Experimental analysis of wheel/workpiece dynamic interactions in grinding
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ABSTRACT

The aim of this work is to study the wheel/workpiece dynamic interactions in high-speed grinding using vitrified CBN wheel and DTG (difficult to grind) work materials. This problem is typical in the grinding of engine valve heads. The influence of tangential force per abrasive grain was investigated as an important control variable for the determination of C ratio. Experiments were carried out to observe the influence of vibrations in the wheel wear. The measurements of acoustic emission (AE) and vibration signals helped in identifying the correlation between the dynamic interactions (produced by forced random excitation) and the wheel wear. The wheel regenerative chatter phenomenon was observed by using the wheel mapping technique.

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1. Introduction

Grinding chatter vibration can be considered a critical problem due to its unfavourable consequences to the workpiece and grinding wheel, such as geometrical-form errors, surface finishing and premature wheel wear [1,2].

A comprehensive study on grinding chatter, its origin and suppression was presented in the 2001 STC-G CIRP keynote paper by Inasaki et al. [1].

Self-excited vibrations are often related to the natural vibration modes of the mechanical system. The regenerative effect is the major cause of chatter in grinding. This effect is created by disturbances in the process causing variations in the cutting force and consequently dynamic excitation of the machine–tool–fixture–workpiece–system, which results in dynamic variation of the depth of cut. Lobes are generated on the workpiece during its subsequent revolutions [3,4].

In a similar manner, wheel regeneration can occur due to irregular wheel wear; however it may develop slower than the workpiece regenerative effect [5,6]. This statement is not yet experimentally proved, since both kinds of chatter can happen simultaneously. Also, the measurement of wheel topography is still a difficult task.

Vibration detection in grinding is usually performed by using accelerometers, acoustic emission (AE) sensors or dynamometers. A considerable amount of research work describes different methods, such as statistical threshold values calculated from fluctuations of normal grinding force and AE [7,8]. In addition, tangential normal force variations were also proved to indicate torsional vibrations of the wheel and/or workpiece spindle, with significant influence on chatter generation [9–12].

Since chatter plays an important role in grinding, stabilization of the process is one of the most studied topics. Analytical and numerical models of the grinding process were developed to determine the effects of structural dynamics, contact stiffness and wheel flexibility on chatter suppression [13,14]. Other studies demonstrate that different types of grinding wheel technologies with lower contact stiffness and controlled variation of grinding wheel and/or workpiece rotational speed are effective for chatter suppression [11,15].

Grinding chatter has been studied deeply. However, there is very little information on how the dynamic interaction between grinding wheel and workpiece can affect the grinding quantities and how induced vibration could be beneficial to the process performance. Since grinding process instabilities during the accelerated spark-in (rough grinding phase) can produce surface quality disturbance that can be corrected during a slow finishing phase or long spark-out, forced process excitation during the spark-in could be used to influence the process positively. This technique has still not been investigated.

This work presents an experimental analysis on the influence of vibration in high-speed grinding with CBN vitrified wheels during plunge cycles. For reference, the basic relationship between grinding parameters and wheel wear was carried out firstly under stable grinding conditions with different DTG (difficult to grind) materials. Two aspects related to grinding vibration have been experimentally studied: the influence of vibration in the G ratio and the analysis of chatter generation for low part stiffness.

Considering that the application of CBN vitrified wheels in DTG materials results in a wide range of G ratio values, the question about the real influence of vibrations on the wheel wear and other process outputs is especially important. A good example is the grinding of low stiffness parts, such as engine valve heads, where chatter can occur only during the roughing phase of the cycle. This is a relevant industrial problem since the grinding of this type of component is rather difficult. The application of vitrified CBN wheels in this case is not yet consistent in industry.

2. Stable CBN grinding of DTG materials

Experiments were performed to study the influence of different specific material removal rate values on the wheel wear under
stable grinding conditions. Such influence must be well understood before testing the grinding under induced vibration or unstable conditions. Here the workpieces were clamped using the tail stock for maximum stiffness and a free-from-vibration process.

The tested workpiece materials were: Inconel (751), 21-2N (VV56) and Silicrome 1 (VV45). The materials and conditions are widely used in engine valves production. Simple plunge cycles were performed in order to reach a specific ground volume ($V_{uw}$) of 8000 mm$^3$/mm for each test. Each plunge cycle had only one infeed phase and a spark-out.

The wheel speed ($V_s$) was set to 100 m/s. A vitrified CBN wheel (B181 VSS Q V 320) was used. The infeed rate values ($V_i$) were 0.6, 1.2, 2.4 and 5 mm/min. Spark-out time and rotational speed of workpiece were set to 0.5 s and 200 rpm, respectively. The CBN wheel was dressed using a side plated diamond disk and constant optimized parameters: dressing overlapping ($U_d$) of 5; dressing depth ($q_d$) of 2 μm; and positive dressing speed ratio ($q_o$) of 0.4. During the tests, the power and AE signals were measured and recorded in a PC. After each experiment the wheel profile was measured for radial wheel wear measurements.

The machinability differences between the tested materials are clearly observed by the obtained $G$ ratio values as presented in Fig. 1. Another observed characteristic in Fig. 1 is the abrupt reduction in the $G$ ratio values with the increasing specific material removal rate between 1 and 2 mm$^3$/(mm s). It indicates two predominant wheel wear modes: friction wear and fracture wear. There is a point where the forces per grain reach the bond fracture. The tangential force per grain can be calculated from the measured power signals by:

$$ F_{t1g} = \frac{F_t}{bCkD} $$

where $F_{t1g}$ is the tangential force per grain, $F_t$ is the grinding tangential force calculated by the measured power and wheel speed, $b$ is the grinding width, $C$ is the length of contact area and $D$ is the grain density of the wheel. The influence of $F_{t1g}$ on wheel wear is shown in Fig. 2 for all tested materials.

An important aspect is that all the data points in Fig. 2 can be fitted to the same curve regardless the material composition. This confirms that the force related wheel wear mechanisms are relevant when compared to others driven by the material composition (e.g. chemical diffusion). Again, there is a threshold force per grain of about 0.1 N above which the $G$ ratio value drops dramatically.

3. Influence of vibration

Experiments were performed to study the dynamic interactions between the wheel and workpiece. The main goal was to understand the influence of the dynamic interaction in the $G$ ratio and part quality.

The same machine and CBN wheel were used to grind the Inconel workpieces. Tests were carried out at constant infeed rate ($V_i$) of 0.4 mm/min, i.e., below the threshold force value described before and presented in Fig. 2. This low infeed rate value was chosen since the dynamic interaction should add instant plunge speeds to the process, influencing the wheel wear. Grinding and workpiece speeds are the same used in the previous tests. A total specific ground volume ($V_{uw}$) of 425 mm$^3$/mm was removed in each ground part.

The test setup (Fig. 3) had an excitation system composed of an electro-dynamic shaker and its amplifier. The shaker is linked to the workpiece by a shaft, bearing housing and bearing assembly. This way made it possible to control the application of vibrations to the part.

A frequency response curve was measured using the setup presented in Fig. 3. Natural frequencies of 125, 205 and 300 Hz were found. Several forms of vibration were applied to the part in preliminary experiments. These included sinusoidal vibrations at the natural frequencies, wheel rotation frequency (to simulate unbalancing) and also random noises. The main conclusion was that the $G$ ratio is reduced for higher vibration speeds. The problem with harmonic excitation was the generation of uncontrolled chatter and very bad part quality, as expected. After an accident resulting in a wheel breakage the tests were focused on the application of random excitation. The results on the chatter formation will be presented in the next section.

A white-noise vibration with a frequency range between 1 to 10 kHz was used for the process excitation in the tests at eight amplitude levels. The frequency range of the white noise applied was chosen to be outside the system natural frequencies and also to result in high dynamic feed rate values.

**Fig. 1.** $G$ ratio versus specific material removal rate.

**Fig. 2.** $G$ ratio versus tangential force per grain.

**Fig. 3.** Setup for induced vibration tests.
The surface roughness and roundness of the ground part and the power signal from the dynamic tests are presented in Fig. 4. The variable $V_{vib}^3$ represents the peak velocity of vibration obtained from the accelerometer attached to the bearing housing. This parameter may not correspond exactly to the real vibration velocity, which occurred in the grinding zone due to the impedance of the bearing assembly, but it can give a good representation for analysis. There was no chatter occurrence.

As expected, the roundness and roughness increase with the vibration velocity. On the other hand, an opposite trend is revealed by the power signal. This behavior is an indication of major kinematic changes in the grinding zone, leading to higher dispersion in the chip thickness for higher random excitation levels. The random mechanical excitation reduces the actual dynamic grain distribution on the wheel surface leading to increased roughness and roundness values and lower power expenditure. This interesting behavior makes the wheel perform like a larger grain size wheel, which can be desirable in roughing situations.

The acoustic map presented in Fig. 5 shows the influence of induced vibration in the grinding power and AE map for a single plunge grinding cycle. The random excitation force was turned on between the time 21 and 37 seconds and then turned off. The map represents the AE distribution around the grinding wheel along the time axis, according to the method proposed by Oliveira and Dornfeld [16,17].

It is clear that the power signal decreases and the AE pattern changes while the excitation is on. The distribution of AE energy during the excitation period shows a more random behavior along the time axis than in the areas without excitation. Some horizontal lines are observed in the chart. These bright lines indicate a high acoustic emission magnitude, due to higher grain–workpiece interaction. As the excitation is turned on, the wheel starts to lose some grains. This can be observed as some regions were bright lines before the vibration was applied and became dark with low acoustic emission amplitude (1st and 2nd regions) after the random excitation was turned off.

As instant vibration velocity ($V_{vib}^3$) increases, actual chip thickness varies. Consequently, excited grinding processes generate chips with more diverse thickness (with increased maximum value) and this variation has an important role in the tangential force per grain. The wheel performs like a tool with lower grain density.

Obviously the increased chip thickness will influence the wheel wear. The influence of vibration velocity in the wheel wear is shown in Fig. 6. The fitting curve of Fig. 6 has a similar behavior to that found in Fig. 2 besides its dynamic nature. The $G$ ratio values are now much lower than in the previous tests where the workpiece was supported by the tail stock. Assuming the $V_{vib}^3$ values as additional instant feed speed, the tangential force per grain will be closely related to vibration velocity. Thus, high vibration velocity values present in the process will generate high wheel wear rates.

4. Chatter formation mechanism

Fig. 7 shows the occurrence of chatter during an experiment with sinusoidal excitation (excitation frequency close to wheel rotational speed). This condition frequently resulted in grinding chatter. This test was repeated 5 times with the same result: intense chatter.

This was a good opportunity to use the AE mapping system to observe how lobes are formed around the grinding wheel. This chatter mechanism is classified as wheel regeneration [5,6].

Fig. 4. Roundness, roughness and power versus instant velocity of vibration.

Fig. 5. Acoustic map and power.

Fig. 6. $G$ ratio versus instant velocity of vibration.

Fig. 7. Acoustic map with chatter.
For the case studied (low stiffness part and DTG materials) the lobes produced on the wheel surface did not progress slowly and were not all around the circumference as previously mentioned. They start in one point on the wheel and get progressively distributed around its surface in few seconds. The cycle has to be interrupted before the lobes reach the whole wheel surface. When the cycle is not interrupted an accident may happen, usually wheel breakage.

This chatter mechanism also happened when other frequencies were used for excitation (such as the natural frequencies of the system). The dominant frequency of the chatter is equal to one of the first natural frequencies of the system, even when the excitation frequency is much lower, such as shown in Fig. 7. The chatter always starts in a position where there is a high AE value. Wheel loading was observed in these positions. Also the chatter fills the dark areas of the map, where the wheel is not touching the part and the valve head is free to vibrate, meaning that forced vibrations can accelerate the occurrence of chatter.

Fig. 8 presents the wheel topography after chatter formation. This picture was built by superposing AE maps built in several consecutive dressing passes. At each dressing stroke the AE amplitude was converted to the $d_0$ value so the topography could be presented in microns. The lobes reached the whole wheel surface in this case. The chatter intensity was so high that the wheel wear level reached values of 200 microns in few seconds, meaning $G$ ratios were much lower than one.

5. Summary

The paper describes the influences of vibration in the grinding quantities for a specific case of low stiffness parts of DTG materials. The results show that induced random vibration (such as white noise) influences the wheel action reducing the grinding power and increasing wheel wear. The chatter tests show the phenomenon where intense chatter quickly progresses around the wheel surface from a starting point.

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