60-T3-BT wheel was used. It was intended to precut 5 passes followed by 5 test passes, as was done with the vitreous wheel; however, the test specimen was so badly cracked and overheated after just two passes by conventional grinding that the test was stopped. For this reason the subsequent vibration test was also limited to two passes. The resulting specimens are shown in Fig. 10. The specimen at the left was ground conventionally while the one on the right was ground with vibration. It will be observed that the conventionally ground specimen was so severely stressed that cracks occurred in all directions. Some of these cracks penetrate more than 1/16 inch below the surface.

The specimen ground with vibration shows three cracks completely across the surface and a fourth one approximately one-half way across. Only two of these cracks were evident immediately after grinding and at that time they had extended from one edge about a third of the way across the surface. Within 12 hours the rest of the cracks developed. These surfaces were studied under the microscope and it was noted that there was considerable localized "necking" in the vicinity of the cracks on the vibrated specimen. This is a rare occurrence since it is generally believed that full hard steel will not undergo any elongation nor reduction of area prior to fracture. It is a coincidence that the level of residual stress was such that some creeping and relaxation could take place. It is obvious that the level of stress in the vibrated specimen was considerably less than in the one ground conventionally. Further, it is obvious that vibration is effective with resin-bonded wheels as well as with vitrified wheels.

Effect of Mode of Vibration

In all previous tests in evaluation of the effects of vibration, the work piece was mounted on top of the transducer and vibrated radially to the grinding wheel. The question arose as to whether the vibration would be similarly effective if the work piece were vibrated across the face of the wheel. Consequently the transducer was mounted on an angle plate so that grinding could be performed on what would otherwise be the side of the specimen. Vibration did improve the surface finish as in previous tests; however, it was demonstrated that the work piece literally vibrates in all directions and further that the vibration energy is reflected from the various surfaces of the test specimen. In other words the "side" of the work piece showed the same manifestations of vibration as did the top in the other orientation of the transducer. Tentatively it may be assumed that a similar attempt to vibrate the work specimen parallel to the direction of grinding would yield similar results.

Grinding Carbide Tools

Two 1/8 x 1/2 x 5/8-inch tips of Carboloy 78B tungsten carbide were brazed to the top of cold-rolled steel supports. The two carbide specimens were ground with a Carborundum DA60J9V20 at a depth of 0.002 inch. The one specimen ground conventionally developed many hairline cracks across the grinding direction. The specimen ground with vibration developed no cracks. This result raised the question as to whether the cracks in the one specimen might not have been caused by brazing, consequently the two specimens were ground a second time using vibration on the specimen that had been cracked with the result that the cracks were removed by grinding. The use of conventional grinding on the other specimen that did not show any cracks once more produced many cracks. It is well known that thermal cracks constitute a widespread problem in the sharpening of carbide tools in industry even where silicon carbide and diamond wheels are used. Aluminum oxide wheels are never recommended for this purpose; yet the use of vibration permitted the use of aluminum oxide for grinding the tungsten carbide tips without producing thermal cracks.

CONCLUSIONS

1. Vibrations in a frequency range of 10-18 KC and amplitudes (half-range) of 0.0002 to 0.0005 inch affect the grinding process.
2. Vibrations of the type described in No. 1 above may reduce surface roughness by as much as 50%.
3. Relative vibration between the abrasive wheel and the work surface reduces the effective temperature considerably.
4. Vibration reduces the incidence of burning or thermal damage of the work surface.
5. Vibration reduces residual tensile stress.
6. Vibration can eliminate thermal cracks during the grinding of carbide tools.
7. Vibration reduces the "loading" of abrasive wheels.
8. Vibration reduces "glazing" of abrasive wheels.
9. Vibration increases the average rate of wheel breakdown.
10. Vibration apparently produces more uniform rate of wheel breakdown.

TABLE III

SURFACE FINISH SUMMARY

(Test Series - 1)

Material	Wheel Grade	Vibrated-V Conventional-C	Roughness - Microinches RMS d=.0002	d=.0005	d=.002
1020	F	C	26	26	23
1020	F	V	20	24	22
1020	J	C	18	36	40
1020	J	V	18	19	30
52100	F	C	21	63	40
52100	F	V	16	38	16
52100	J	C	18	21	23
52100	J	V	14	25	13

TABLE IV

SURFACE-FINISH DATA

(Test Series - 1)

Depth of Cut "d" = .002 in.

Grinding Procedure: (1)Dress Wheel; (2) Precut "Out" Grinding, 5 Passes d = .001 in., f = .050 in.; (3) Test Cut "Out" Grinding, 5 Passes v = 40 fpm; (4) Collect Dust Samples; (5) Measure Surface Roughness.

Note: On Vibrated Tests Amplitude Approx. = .0005 in.
Frequency = 11 KC

Material	Wheel Grade	Vibrated-V Conventional-C	Roughness Parallel µ in. RMS	Roughness Perpendicular µ in. RMS	Remarks
1020	F	C	(7-11)* 9	(20-25) 23	
1020	F	V	(8-15) 12	(16-26) 22	Severe wheel breakdown
1020	J	C	(9-13) 10	(35-44) 40	
1020	J	V	(8-12) 10	(25-33) 30	
52100	F	C	(6-10) 8	(35-43) 40	
52100	F	V	(4-6.5) 5.5	(14-19) 16	
52100	J	C	(7-11) 9	(20-25) 23	Work surface was burned for distance approx. 1/2 of feed
52100	J	V	(4-6.5) 5	(10-15) 13	

* Range of roughness is within parentheses.

TABLE V

SURFACE FINISH DATA

(Test Series - 1)

Depth of Cut "d" = .0005 in.

Grinding Procedure: (1) Dress Wheel; (2) Precut "Out" Grinding, 5 passes d = .001 in., f = .050 in.; (3) Test Cut "Out" Grinding, 5 Passes, v = 40 fpm; (4) Collect Dust Sample; (5) Measure Surface Roughness.

Note: On Vibrated Tests Amplitude Approx. = .0005 in.
Frequency = 11 KC

Material	Wheel Grade	Vibrated-V Conventional-C	Roughness Parallel μ in. RMS	Roughness Perpendicular μ in. RMS	Remarks
1020	F	C	(10-12)* 12	(22-28) 26	
1020	F	V	(13-17) 15	(22-26) 24	
1020	J	C	(8-13) 11	(32-40) 36	
1020	J	V	(8-13) 11	(16-20) 19	
52100	F	C	(16-25) 19	(50-70) 63	
52100	F	V	(11-14) 13	(34-42) 38	
52100	J	C	(7-13) 9	(18-22) 21	
52100	J	V	(10-14) 12	(22-26) 25	

* Range of Roughness is within parentheses.

TABLE VI

SURFACE FINISH DATA

(Test Series - 1)

Depth of Cut "d" = .0002 in.

Grinding Procedure: (1) Dress Wheel; (2) Precut "Out" Grinding, 5 Passes d = .001 in., f = .050 in.; (3) Test Cut "Out" Grinding, 5 Passes v = 40 fpm; (4) Collect Dust Sample; (5) Measure Surface Roughness.

Note: On Vibrated Tests Amplitude Approx. = .0005 in.
Frequency = 11 KC

Material	Wheel Grade	Vibrated-V Conventional-C	Roughness Parallel µ in. RMS	Roughness Perpendicular µ in. RMS	Remarks
1020	F	C	(7-11)* 9	(24-29) 26	
1020	F	V	(7-12) 8	(19-22) 20	
1020	J	C	(6-11) 9	(15-19) 18	
1020	J	V	(10-12) 11	(16-19) 18	
52100	F	C	(9-12) 10	(19-23) 21	
52100	F	V	(5-10) 7	(15-18) 16	
52100	J	C	(4-7) 5	(15-20) 18	
52100	J	V	(6-11) 9	(13-19) 14	

* Range of Roughness is within parentheses.

TABLE VII

GRINDING RATIO

(Test Series - 1)

Depth of Cut	Sample No.	Gross Wt.-Mg.	(a) Abrasive Wt.-Mg.	(b) Metal Wt.	b/a
.0002	JAC	21.8	4.4	17.4	3.96
	JAV	29.4	10.6	18.8	1.77
.002	FAC	320.7	62.8	247.9	4.12
	FAV	381.5	165.2	216.3	1.31
	JAC	495.0	19.2	475.8	24.80
	JAV	627.3	104.6	522.7	5.00

TABLE VIII

SURFACE FINISH AND GRINDING RATIO DATA

(Series - 2)

VARIABLE DEPTH OF CUT

Grinding Procedure: (1) Dress Wheel; (2) Precut "Out" Grinding, 5 Passes d = .001 in., f = .050 in.; (3) Test Cut "Out" Grinding, 5 Passes v = 30 fpm; (4) Collect Dust Sample; (5) Measure Surface Roughness.

Note: On Vibrated Tests Amplitude Approx. = .0005 in.
Frequency = 10 KC

Material	Wheel Grade	Vib. or Conv.	Depth of Cut	Roughness Parallel μ in. RMS	Roughness Perpendicular μ in. RMS	Burning	Grind. Ratio
52100	J	C	.0005	(4-6) 5	(20-24) 22	None	5.20
52100	J	V	.0005	(4-7) 5.5	(12-16) 14	None	6.67
52100	J	C	.0020	(4-6) 5	(16-21) 18.5	Some	12.37
52100	J	V	.0020	(5-7) 6	(13-15) 14	None	9.09
52100	J	C	.0040	(3-4.5) 4	(14-18) 16	Some	7.29
52100	J	V	.0040	(5-7) 6	(13-17) 15	None	7.20
52100	J	C	.0080	(3.5-10) 6	(12-15) 15	Burn	3.53
52100	J	V	.0080	(8-12) 9	(12-15) 13.5	None	3.69

TABLE IX

SURFACE FINISH AND GRINDING RATIO DATA

(Series - 2)

VARIABLE TABLE SPEED

Grinding Procedure: (1) Dress Wheel; (2) Precut "Out" Grinding, 5 Passes d = .001 in., f = .050 in.; (3) Test Cut "Out" Grinding, 5 Passes d = .002 in.; (4) Collect Dust Sample; (5) Measure Surface Roughness.

Note: On Vibrated Tests Amplitude Approx. = .0005 in.
Frequency = 10 KC

Material	Wheel Grade	Vib. or Conv.	Table Speed fpm	Roughness Parallel μ in. RMS	Roughness Perpendicular μ in. RMS	Burning	Grind. Ratio
52100	J	C	5	(4-12) 7.5	(11-15) 13	Burn	22.57
52100	J	V	5	(3-6) 4.5	(8-10) 9	None	54.02
52100	J	C	20	(5-10) 7	(18-22) 20	Burn	28.95
52100	J	V	20	(5-8) 6.5	(9-12) 10.5	None	19.81
52100	J	C	40	(4-9) 6.5	(12-16) 14	None	13.36
52100	J	V	40	(6-9) 7	(13-16) 15	None	8.51
52100	J	C	80	(4-8) 6	(11-13) 12	None	15.66
52100	J	V	80	(4-8) 6	(9-11) 10	None	5.97

TABLE X

SURFACE FINISH AND GRINDING RATIO DATA

(Series - 2)

VARIABLE CROSS FEED

Grinding Procedure: (1) Dress Wheel; (2) Precut "Out" Grinding, 5 Passes d = .001 in., f = .050 in.; (3) Test Cut "Out" Grinding, 5 Passes v = 30 fpm; (4) Collect Dust Sample; (5) Measure Surface Roughness.

Note: On Vibrated Tests Amplitude Approx. = .0005 in.
Frequency = 10 KC

Material	Wheel Grade	Vib. or Conv.	Cross Feed in.	Roughness Parallel μ in. RMS	Roughness Perpendicular μ in. RMS	Burning	Grind. Ratio
52100	J	C	.025	(4-7) 5.5	(18-22) 20	None	10.56
52100	J	V	.025	(4-5.5) 5	(10-12) 11	None	10.29
52100	J	C	.050	(5-7) 6	(13-18) 16	Some	13.62
52100	J	V	.050	(5-8) 6.5	(10-14) 12	None	10.50
52100	J	C	.100	(4-8) 6	(16-23) 21	Some	8.80
52100	J	V	.100	(5-8) 6.5	(15-19) 17	Slight	7.36
52100	J	C	.200	(7-12) 9.5	(16-24) 21	Some	9.19
52100	J	V	.200	(5-13) 9	(18-25) 22	Slight	3.38

TABLE XI

SURFACE FINISH DATA

(Series - 2)

VARIOUS MATERIALS

Grinding Procedure: (1) Dress Wheel; (2) Precut "Out" Grinding, 5 Passes d = .001 in., f = .050 in.; (3) Test Cut "Out" Grinding, 5 Passes v = 40 fpm d = .002 in.; (4) Collect Dust Sample; (5) Measure Surface Roughness.

Note: On Vibrated Tests Amplitude Approx. = .0005 in.
Frequency = 10 KC

Material	Wheel Grade	Vibrated-V Conventional-C	Roughness Parallel μ in. RMS	Roughness Perpendicular μ in. RMS	Remarks
RC 130B Titanium	J	C	(10-13) 12	(14-16) 15	
RC 130B Titanium	J	V	(10-13) 11	(14-18) 16	
Ti 150A	J	C	(8-12) 10	(13-19) 15	
Ti 150A	J	V	(7.5-9.5) 8	(14-17) 15	
2 S Alum.	J	C		(70-150)	Badly torn surface
2 S Alum.	J	V		(60-200)	Badly torn surface
24 ST Alum.	J	C		(35-42) 38	Badly torn surface
24 ST Alum.	J	V		(43-49) 47	Badly torn surface
Red Brass	J	C	(12-18) 15	(25-32) 30	Much wheel loading
Red Brass	J	V	(9-14) 12	(20-25) 23	Less wheel loading
Bakelite (Black)	J	C	(13-22) 17	(22-26) 25	
Bakelite (Black)	J	V	(12-19) 15	(22-26) 24	

TABLE XII

GRINDING RATIO STUDY

(Series - 2)

Test Code	No. of Passes in Sample	Grinding Ratio = $\frac{\text{Volume of Metal}}{\text{Volume of Abrasive}}$
JAk1C	1	5.80
JAk2C	2	10.51
JAk3C	5	13.63
JAk4C	50	39.80
JAk1V	1	2.18
JAk2V	2	3.24
JAk3V	5	10.68
JAk4V	50	24.35

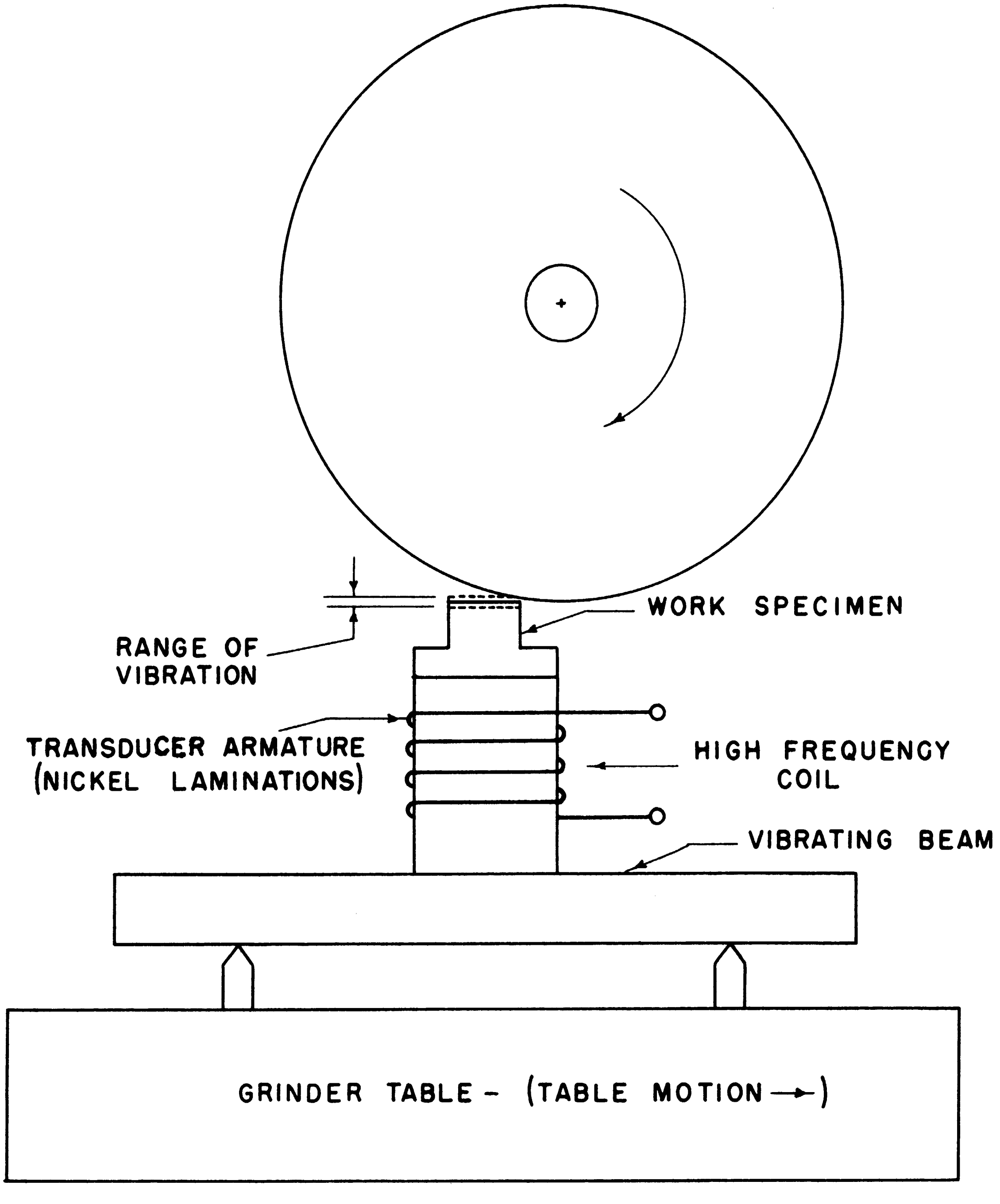
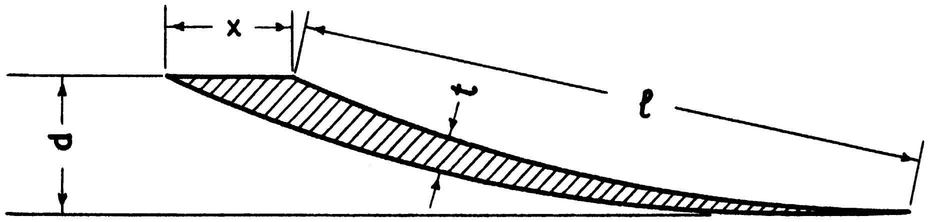


FIG. I. SHOWING THE RELATIONSHIP OF THE GRINDING WHEEL, WORK SPECIMEN AND TRANSDUCER. THE WORK IS VIBRATED RADIALLY TO THE WHEEL WHILE THE TABLE MOVES TO THE RIGHT.

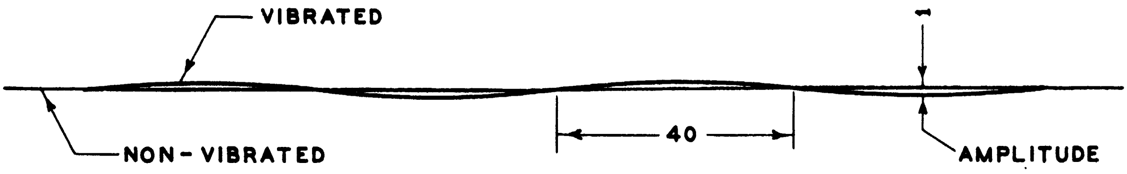
Fig. 2, 3, 5, 6, 7, 8

are mounted picture pages.

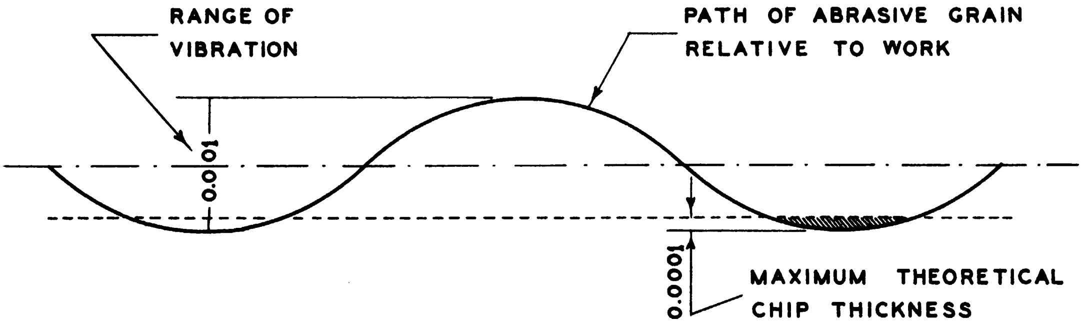
See ERI File Copy



(a) THEORETICAL PROPORTIONS OF GRINDING CUT WITHOUT VIBRATION.



(b) CHANGE IN VELOCITY OF ABRASIVE GRAIN RELATIVE TO WORK DUE TO VIBRATION.



(c) RELATION OF VIBRATION TO THICKNESS OF CHIP.

Fig. 4. GEOMETRICAL RELATIONSHIPS IN GRINDING. VIBRATION ASSUMED TO BE 10 KC WITH A RANGE OF 0.001 INCHES.

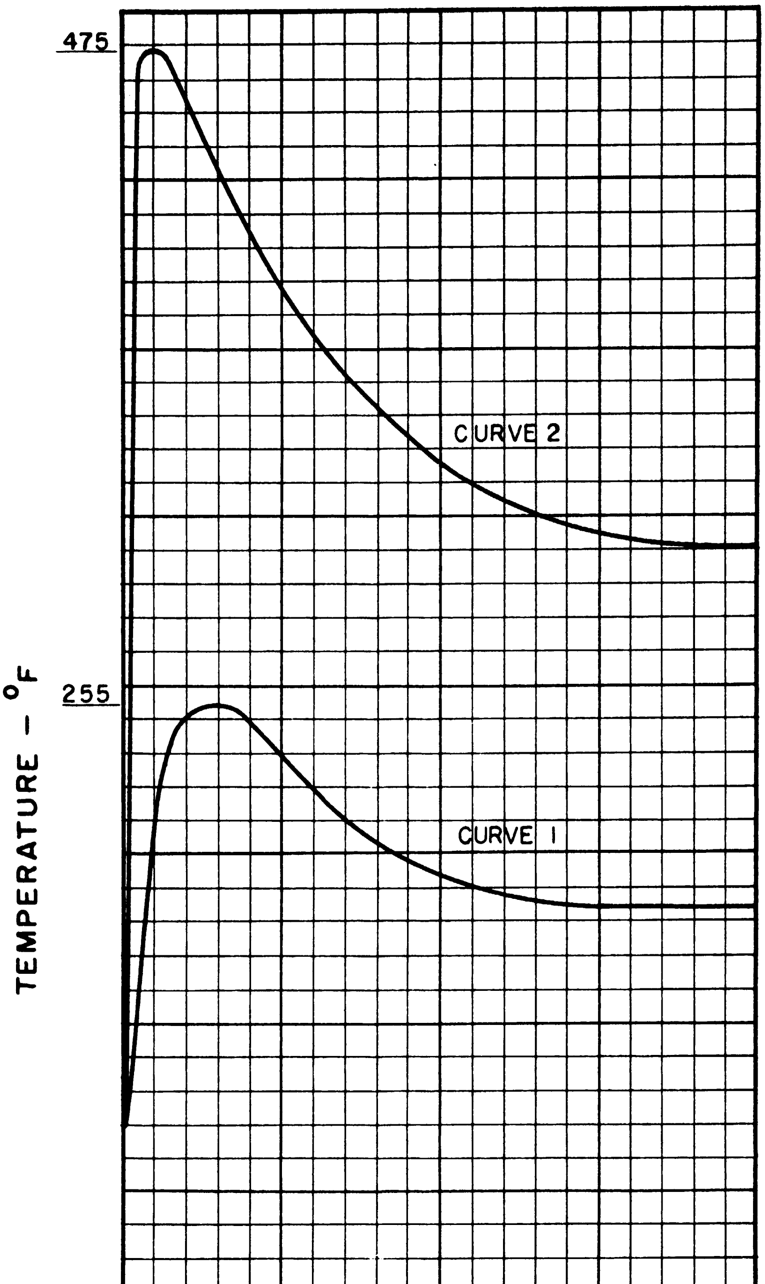


FIG. 9. OSCILLOSCOPE TRACE OF TEMPERATURE RISE IN GROUND SPECIMEN 0.027" BELOW GROUND FACE.

CURVE 1: VIBRATED.

CURVE 2: NOT VIBRATED.

0.002" DEPTH OF CUT, 22 FT. PER MINUTE TABLE SPEED.