Wheel Loading Reduction with Vibration Assisted Grinding

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ABSTRACT
Chip accumulation (loading) on a grinding wheel causes a number of deleterious effects, particularly when grinding with fine grain wheels. Methods for reducing wheel loading include frequent dressing, in-process dressing, self-dressing, application of cryo-cooling, and optimum position of coolant. As an alternative to these techniques, we present vibration assisted grinding. Experiments show that wheel loading decreases with increased vibration frequency and amplitude. Under some circumstances, loading reduces almost 80%. In examining the underlying mechanisms of this loading reduction we focus on the role of grinding temperature and chip geometry. With artificial heating, wheel loading could be made to increase almost 200%. The temperature reduction observed in vibration assisted grinding is, therefore, considered the primary reason for loading reduction in this process. The role of chip size was also investigated through experimentation. Vibration assistance produces a higher percentage of small chips. The change in chip size distribution in vibration assisted grinding is postulated as a secondary reason for loading reduction.

INTRODUCTION
Grinding is an effective machining process in the manufacture of hard materials due to its multiple abrasive cutting particles. While a single point may dull and require re-sharpening, a grinding wheel distributes wear over many cutters and is capable of replenishing itself. However, the condition of the grinding wheel constantly changes as grits wear and chips accumulate in the spaces between grits. Chip accumulation (or loading) is particularly problematic with fine grit wheels. It occurs when workpiece chips either adhere to the grits or embed in the spaces between them. Wheel loading can result in deterioration in the surface finish, as well as an increase in grinding forces and temperature. As a consequence of higher temperature, the rate of abrasive wear increases. Thus the overall performance of the grinding operation is directly affected by the amount of wheel loading.

Wheel loading occurs when chips adhere to active wheel grains. Mechanical interlocking of chips with the surface asperities of the grinding wheel is a common mechanism for wheel loading, and is influenced by the space between grains and chip size [1]. Chemical affinity and diffusion affect adhesion between wheel and workpiece [2]. In addition, temperature is a possible major contributor in adhesion [3].

Methods for reducing wheel loading include frequent dressing, in-process dressing, more aggressive grinding conditions and self-dressing, application of cryo-cooling, and optimum position of coolant [4-8]. Our research investigates vibration assisted grinding as a way of reducing wheel loading. In early studies of the vibration assisted grinding process, differences in the extent of wheel loading were observed but not quantified [9]. This paper looks more closely at the effects of vibration parameters on loading as well as the role of chip size/shape and temperature in the loading process.

MEASUREMENT OF WHEEL LOADING
Methods for measuring wheel loading include chemical detection, calorimetry, spectroscopy, eddy current sensing, magnetization, radio-tracing, and x-ray fluorescence [10-14]. We adopted a simple approach employing microscope images and image analysis software. A portable, long-range microscope (Scionscope) and camera would capture images of the full width of the wheel surface. Then image analysis software would determine the percentage of chip loading. Figure 1 shows a typical image first as acquired and then after conversion to black-and-white. The black area represents the chip area, and the software can calculate its percentage. In our testing, we took seven images around the wheel, analyzed each image, and recorded the average percentage value as the chip loading condition for each situation.

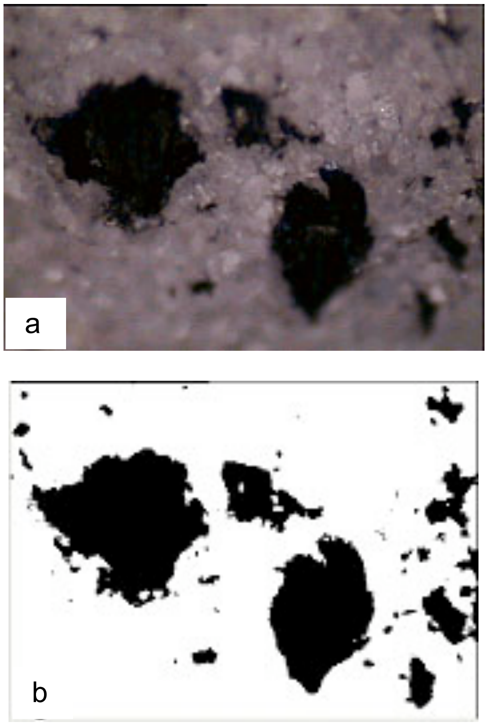

FIGURE 1. (a) Raw image of wheel surface; (b) black and white image

EXPERIMENTAL PROCEDURE

The effects of vibration assistance on loading were measured in a series of experiments. Amplitude and frequency of vibration were varied, and loading of the grinding wheels was measured. Figure 2 shows the experimental setup. A magnetostrictive actuator vibrates the workpiece. The vibration amplitude is measured using a capacitance gauge connected to a digital oscilloscope. A signal generator modulates the actuator and the workpiece in the radial direction with respect to the wheel.

Before each grinding test the wheel is trued with a diamond nib for five passes with a depth of cut of 10 µm. (In one truing pass, the diamond nib moves back and forth one time across the width of the wheel surface). Next, the workpiece is ground flat. Again, the wheel is trued. The actuator then begins modulating the workpiece, and vibration parameters are set with the signal generator. The workpiece feeds past the rotating grinding wheel with a desired depth of cut. After each back and forth grinding pass the depth of cut is indexed. At regular intervals, the grinding process is stopped, and images of the wheel are collected.

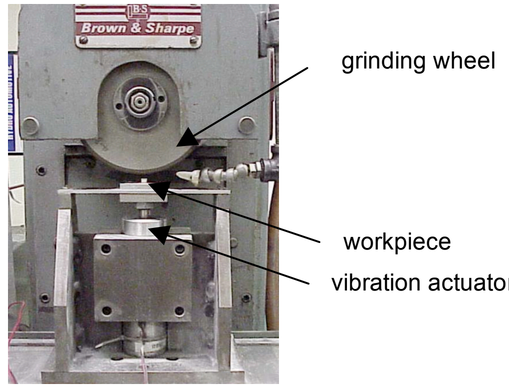

FIGURE 2. Experimental setup for wheel loading tests

FREQUENCY AND AMPLITUDE EFFECT

To determine the effects of vibration frequency and amplitude on loading, tests were conducted with aluminum oxide wheels grinding 1018 steel workpieces. Table 1 describes the conditions common to all the tests. Starting with freshly trued wheels, loading was measured at regular time intervals. Figure 3 shows a representative result for the effect of frequency on the evolution of loading whereby the rate of wheel loading tends to decrease with increased vibration frequency.

TABLE 1. Conditions for wheel loading tests

Workpiece	12.7x12.7x50.8 mm 1018 steel
Wheel	38A80-IVBE
Wheel rpm	2900 rpm
Depth of cut	0.020 mm
Coolant	None

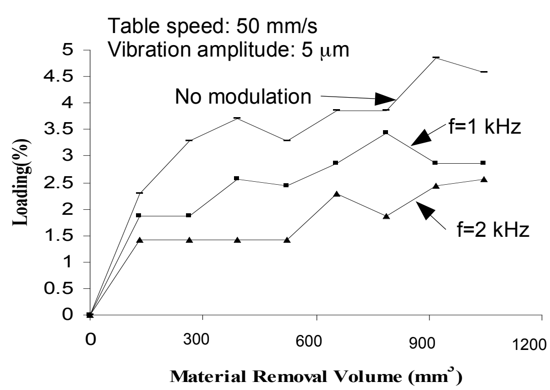

FIGURE 3. Effect of vibration frequency on loading

To investigate the effect of amplitude, four tests were performed at three different amplitude conditions, with the loading percentage measured only at the end of each test (after 100 grinding passes). Figure 4 shows the results for amplitudes of 1.25, 2.5, and 5 μm. The middle point of each bar is the average loading value; the upper and lower points are the average ± one standard deviation. Wheel loading clearly decreases with increased vibration amplitude.

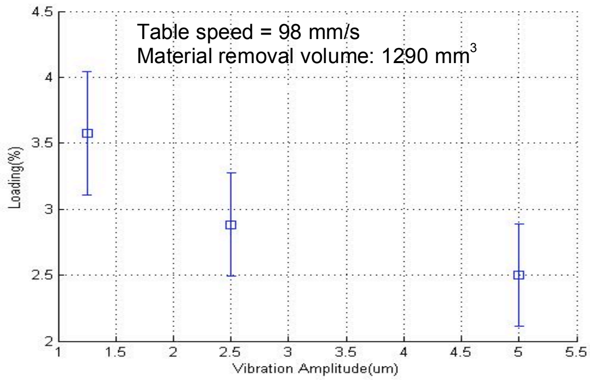

FIGURE 4. Effect of vibration amplitude on loading

GRINDING TEMPERATURE

In an attempt to explain the reduced loading with modulation, two factors–temperature and chip dimensions–were investigated further. A primary advantage of vibration assisted machining processes is reduced machining temperature (and thus tool wear). In surface grinding experiments workpiece temperatures were measured approximately 1 mm below the surface [17]. Surface temperatures were then estimated using a band moving heat source model [18]. Figure 5 plots surface temperature as a function of vibration frequency and amplitude. Higher frequencies and amplitudes correspond with lower temperatures.

The relationship between temperature and loading was subsequently explored in a set of grinding tests in which the workpiece was artificially heated. A disk shaped heater (10 mm OD with a 2 mm ID center hole) was placed under the workpiece. The workpiece was heated to four different initial temperature, and 50 passes of grinding were done. The temperatures immediately before and after grinding were recorded. Experiments at each condition were conducted four times. Figure 6 shows the average loading percentage at each condition (identified by its final temperature). The error bars indicate ± 3 standard deviations. The figure shows that wheel loading increases substantially with increased external heat.

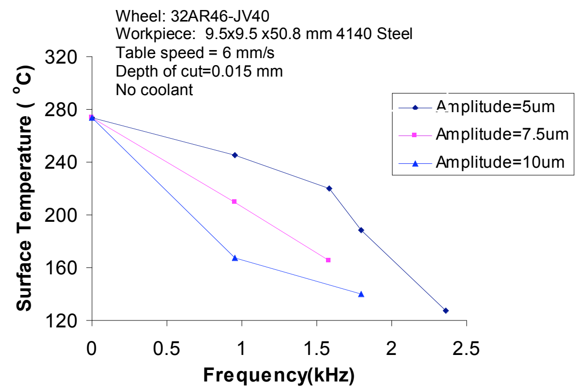

FIGURE 5. Effect of vibration assistance on workpiece surface temperature

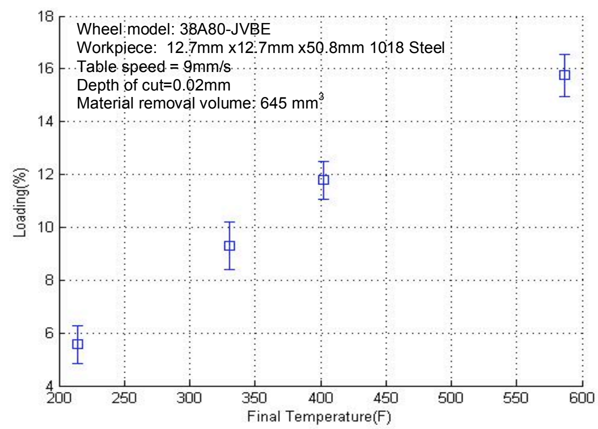

FIGURE 6. Effect of workpiece temperature on loading

One reason for the strong temperature effect may be that, at elevated temperatures, chips are more inclined to deform to the shape of the grinding wheel and to embed in the space between grits. Also, high temperature allows more diffusion between wheel material and workpiece material, thus promoting adhesion. Because temperature is a very important factor affecting wheel loading, it needs to be considered when searching for ways to reduce loading. Vibration assistance offers a means for reducing temperature and, consequently, loading.

CHIP SIZE AND SHAPE

We postulated that a second cause for reduced loading in vibration assisted grinding is modification of chip size and shape. To test this hypothesis we collected and analyzed approximately 500 hundred chips. Figures 7 and

8 are typical SEM images of 1018 steel chips from both conventional and vibration assisted grinding processes. No obvious differences are evident; they are both long, curled and have machining marks. The analysis was made quantitative by using SEM images and image analysis software to calculate aspect ratios and areas of chips. The aspect ratio is defined as the ratio of the major to minor axis a/b of the best fitting ellipse (see Figure 9).

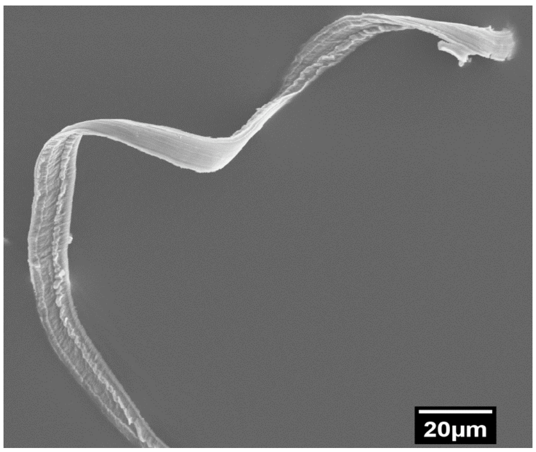

FIGURE 7. Chip from conventional grinding

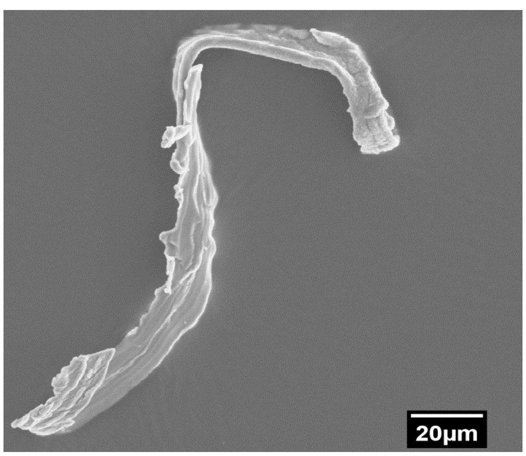

FIGURE 8. Chip from vibration assisted grinding (f=2 kHz, A=5 μm)

Figure 10 compares the distribution of aspect ratios. It shows little difference between conventional and vibration assisted grinding.

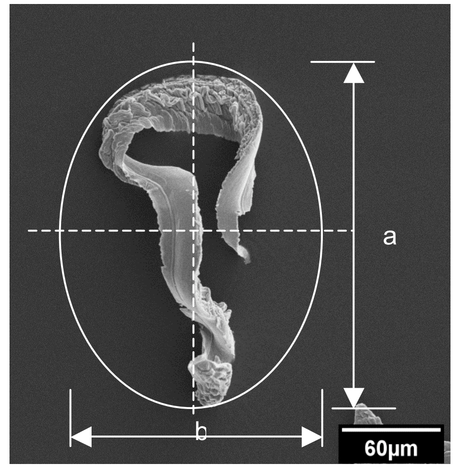

FIGURE 9. Calculation of chip aspect ratio

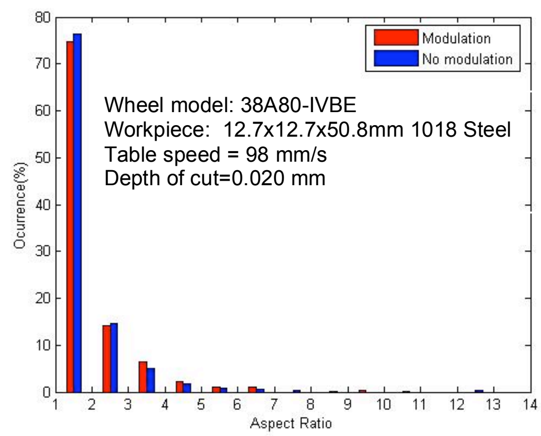

FIGURE 10. Comparison of chip aspect ratios

Figure 11 compares chip size distributions. Chip sizes range from 50 μm^2 to 10,000 μm^2, but most are less than 2,000 μm^2. The vibration assisted grinding process produces more small chips than the conventional grinding process. The correlation between smaller chips and reduced loading rates allows for the possibility that smaller chips is the reason for reduced loading in vibration assisted grinding. Perhaps smaller chips get cleared out of the contact zone more easily and are less likely to become lodged between grits by mechanical interlocking.

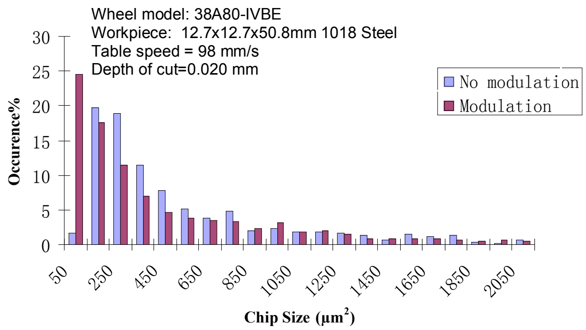

FIGURE 11. Comparison of chip sizes

CONCLUSIONS

By introducing high frequency vibratory motion to the workpiece, a reduction in grinding wheel loading was realized. Wheel loading decreases with increased vibration frequency and amplitude. Under some circumstances, loading reduces almost 80% in our testing. Temperature is identified as a primary reason for loading reduction in the vibration assisted grinding process. In our testing, wheel loading was made to nearly triple with an artificial increase in temperature. By analyzing chip shape and size, a correlation between chip size and wheel loading was found. Smaller chip sizes in vibration assisted grinding may be another cause of reduction in wheel loading.

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