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Structural design of a carbon fiber-reinforced polymer wheel for ultra-high speed grinding

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ABSTRACT

Ultra-high speed grinding (UHSG) is receiving considerable attention owing to its ability to achieve high machining accuracy and productivity. The materials and design of the grinding wheels play a significant role in this technology. Wheels with steel bodies are currently widely used, but have deficiencies such as a large mass loading imposing on the spindle, along with high power consumption, large stress and deformation, and limited practical grinding wheel speed. Wheel bodies made of carbon fiber-reinforced polymer (CFRP) show promise for use in UHSG because of the low density and high specific strength of this material. The main aim of this paper is to carry out a structural design of a CFRP grinding wheel for UHSG. Comparisons of stress and deformation, dynamic characteristics, thermal deformation, and power consumption between steel and CFRP wheel bodies reveal the superior performance characteristics of CFRP. The design of the laminate structure of the CFRP is then optimized, considering various laminate processes. The abrasive layers are designed with regard to the number and thickness of segments. Finally, a CFRP wheel for UHSG is developed based on the design proposal.

1. Introduction

Rapid advances in various areas of science and technology have resulted in increased innovation in the field of production engineering. This has led to a growing challenge to satisfy industrial demand for improved productivity while simultaneously achieving high workpiece quality. In particular, novel materials with high hardness, good functional characteristics, high-temperature strength, high-temperature resistance, and corrosion resistance are receiving considerable attention in fields such as aeronautics, astronautics, marine engineering, and the petrochemical industry. However, most of these materials are hard to cut owing to their high comprehensive intrinsic properties [1–3]. New technologies such as ultra-high speed grinding (UHSG), which employs pendulum grinding with increased table and grinding wheel speeds, represent a promising and competitive method for improving both productivity and surface quality [4–6]. UHSG technology is especially appropriate for grinding hard-to-cut materials. This is due to the significant decrease in grinding force, grinding wheel wear, and grinding power during the machining process [7]. In addition, UHSG exhibits improved performance compared with conventional grinding with regard to technical requirements and the grinding mechanism [8].

In the UHSG process, considerably higher centrifugal and process forces are exerted on the grinding wheel. Meanwhile, the diameter of the wheel expands exponentially as a function of the wheel's rotational speed. This results in an expansion in wheel diameter that is significantly higher than that in conventional grinding. Because of this, grinding wheel dynamic behavior plays a crucial and decisive role in UHSG.

The damping characteristics of the grinding wheel are also significant, since they affect vibration occurring between the wheel and workpiece in the contact zone. Changes in damping characteristics can influence cutting thickness, which can alter form accuracy and surface quality [9]. In addition, parameters such as fracture and wear resistance, high rigidity, and good thermal conductivity are desirable for UHSG tools.

Steel-bodied grinding wheels with CBN (cubic boron nitride) abrasives have achieved long-term and wide applications in UHSG because of their high rigidity and the maturity of the associated technology. However, both experience in large-scale industrial production and the results of research studies have revealed several disadvantages in the use of steel-bodied grinding wheels. For example, because of the large mass of such wheels, installation and disassembly are often tedious procedures, and this has a serious effect on process efficiency. In addition, the higher mass increases the load on the main shaft, which leads to severe heating and abrasion damage on the main shaft bearings, thereby reducing the service life of the main shaft. The inner stress, radial deformation, and vibration amplitude of the grinding wheel also increase dramatically with increasing grinding speed. This is especially seen at ultra-high grinding speeds of 150 m/s or more. As a result, the safety of the grinding wheel and the machining accuracy of workpieces are seriously compromised. Moreover, the power consumption of the grinding wheel spindle system significantly increases with increasing wheel speed. Most of this is wasted power and is due to the kinetic energy of

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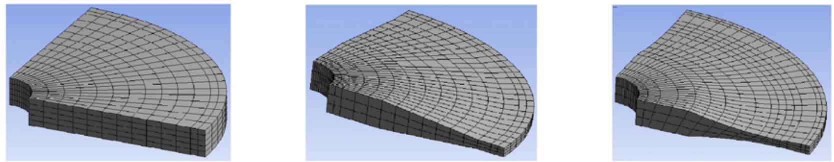

(a) Plain cross-section (b) Tapered cross-section (c) Curved cross-section

Fig. 1. Finite element models of three cross-sectional shaped bodies. (a) Plain cross-section. (b) Tapered cross-section. (c) Curved cross-section.

the grinding wheel, which increases linearly with increasing mass of the wheel. Thus, the common use of grinding wheels with steel bodies results in a considerable waste of power. For these grinding wheels, the maximum speed that can be reached is 280 m/s. This limit on speed is related to the lower yield strength of the steel material [10]. All these problems restrict the widespread application of UHSG technology for machining applications.

Recently, progress has been made in fabrication processes for grinding wheels using carbon fiber-reinforced polymer (CFRP) materials. These have excellent performance characteristics, such as low density, improved design, and easy-forming characteristics, along with superior mechanical properties compared with traditional mechanical construction materials such as aluminum and steel [11]. Ohshita [12–15] implemented multiple design schemes for super-abrasive grinding wheels using CFRP bodies and analyzed significant properties of the wheel to improve cost efficiency. Asen [16] designed an internally cooled grinding wheel based on CFRP material and used it for high-speed grinding followed by a performance analysis. CFRP grinding wheels have obvious advantages such as good designability and easy-forming characteristics that favor their development as high-performance grinding wheels. However, despite extensive discussion in the patent literature, there has been a lack of experimental verification of the proposed methods, and subsequent grinding applications have rarely been reported in the literature.

Ohshita and Ogura [17] developed a new vitrified bonded fiber-winded CFRP (FW-CFRP) grinding wheel with speeds reaching up to 200 m/s. Experimental results demonstrated the application potential of such a grinding wheel. Increases were shown in the grinding amount and grinding efficiency. However, the grinding mechanism using CFRP grinding wheels is not clearly understood. Moreover, experiments to verify these results are still lacking. Tawakoli and Vesali [18] combined experiments with finite element simulation to study the static and dynamic characteristics of a vitrified bonded CBN grinding wheel with a CFRP body and their influence on the grinding of quenched steel. However, their vibration study did not take full account of the influence of the degree of accuracy on measurements of dynamic balance when comparing grinding wheels made of steel and CFRP respectively. Their analysis of results for the eccentric installation clearance and the dynamic balancing technology used during the grinding process was relatively superficial. Some industrial research [19–21] on the development of CFRP grinding wheels has been reported along with practical applications. However, there have been few reports of systematic research and analysis to illustrate the advantages of CFRP grinding wheels.

Another factor to be considered is that the maximum grinding speed of current CFRP grinding wheels is only 200 m/s, which has further limited research on their use in UHSG technology.

In order to investigate and clarify the chip formation mechanism in UHSG of hard-to-cut materials such as titanium and superalloys, a novel supersonic grinding machine tool has been developed by our research group [22]. Experiments showed that it was difficult to exceed a grinding speed of 300 m/s when using a wheel with a metal body. This limitation was due to the high vibration and restricted power of the wheel spindle. Therefore, the use of CFRP has been proposed as a prerequisite for developing a high-performance UHSG wheel.

Based on the above considerations, this study focuses on the structural design of a high-performance CFRP grinding wheel for UHSG, especially for grinding at speeds up to 400 m/s. Using computer-aided design (CAD), the shape and material of the grinding wheel body are optimized by minimizing stress and deformation, while improving dynamic characteristics and thermal performance. Based on the CAD results, the focus is on a laminate process for the wheel body, using CFRP. Furthermore, a comparative study of the discontinuous abrasive layer, along with the number and thickness of abrasive segments, is carried out to determine the abrasive layer parameters. This allows the structural design of a CFRP grinding wheel for use at speeds up to 400 m/s based on an optimized design proposal.

2. Design and material of grinding wheel body

The body of a high-performance grinding wheel plays a significant role in determining the capabilities of the wheel. Thus, the design and choice of material of the wheel should be primarily focused on the body. In this section, the design of the wheel body is analyzed in terms of stress and deformation. The aim is to further clarify the influence of different wheel body shapes on wheel capability and to determine the optimal shape of the wheel body. Three materials, namely, steel, aluminum, and CFRP, are compared with regard to stress and deformation, dynamic characteristics, thermal deformation, and power consumption. Finally, with specific reference to a CFRP grinding wheel body with a plain cross-sectional shape, the lamination process of the CFRP is optimized by analyzing the stress, deformation, and dynamic performance of the wheel body.

2.1. Design of wheel body

The cross-sectional shape of the grinding wheel body has a significant influence on stress and deformation due to centrifugal loading. Taking frequently used body shapes as examples, three shaped cross-sections with the same diameter and thickness at the bore and the same outer diameter were modeled and meshed (Fig. 1). The dimensions of the grinding wheel body were Φ240 mm × 15 mm × Φ40 mm and it was made of 45# steel. The wheel body can be regarded as a thin-walled component, so the

Table 1
Properties of the three materials used [10].

Material	Density (kg/m^3)	Elastic modulus (GPa)	Poisson's ratio	Thermal conductivity (W/(m·K))	Thermal expansion coefficient (10^{-6}/K)
Steel	7850	200	0.27	45	12
Aluminum	2752	70	0.33	204	20
CFRP	1500	189	0.3	20	0.2