

Force and Temperature Measurements in Vibration Assisted Grinding

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Introduction

Grinding is a high-energy process where a substantial amount of heat is generated due to friction and plastic deformation in the region where the wheel interacts with the workpiece. The heat generated in the grinding zone either enters the workpiece and wheel or is carried away by the chips and the grinding fluid. The heat entering the workpiece is of primary importance because it causes thermal damage to the workpiece and degrades the quality of the finished part. Excessive temperatures lead to distortion of workpiece dimensions, changes in metallurgical structure and residual stress distribution in the finished part. High temperatures also accelerate the wheel wear, which abets further heat generation.

Numerous research studies [1-8] in the past have shown that the superposition of high frequency vibration to the workpiece over the regular kinematics of a grinding process reduces forces and temperatures and affects tool wear, surface quality and sub-surface properties (residual stress and bending stresses) of the workpiece. While grinding steel, Colwell [1] observed that high frequency vibration could improve the surface finish and reduce the incidence of thermal cracking. Uhlmann et al. [2, 7] and Warnecke et al. [3] have published extensive literature on the effects high frequency modulations to the grinding tool on the forces, surface quality and residual stress distribution in ceramics. Markov [4] observed that modulation to the workpiece improved coolant penetration in the cutting zone.

This paper focuses on evaluating the effect of vibration frequency and amplitude on the temperatures in grinding.

Experimental Setup

Figure 1 shows the grinding test set up. A 50 x 9.5 x 9.5 mm steel workpiece is attached to an aluminum workpiece holder that is threaded to the tip of a magnetostrictive actuator. A flexure that is sandwiched between the actuator and the workpiece holder serves to contain the displacement of the workpiece in the x-y plane. The actuator vibrates the

workpiece sinusoidally in the z direction. E Type thermocouples are threaded to the bottom of the workpiece. The tip of the thermocouple is at distance of 1-2 mm from the top surface. The actuator holder is attached to a tri-axial force transducer. The force and temperature signals are recorder simultaneously using a data acquisition system.

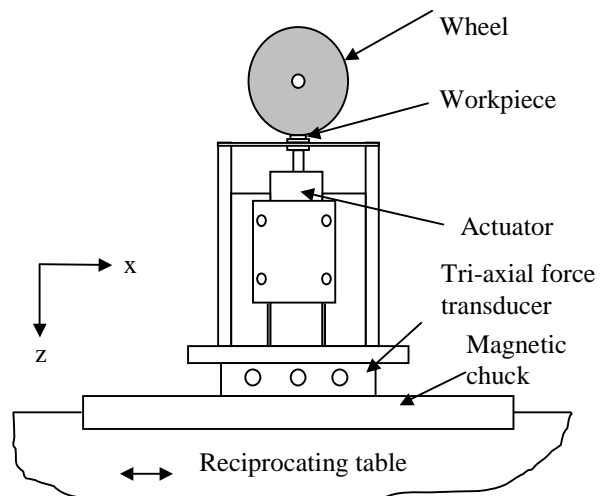


Figure 1: Experimental Setup for grinding with modulation to the workpiece

Grinding Runs at Moderate Frequency Modulation (0-2.65 kHz)

Table 1: Grinding Conditions – Moderate Frequency

Workpiece Material	4140 Steel 50 x 9.5 x 9.5 mm
Grinding Wheel	Aluminum oxide 32AR46-JV60 178 mm dia. x 12.7 mm
Wheel Speed	27.0 m/s
Feed Rate	0.05 m/s
Depth of Cut	15 μ m
Vibration amplitude	5 μ m, 7.5 μ m (p-v)
Vibration frequency	0, 1.039, 1.727, 2.65 kHz.

Table 1 lists the test conditions for moderate frequency dry (no coolant), down grinding tests. The tests were performed within a frequency range of 0 kHz to 2.65 kHz. These particular frequencies were

chosen because actuator amplitude of $7.5\mu\text{m}$ could be readily achieved at these frequencies. Three observations were recorded corresponding to each frequency and amplitude. Before the first test a pre-pass was done under the same grinding conditions to ensure that the depth of cut remains alike for all the consecutive passes. Without the pre-pass the material removal rate for the first pass would be more than successive passes as indicated in figure 2. The wheel was trued before every pre-pass to ensure sharp cutting properties of the abrasive grit during the test passes.

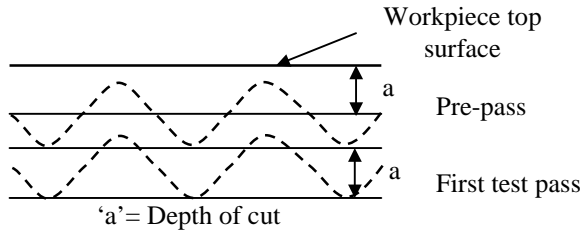


Figure 2: Grinding pre-pass

Figure 3 & 4 compare the tangential force and the normal force at 0, 1.039, 1.729 and 2.65 kHz due to modulation at $7.5\mu\text{m}$ amplitude and a depth of cut of $15\mu\text{m}$. The dotted smooth line shown in the figures passes through the average data point at corresponding frequencies.

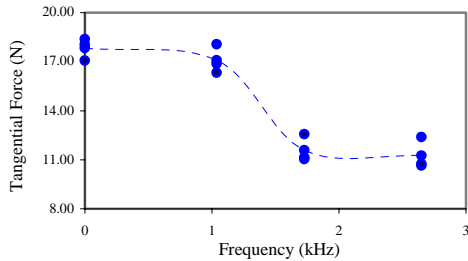


Figure 3: Tangential force at $7.5\mu\text{m}$ amplitude and $15\mu\text{m}$ depth of cut

The force results are summarized in Table 2 and 3. We observed that with the increase in frequency from 0 kHz to 2.65 kHz a substantial drop in force occurred. The tangential force decreased by 36.84% and the normal force by 32.09%. The reduction of force may be attributed to the disturbance in the adhesive wear mechanism between the abrasive grit and the workpiece and the presence of splintered sharp grits due to hammering effect of the wheel as observed by Uhlmann [2].

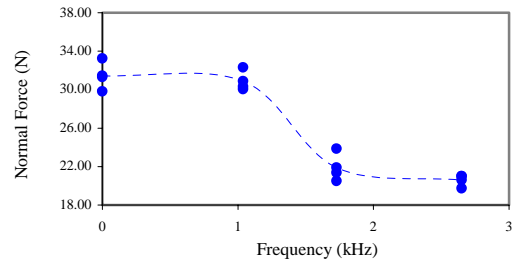


Figure 4: Normal force at $7.5\mu\text{m}$ amplitude and $15\mu\text{m}$ depth of cut

Table 2: Summary of Tangential Forces with $7.5\mu\text{m}$ amplitude

Vibration Frequency (kHz)	Average Tangential Force (N)	% Reduction when Compared to no Vibration
0	17.82	-
1.039	17.08	4.15
1.727	11.58	35.03
2.65	11.26	36.84

Table 3: Summary of Normal Forces with $7.5\mu\text{m}$ amplitude

Vibration Frequency (kHz)	Average Normal Force (N)	% Reduction when Compared to no Vibration
0	31.46	-
1.039	30.89	1.79
1.727	21.91	30.35
2.65	21.36	32.09

To investigate the influence of amplitude the experiments were repeated with modulation of $5\mu\text{m}$ ($p-v$) within the same frequency range. Figure 5 & 6 compare the tangential forces and the normal forces at 0, 1.039, 1.729 and 2.65 kHz with $5\mu\text{m}$ amplitude. The results are tabulated in Table 4 & 5. The average cutting force and normal force decreased by 30.28% & 21.65%, respectively, from 0 kHz to 2.65 kHz. From Tables 2 and 4 one might conclude that the percentage reductions in forces at $5\mu\text{m}$ amplitude are lower when compared to $7.5\mu\text{m}$. However a careful analysis by performing a two factor ANOVA on the cutting force data indicates that the effect of vibration amplitude within the given data range is not significant. In fact the analysis indicates that the vibration frequency of vibration and the interaction between frequency and amplitude are the only significant factors. The analysis was performed assuming 95% confidence interval.

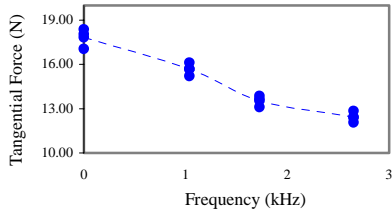


Figure 5: Tangential force at 5 μm amplitude and 15 μm depth of cut

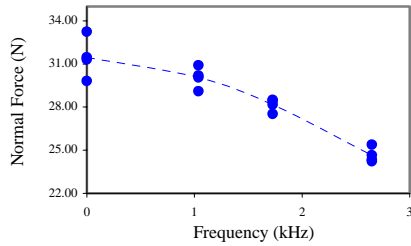


Figure 6: Normal force at 5 μm amplitude and 15 μm depth of cut

Table 4: Summary of Tangential Force with 5 μm amplitude

Vibration Frequency (kHz)	Average Tangential Force (N)	% Reduction when Compared to no Vibration
0	17.82	-
1.039	15.67	12.06
1.727	13.24	25.72
2.65	12.43	30.28

Table 5: Summary of Normal Force with 5 μm amplitude.

Vibration Frequency (kHz)	Average Normal Force (N)	% Reduction when Compared to no Vibration
0	31.46	-
1.039	30.07	4.42
1.727	27.83	11.54
2.65	24.65	21.65

For all the tests, temperature rise above the ambient was recorded by a thermocouple at known spatial location in the workpiece. The temperature rise depends upon the distance of the thermocouple tip from the heat source. This distance however, changes for consecutive test runs. Therefore the temperature rise is not a true indicator of the thermal loads on the workpiece. However, the heat entering the workpiece is independent of the thermocouple distance from the

heat source and would truly represent the effect of thermal load on the workpiece.

Estimation of Heat Source Strength and the Energy Partition Coefficient

The net power required for removing material in grinding is given by:

$$P_{net} = F_t v \quad (1)$$

where ' F_t ' is the tangential force and ' v ' is the peripheral wheel speed.

The heat source strength per unit length at the workpiece surface is given by:

$$q' = P_{w/p} / b \quad (2)$$

where ' $P_{w/p}$ ' is the heat entering the workpiece and ' b ' is the width of the workpiece. The heat source is assumed to be an infinite line of constant heat strength parallel to y-axis traversing at a constant velocity ' v ' over a semi-infinite body. Due to the small depth of cut in our experiments we have assumed that the line source is a reasonable approximation. Also the contact width ' b ' is much less than the length of the workpiece. Therefore the assumption of semi-infinite body is also reasonable. Carslaw and Jaeger's model [8] was used to estimate the temperature rise at a desired spatial coordinate (x, z). The temperature rise above ambient is given by:

$$\theta = \frac{q'}{\pi k} e^{\frac{vz}{2\alpha}} K_0 \left[v \frac{(x^2 + z^2)^{1/2}}{2\alpha} \right] \quad (3)$$

where ' k ' & ' α ' are the thermal conductivity and thermal diffusivity of the workpiece material and ' K_0 ' is the modified Bessel function of the second kind. The temperature rise for a known depth is recorded during the test and is used to back calculate ' q' ' by matching the recorded peak temperatures with the modeled value. The energy partition coefficient, i.e. the ratio of ' $P_{w/p}$ ' and ' P_{net} ' is then estimated.

Figure 7 & 8 show the effect of frequency on the heat entering the workpiece and the energy partition coefficient for tests with 7.5 μm amplitude. The percentage heat drop and the average energy partition coefficient are listed in Tables 6 & 7. The results indicate a huge drop of 63.82% in the heat entering the workpiece per unit length from 0 kHz to 2.65 kHz. The observed drop in the heat entering the workpiece is not only due to the reduction in the cutting forces but also due to the decrease in the energy partition coefficient symbolizing effective transfer of heat away from the grinding zone. The energy partition coefficient steadily reduced from

0.30 to 0.18 signifying a reduction of almost 40% from 0 kHz to 2.65 kHz.

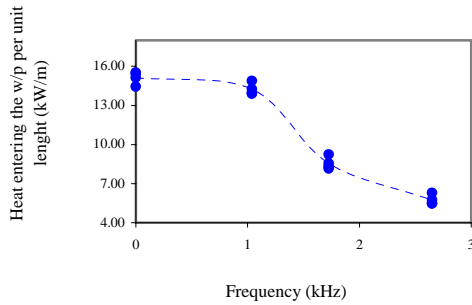


Figure 7: Average heat entering the w/p per unit length - 7.5µm amplitude

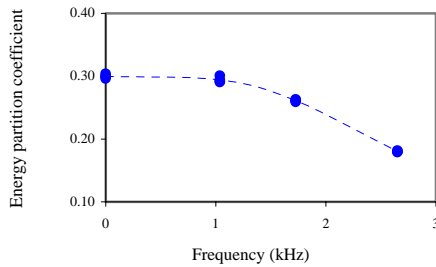


Figure 8: Effect of frequency on energy partition coefficient - 7.5µm amplitude

Table 6: Summary of heat entering the workpiece with 7.5µm amplitude

Vibration Frequency (kHz)	Avg. heat entering the w/p per unit length (kW/m)	% Reduction when Compared to no Vibration
0	15.13	-
1.039	14.29	5.89
1.727	13.56	43.46
2.65	9.13	62.05

Table 7: Summary of the energy partition coefficient with 7.5µm amplitude

Vibration Frequency (kHz)	Avg. energy partition coefficient	% Reduction when Compared to no Vibration
0	0.30	-
1.039	0.29	1.94
1.727	0.26	13.10
2.65	0.18	40.00

Figures 9 & 10 show the effect on the heat entering the workpiece and the energy partition coefficient for

5µm amplitude. The heat and the energy partition results are tabulated in Table 8 & 9.

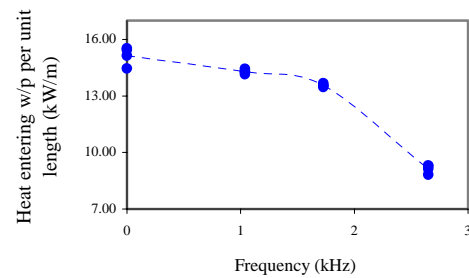


Figure 9: Average heat entering the w/p per unit length— 5µm amplitude

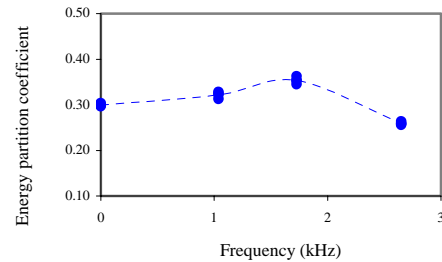


Figure 10: Effect of frequency on energy partition coefficient— 5µm amplitude

Table 8: Summary of heat entering the workpiece with 5µm amplitude

Vibration Frequency (kHz)	Avg. heat entering the w/p per unit length (kW/m)	% Reduction when Compared to no Vibration
0	15.13	-
1.039	14.29	5.55
1.727	13.56	10.37
2.65	9.13	39.66

Table 9: Summary of the energy partition coefficient with 5µm amplitude

Vibration Frequency (kHz)	Avg. energy partition coefficient	% Reduction when Compared to no Vibration
0	0.30	-
1.039	0.32	-7.26
1.727	0.35	-17.82
2.65	0.26	13.60

The results indicate a gradual reduction in the heat entering the workpiece from 15.13 (kW/m) to 9.13

(kW/m), a reduction of almost 40% over a frequency range of 0 kHz to 2.65 kHz. On the other hand, the energy partition coefficient increases slightly at 1.309 & 1.727 kHz frequency. (Negative values in the percentage reduction column indicate increase in magnitude above corresponding no vibration test.)

Grinding Runs at Very High Frequency Modulation (up to 12.63 kHz)

To investigate avenues for further force and heat reduction, grinding tests were performed at 3.21, 6.25 and 12.63 kHz frequencies. However, the workpiece could not be modulated at amplitudes higher than 1.57µm due to limitations of the actuator. The depth of cut was also reduced to 5µm so as to maintain an acceptable S/N ratio. The test parameters are summarized in Table 10.

Table 10: Grinding Conditions – Higher Frequencies

Workpiece Material	4140 Steel 50 x 9.5mm x 9.5 mm
Grinding Wheel	Aluminum oxide 32AR46-JV60 178 mm dia. x 12.7 mm
Wheel Speed	27.0 m/s
Feed Rate	0.05 m/s
Depth of Cut	5µm
Vibration amplitude	1.57µm (p-v)
Vibration frequency	0, 3.21, 6.25, 12.63kHz.

Three test runs were performed at each frequency after a pre-pass. The force results of the tests are shown in Figures 11 and 12 and are tabulated in Tables 11 and 12.

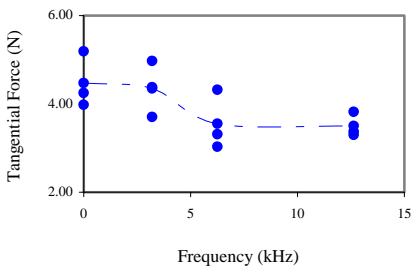


Figure 11: Tangential force at 1.57 µm amplitude and 5µm depth of cut

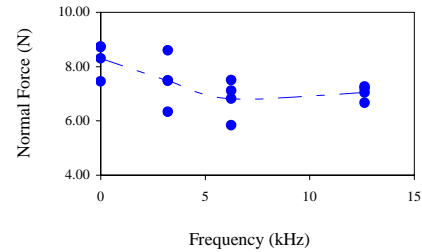


Figure 12: Normal force at 1.57 µm amplitude and 5µm depth of cut

Table 11: Summary of Cutting Forces with 5µm amplitude

Vibration Frequency (kHz)	Average Tangential Force (N)	% Reduction when Compared to no Vibration
0	4.47	-
3.21	4.35	2.68
6.25	3.55	20.51
12.63	3.50	21.77

Table 12: Summary of Normal Forces with 5µm amplitude.

Vibration Frequency (kHz)	Average Normal Force (N)	% Reduction when Compared to no Vibration
0	8.30	-
3.21	7.47	9.96
6.25	6.82	17.87
12.63	7.04	15.22

Although the force data show a downward trend, any conclusive inference cannot be made due to the variation associated with the data.

Figures 13 & 14 indicate the effect of high frequency modulation on the heat entering the workpiece and on the energy partition coefficient. The results are tabulated in Tables 13 & 14. The heat entering the workpiece dropped by almost 14.46% from 0 kHz to 12.63 kHz. However, the energy partition coefficient increased above the no-vibration condition by almost 12% indicating that the workpiece retained more heat at very high frequencies.

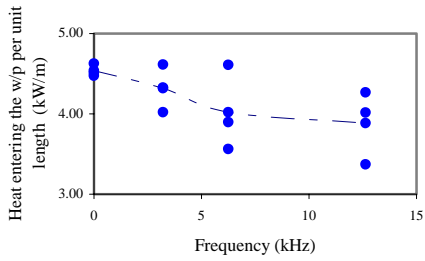


Figure 13: Average heat entering the w/p per unit length– 1.57 μ m amplitude

Table 13: Summary of heat entering the workpiece with 1.57 μ m amplitude

Vibration Frequency (kHz)	Avg. heat entering the w/p per unit length (kW/m)	% Reduction when Compared to no Vibration
0	4.54	-
1.039	4.32	4.85
1.727	4.02	11.42
2.65	3.88	14.46

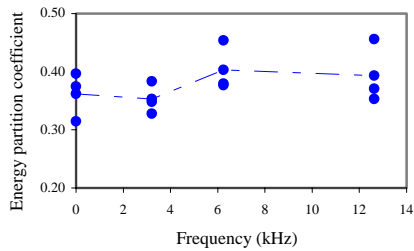


Figure 14: Effect of Frequency on energy partition coefficient– 1.57 μ m amplitude

Table 14: Summary of the energy partition coefficient with 1.57 μ m amplitude

Vibration Frequency (kHz)	Energy partition coefficient	% Reduction when Compared to no Vibration
0	0.36	-
1.039	0.35	1.92
1.727	0.40	-11.98
2.65	0.39	-9.21

Conclusions

Modulation of the workpiece at moderate frequencies has shown to reduce forces and temperatures in grinding. Vibration at moderate frequencies and 7.5 μ m amplitude reduced the forces by almost 37%

and reduced the thermal load by almost 62%. In addition the energy partition coefficient decreased by 40%. Tests at higher frequencies with smaller amplitudes are less conclusive due to variation in the results. A decrease in force and heat flux with increasing frequency is apparent. However contrary to the low frequency results, the energy partition coefficient appears to increase with frequency. Development of a thermal model to predict effects of vibration on temperature is underway.

Acknowledgment

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References

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