Thermal Effects in Vibration Assisted Grinding

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Introduction

Compared to other machining processes, grinding is a high energy process that generates significant heat. A number of researchers have investigated thermal aspects of grinding and other machining processes. Of particular interest are the total heat generated and its partitioning between the workpiece and elsewhere (chips, coolant, wheel) [1-5].

The amount of heat that enters the workpiece is important because it impacts the quality of the finished part. Excessive temperature can lead to workpiece burn, thermal softening, and dimensional distortion. In addition to workpiece effects, heat generation in the grinding process accelerates wheel wear and necessitates coolant usage. Temperature also influences the mechanism of material removal: temporary softening of the workpiece, due to high temperatures, promotes ductile flow in the grinding of brittle materials. (In one of our tests the temperature rose to more than 400 °C at a point 40 μm below the surface.)

Colwell showed that the introduction of high frequency vibrations to the grinding process reduces the incidence of thermal cracking [6]. Markov [7] and Ishikawa et al. [8] observed that high frequency vibrations permit better coolant penetration. Moreover, several researchers have observed that high frequency vibration reduces machining force and thus machining energy [9,10]. Chandra et al. observed that high frequency modulation can reduce the depth of penetration of median cracks in Pyrex glass [11]. This paper further investigates the effect of high frequency vibrations on grinding temperatures. It describes tests at moderate vibration frequencies (up to 3 kHz) and ultrasonic frequencies. Based on measurements of grinding energy and workpiece temperature, estimates of the portion of heat energy that enters the workpiece (the energy partition) are made.

Grinding Tests at Moderate Vibration Frequencies (0 to 3 kHz)

Force and temperature measurements were made during surface up-grinding experiments in which the workpiece could be vibrated (or “modulated”) vertically at frequencies up to 3 kHz. Figure 1 shows the experimental setup. A 10.2 x 25.4 mm steel workpiece is glued onto a workpiece holder that is in turn clamped to a magnetostrictive actuator. The actuator vibrates sinusoidally in the Z direction. An E type thermocouple threads into the workpiece parallel to the work surface in the Y direction. Its tip touches the workpiece at its centerline 3 to 4 mm below the surface. The grinding wheel is aluminum oxide. The actuator assembly attaches to a three-axis force dynamometer. A data acquisition system simultaneously records the dynamometer and thermocouple signals.

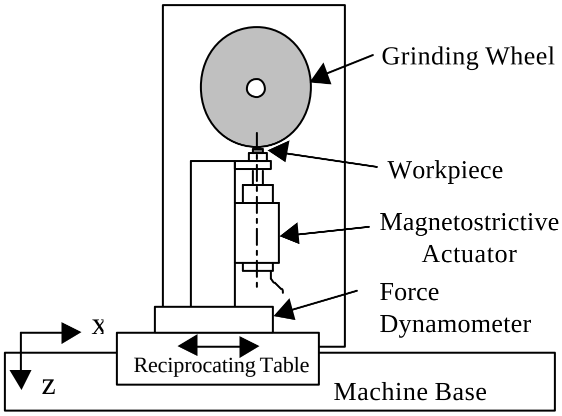

Figure 1: Setup for vibration assisted surface grinding experiments

Table 1: Grinding conditions

Workpiece mat’l	4140 mild steel Hardness : RC31 25.4 x 10.2 x 10 mm
Grinding wheel	Carborundum 32AR46-JV40 178 mm dia. x 12.7 mm
Wheel speed	26.6 m/s
Table speed	0.038 m/s
Wheel depth of cut	10 μm (dry tests) 25 μm (wet tests)
P-V vibration ampl.	7.5 μm
Vibration frequency	0, 1, 2, and 3 kHz (dry tests) 0 and 3 kHz (wet tests)

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Table 1 outlines the conditions for the experimental trials. Force and temperature measurements were made during a single traverse of the grinding wheel across the work surface. Before each measurement pass we made a preparatory pass under the same conditions. This preparatory pass was necessary to properly set the depth of cut for the measurement pass. Without it, a vibration assisted pass would remove more material than a no-vibration pass. A set of tests was performed dry (without coolant) at vibration frequencies ranging from 0 to 3 kHz. We also performed a set of tests with coolant both without vibration and with 3 kHz vibration.

Figure 2 shows the workpiece temperature during dry grinding with and without 3 kHz vibration. The temperature starts at an ambient of 22.5°C, climbs to a peak temperature after the grinding wheel passes by, and then gradually decreases (eventually returning to ambient). The high frequency component of these signals is electrical noise. For the case without modulation, the peak temperature is 49.2 °C. With 3 kHz modulation, the peak temperature is 40.5 °C.

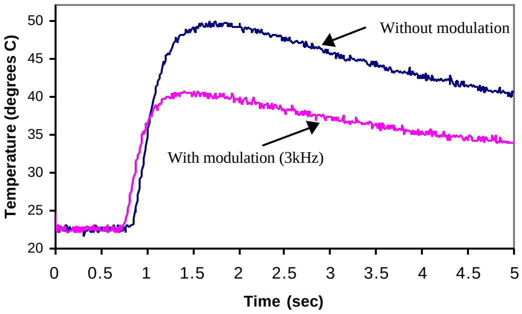

Figure 2: Temperature under dry condition as measured by thermocouple 3.8 mm below work surface

Table 2: Summary of force and temperature measurements for dry grinding tests at 10 µm depth of cut

Modulation Freq. (kHz)	**Avg. Force** (N)	**Avg. Peak Temp. Rise** (°C)
0	14.5	26.5
1	13.1	21.1
2	12.5	19.0
3	12.3	17.6

Table 2 presents the average results of the grinding tests performed under dry conditions. Four tests were performed at each condition and averaged. From 0 kHz to 3 kHz, the average force decreases by 15% and the average peak temperature rise decreases by 34%.

Experiments were also performed with coolant. To increase overall temperatures and improve the signal-to-noise ratio, we increased the depth of cut to 25 µm for the tests with coolant. With 3 kHz modulation the average measured force decreased from 23.3 to 21.3 N (8.6% reduction), and the average peak temperature rise decreased from 18.0 to 14.3 °C (21% reduction).

Estimate of Energy Partition

The results from the previous section show that modulation has a greater influence on temperature than on force. The temperature drop is a result of both a reduction in total energy (proportional to force) and a reduction in the energy partition (or the portion of the total energy that flows into the workpiece). Based on the experimental results we determined how modulation influences the energy partition.

The total power can be estimated as:

$$P_{total} = F_c V \qquad (1)$$

where F_c is the cutting force and V is the cutting speed. For the unmodulated dry case, the total cutting power is (14.5 N)(26.6 m/s) = 386 W.

The workpiece heating power is:

$$P_{work} = q'w \qquad (2)$$

where q' is the heat power per unit length of the heat source and w is the width of the workpiece. To estimate q', we adopted the moving line source model of Carslaw and Jaeger [12]. It calculates the temperature rise in a semi-infinite body at any (x,z) position due to a line source parallel to the y direction that moves in the x direction. The temperature rise in the workpiece is:

$$T(x,z) - T_o = \frac{2q'}{\pi k} e^{\frac{vx}{2a}} K_o\left[\frac{v\left(x^2+z^2\right)^{1/2}}{2a}\right] \qquad (3)$$

where T_o is the ambient temperature; k and a are the work material's conductivity and diffusivity, respectively; v is the table feed rate; K_o is the modified Bessel function of the second kind; and q' is the heat power per unit length of the line source. For our experiments, z was approximately 3.8 mm and x changes with time according to $x = vt$. To estimate q', we guessed a q' and attempted to match the maximum temperature from Equation (3) with the maximum temperature from the experiments at the location of the thermocouple. We also estimated q' based on a moving strip source model [12] and found that the results were nearly the same; we concluded that the small depth of cut in our experiments makes the width of the strip source small enough that the line source is a reasonable representation.

Figure 3 shows a plot of the experimentally measured temperature for a dry unmodulated case as well as a plot of temperature as calculated from Equation (3). To generate the modeled plot, a q¢ value of 29,610 W/m was assumed. With a workpiece width (or line source length) of 10.2 mm, the estimated heat power into the workpiece is then (29610)(0.0102)=302 W.

The energy partition, R_w, is defined as the portion of the total energy that flows into the workpiece. In the unmodulated case, R_w is 302/386 = 78%. Table 3 summarizes the effect of modulation on the energy partition for the dry and wet cases. The energy partition decreases as frequency increases.

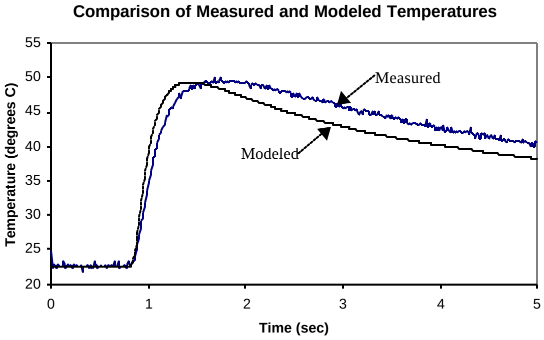

Figure 3: Comparison of measured temperature for the no modulation case alongside temperature as calculated from Equation (3)

Table 3: Summary of effect of modulation on energy partition

Coolant Use	Modulation Freq. (kHz)	Energy Partition Percentage
dry	0	78
	1	68
	2	65
	3	60
wet	0	33
	3	28

Temperature Near Work Surface

In all the experiments described above, the temperature rise in the workpiece is modest because it is measured 3.8 mm below the surface. We performed additional temperature measurements with the thermocouple positioned closer to the work surface. Figure 4 shows the temperature for *z* values (distance from thermocouple tip to work surface) ranging from 0.04 mm to 3.8 mm. The absolute temperature reduction near the surface is several hundred degrees.

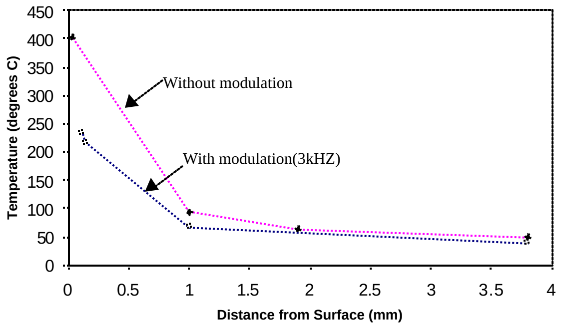

Figure 4: Temperature at varying depths below the grinding surface

Grinding Tests at Ultrasonic Frequency

To further explore the influence of modulation frequency and amplitude on the grinding process , we performed additional tests at a modulation frequency of 40 kHz. Table 4 summarizes the conditions for these experiments. The wheel was dressed once with a diamond nib before beginning the experiments but not before every test.

Table 4: Grinding conditions

Workpiece mat'l	Steel, Hardness: RC19 12.34 x 6.24 x 3.0 mm
Grinding wheel	Carborundum 32AR46-JV40 178 mm dia. x 12.7 mm
Truing Speed	0.353mm/s
Wheel speed	26.6 m/s
Table speed	0.025 m/s
Wheel depth of cut	10 µm
P-V vibration ampl.	0, 0.9, 1.8, 2.8 µm
Vibration frequency	40 kHz

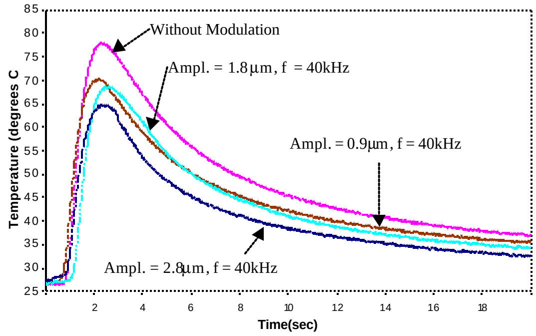

Figure 5: Temperature under dry grinding as measured by thermocouple 1.99 mm below work surface

Figure 5 shows the effect of vibration amplitude on grinding temperatures. For the case without modulation, the peak temperature is 78.1 °C. With

40 kHz modulation and peak-to-valley amplitude of 2.8 μm, the peak temperature is 64.9 °C.

Table 5: Summary of force and temperature measurements for dry grinding tests with 40 kHz modulation

P-V Modulation Ampl. (μm)	**Avg. Force (N)**	**Avg. Peak Temperature Rise (°C)**
0	28.50	52.60
0.9	22.19	50.20
1.8	21.06	41.51
2.8	19.34	37.85

Table 5 presents the average results of the grinding tests performed under dry conditions at 40 kHz. Three tests were performed at each condition and averaged. Increasing the modulation amplitude from 0 to 2.79 μm reduces the average force by 31% and the average peak temperature rise by 28%. The energy partition factors for these tests were all approximately 30% and did not change significantly with amplitude. However, the small workpiece used in this test invalidates the semi-infinite assumption used in calculating partition factors. Note that the measured forces in these tests are higher than those in the 0–3 kHz set. This is due to a harder workpiece material.

Conclusions

Vibration assisted grinding experiments at relatively modest frequencies as well as ultrasonic frequency indicate that modulation reduces cutting force and temperature. Modulation at 3 kHz and 7.5 μm amplitude reduced the force by 15% and peak temperature rise by 34% over the unmodulated case. Modulation at 40 kHz and 2.8 μm amplitude reduces the cutting force by 31% and the peak temperature rise by 28% over the unmodulated case. The reduction in temperature is on the order of several hundred degrees near the work surface. Somewhat surprisingly, moderate modulation frequencies appear to produce as much benefit as ultrasonic frequencies (with reduced amplitudes). The effect of frequency and amplitude on energy partition requires further study. The mechanisms for the force and temperature reduction are currently under investigation.

Acknowledgments

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