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An Experimental Study on the Dynamic Behavior of Grinding Wheels in High Efficiency Deep Grinding

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Abstract

The design and material of the grinding wheel hub determine its static and dynamic behaviors which, in turn, play significant roles in grinding performance. This can be of special interest in high efficiency deep grinding (HEDG) process, in which the wheel is subjected to extremely high centrifugal and grinding forces. On the other hand, controlling the dynamic behavior of the grinding wheel through an in-process monitoring and a post-process measurement seems an appropriate approach to optimize the grinding process. This paper addresses the effects of the Carbon fiber-reinforced polymer (CFRP) hub body on the grinding process efficiency through comparing the results of the experiments carried out by two CBN vitrified bonded wheels with different hub materials, CFRP and steel. The experiments were conducted using a new in-process measurement system. It was proved that the dynamic behavior of grinding wheels can affect the chip removal mechanism, and in turn, influences the finished surface roughness. Furthermore, using the CFRP as the hub material leads to a reduction in the wheel radial expansion during the operation and grinding forces. High amplitudes and frequencies have been measured when using the steel grinding wheel, while they can be damped by employing CFRP hub material.

Keywords: HEDG, In-Process Monitoring, CFRP, grinding wheel hub, dynamic behavior;

1. Introduction

An efficient grinding process, especially HEDG and creep feed grinding processes; can only be operational if using a high performance grinding machine with a proper grinding wheel and an adequate coolant lubricant supply system [1]. Regarding the considerably high centrifugal force and the process forces loaded on the grinding wheel at one time in the HEDG, the grinding wheel dynamic behavior plays a decisive role in this process [1, 2]. Besides, in the HEDG process due to the high wheel and workpiece speeds, relatively high elastic deformation of the grinding wheel takes place. The elastic deformation of the grinding wheel that is influenced by the contact stiffness affects the material removal mechanism and induces machining errors. The contact stiffness of the grinding wheel is defined as the relationship between the normal compressive force, \( F_n \) applied to the wheel at the contact zone and the elastic radial deformation of the wheel, \( \delta \). This is affected, amongst others, by grinding operation, grinding parameters and grinding wheel specifications such as stiffness characteristics of the wheel [3-7].

Another significant property of a grinding wheel is its damping characteristics that influence vibration between the wheel and workpiece in contact zone and consequently the workpiece surface roughness and waviness [3, 5]. On the other hand, the instability in the system creates a regular variation in the depth of cut and therefore grinding forces which, in turn, result in a non-uniform wear of the wheel [3].

The HEDG process is generally conducted using CBN or Diamond superabrasives. A superabrasive wheel consists of a hub body coated by a superabrasive layer. The design and material of the hub body determine the static and dynamic behaviors of the grinding wheel.
Currently, various materials are used for hub body of superabrasive wheel. Basic requirements for the material of a hub body are: high thermal conductivity, high mechanical strength, and good vibration damping. Common materials for hubs of superabrasive wheels are:

- aluminum,
- steel,
- synthetic resin with metallic/non-metallic fillers,
- ceramics, and
- composites.

The choice of the hub material is based on the operational area of the grinding wheel. In the high speed and high performance deep grinding, in fact, only steel and aluminum bodies are used. These metallic bodies are characterized by high strength. By construction of a hub body without a center hole and as a body with an approximately constant stress over the cross section of the hub body, theoretically, a peripheral speed of 500 m/s may be achieved. The highest practically realized peripheral speed is 280 m/s. Since the ratio of elastic modulus to density for steel and aluminum as a function of their compositions differs only minimally, strain levels are nearly identical at any given rotational speed [8].

Another material for the manufacture of high performance grinding wheels is Carbon fiber-reinforced polymer (CFRP). CFRP materials are distinguished by their extremely high strength and rigidity, and very high strength-to-weight ratio. Changing the hub material from steel to CFRP reduces wheel expansion by a factor of 3. CFRP hubs with lower CF (carbon fiber) content are available for lower wheel speeds that offer purely weight benefits. Due to its low density, up to 90% less weight, CFRP could provide some additional damping, although the reduced weight of grinding wheel hub increased significantly the natural frequency of the wheel [3, 9].

So far the influence of the hub material on the grinding process, especially the behavior of CFRP, has been rarely investigated. For instance, Muckli investigated the performance of aluminum and steel grinding wheel hub by high cutting speed of 305 m/s using finite element method. His analysis results showed that both the geometry and the material of the body affect the stresses on the vitrified bonded CBN layer of the wheel. It was also shown that the steel body is subjected to a smaller expansion, but higher stresses [10].

Warnecke et al. have also compared the performance of two different grinding wheel hubs, namely synthetic resin aluminum composite and rigid aluminum hub. The experimental results showed that the soft synthetic resin aluminum composite hub was significantly deformed whereas the rigid aluminum wheel body strongly supports the bond. Furthermore, grinding forces and material removal mechanism are affected by grinding wheel hub elasticity and cutting speed [4].

In this work, two CBN grinding wheels with different hub materials, namely CFRP and steel, were employed in high efficiency deep grinding of the hardened steel materials in order to show how the CFRP hub material may influence on the grinding process. The results focus on the wheel vibration and deformation, the grinding forces and ground surface quality.

2. Experimental setup

2.1. New developed measurement system

As above mentioned, the grinding results are strongly influenced by the wheels hub static and dynamic behaviors. For a proper investigation and analysis of the hub material influence on the grinding process, the vibration propagation in the hub body during grinding should be detected.

For this purpose, a new vibration measurement system was developed and used for in-process monitoring. The system consists of three AE sensors integrated in the hub in different radial positions with 120° angular difference to each other (Fig. 1). The detected signals are transmitted to an evaluation unit (AE6000 of Dittel Messtechnik GmbH) via a non-contact data transmission system. This system consists of a data transmitter ring mounted on the wheel body and a receiver ring mounted in front of the wheel with a small distance, as shown in Fig. 1.

Fig. 1. Illustration of the integrated vibration measuring system: (a) integrated sensor, (b) steel wheel with integrated sensors, (c) CFRP wheel with integrated sensors, d) non-contact data transmission system

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Fig. 1(d). Afterwards, the signals are transmitted through a spectrum analyzer (Type 4424) to a personal computer (PC). This system allows the detection of the wheel vibration amplitudes and frequencies in different location of the wheel body during grinding.

2.2. Experimental parameters

In order to evaluate the influence of the hub material on the grinding process, a series of tests were carried out using two vitrified bonded CBN wheels with the same geometries and CBN layer specifications but different hub materials. The tests conditions are detailed in Table 1. The mechanical properties of the wheel hub materials are listed in Table 2. The experiments were equipped by the following machines and devices:
- Machine tool: Elb Micro-Cut AC8 CNC universal surface grinding machine
- Surface roughness and profile tester: Hommel-Werke model T-8000
- Dynamometer: Kistler piezoelectric dynamometer model 9255B

The experiments have been carried out with high grinding wheel speeds and feed rates, i.e. in HEDG working area.

<table>
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<tr>
<th>Table 1: Grinding and dressing parameters</th>
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<td>Grinding process</td>
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<td>Grinding parameters</td>
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<th>Table 2: Properties of the used grinding wheels hub materials [11, 12]</th>
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<td>Core Material</td>
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<td>CFRP</td>
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<td>Steel</td>
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3. Analysis of the results

In grinding process, especially in HEDG and creep-feed grinding, the aggressive depth of cuts can result in a considerable wheel loading. This phenomenon occurs when the swarf do not get completely washed away with the supplied coolant lubricant. The use of high pressure cleaning jets, directed towards the wheel surface, prevents grinding wheel from loading with workpiece material. Furthermore it breaks the air barrier. For this purpose a flowrate of 0.3 liter/min at a pressure up to 80 bar has been suggested. The effectiveness of these measures depends more on the fluid pressure than on the volume flow. This can affect the dynamic behavior of the grinding wheel, which has been already investigated in the present study.

For this purpose, the dynamic behavior of both grinding wheels under similar conditions using high pressure cleaning nozzle has been measured. The experimental results suggest that the grinding wheels can be vibrated by the high pressure cleaning jet, as expected (Fig. 2). This is approved by the comparison between the signals of CFRP with and without cleaning nozzle in figure 2. As shown in this figure, the grinding wheel with steel hub material has considerably higher amplitudes comparing to the CFRP grinding wheel. It demonstrates that the generated vibration in grinding wheel can be clearly damped using the CFRP hub material.

![Fig. 2. Influence of the high pressure cleaning nozzle on the grinding wheel dynamic behavior with CFRP and Steel hub material](image_url)

An exact description of the impact of coolant lubricant, cleaning jet and their flow rate and pressure on the grinding wheels dynamic behaviour needs further investigations, which are currently being conducted at KSF.

In addition, the effect of this dynamic behaviour on grinding process has been investigated. Fig. 3 presents the maximum measured amplitudes on the wheel which was detected by sensor 1 (Fig. 1) for both wheels at the same grinding conditions.

It can be seen that the higher damping of CFRP leads to a significant reduction in the hub vibration amplitudes.
Besides, the amplitude spectrum of the steel wheel with a wider frequency band is due to the lower damping of the steel in comparison with CFRP.

The hub material influences also on the contact stiffness of the grinding wheel, as well as its radial expansion caused by centrifugal forces. Hence, the geometry of the grinding contact zone is affected by the hub material which could be approved with the following test. First, four slots were ground with a constant depth of cut of 0.1 mm, a cutting speed of 15 m/s, and a feed rate of 50 mm/min. Two outer slots, namely slots 1 and 4, were used as references by measuring the depth of other slots. The second slot was ground in only one pass with a depth of cut of 0.5 mm, the cutting speed of 120 m/s and the feed rate of 500 mm/min. The third slot was primarily ground like the second one. Subsequently it was ground 10 passes without other extra infeed to spark out. So, the depth of the third slot can be used for finding the wheel expansion and depth of the second slot for calculating the grinding contact stiffness of the wheel.

In fact, the radial expansion of a wheel can be decreased significantly by using materials like CFRP which possess high value of E/\( \rho \) ratio [11, 12].

The comparison of the slot depths before and after spark out for both wheels presents a higher difference for CFRP wheel. This shows a lower contact stiffness of this wheel as a result of the lower E-module of CFRP.

The grinding wheel expansion \( \Delta D \) increases quadratically with the wheel speed \( v_c \). Furthermore, it depends on elastic modulus, \( E \), and on the \( E/\rho \), as mentioned. The grinding wheel expansion can be theoretically calculated using equation (1) [12].

\[
\Delta D = \frac{\rho v_c^2}{E D A} \left[ (3 + \nu) \cdot H^2 + (1 - \nu) \cdot D^2 \right]
\]

For both CFRP and Steel grinding wheels, the increase of the external diameter of the wheels was calculated. Fig. 5 shows the comparison between calculated and measured radial expansion of the wheels. It can be seen that in spite of the values difference, both measured and calculated results show the same tendency. Based on these results the higher damping effect of the CFRP grinding wheel is proved.

The measured ground surface roughness and normal grinding forces are shown respectively in Figs. 6 and 7 versus the feed rate, \( v_{nf} \), at two different depths of cut. It is obvious that an increase of the feed rate from 500 mm/min to 6000 mm/min leads to a rougher surface roughness. This is due to the larger chip thickness which occurs by higher feed rates. Furthermore, Fig. 6 shows that a finer surface roughness could be also achieved when using the steel grinding wheel. On the other hand, Fig. 7 shows a significant reduction in normal grinding force when using CFRP grinding wheel.
The finer surface roughness generated by the steel grinding wheel, despite the same grinding conditions for both wheels, can only be explained if the chip formation mechanism is declared. For this purpose the finished surfaces by both grinding wheels were photographed using confocal microscope (NanoFocus, model: µsurf). In Fig. 8, it can be clearly seen that two different surface structures have been created by two different chip formation mechanisms. There are numerous visible grinding grooves on the surface ground by the CFRP grinding wheel, while a crater-like structure is seen on the surface ground by the steel grinding wheel.

The crater-like surface can be attributed to the high frequency vibration generated in the grinding wheel with the steel hub material that leads to a brittle material removal [4].
As well known, in ultrasonic assisted grinding a combination of brittle and ductile chip formation mechanism can occurs, no matter if it is generated by an external source or by the vibration in the grinding wheel body. For this reason, the pulse-like grit engagements (chisel-effect) can be assumed as an ultrasonic assisted grinding, which its source is the radial vibration in the grinding wheel. This vibration affects the chip formation mechanism, which in turn generates different surface structures [4, 12-17].

It should be noted that the steel grinding wheel has a larger radial expansion, comparing to the CFRP grinding wheel (Fig. 4). It means that the fine surface with closed tolerance may deteriorate by using the steel grinding wheel if the precision machining is desired.

4. Conclusion

The main results obtained in this study are summarized as follows:

- In the grinding process the static and dynamic behaviors of a grinding wheel hub has a decisive influence on grinding process especially in high efficiency deep grinding.
- It could be experimentally shown that the contact stiffness of the CFRP wheel is significantly lower than that of the steel wheel. This is due to the lower modulus of elasticity of CFRP. However, higher values of E/ρ ratios of CFRP lead to a lower radial expansion of the CFRP wheels during operation. In addition, the higher damping property of CFRP results in a reduction in grinding forces.
- Besides, the chip formation mechanism can be affected by dynamic behavior of the grinding wheels. Using the steel grinding wheel hub material leads to generation of a crater-like finished surface. This can be attributed to its high vibration frequency and amplitude during grinding process.

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