Study On The Cutting Performance of High-Speed Machining Zr-Based Bulk Metallic Glass

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Abstract

The cutting performance of high-speed machining (100-350 m/min) Zr₅₇Cu₂₀Al₁₀Ni₈Ti₅ (at.%) bulk metallic glass (Zr57 BMG) was studied, as compared with industrial pure zirconium (Zr702). The effect of cutting speed on cutting force, surface roughness, surface morphology and chip morphology was analyzed. Although the strength of Zr57 BMG is much higher than that of Zr702, the difference in main cutting force is small, which can be attributed to the thermal softening of Zr57 BMG material during machining. The machined surface characteristics and the formation of chips were investigated. Different from low-speed machining, the groove marks and adhesions on machined surface evolve into wave patterns and molten droplets with the cutting speed increasing from 100 m/min to 350 m/min. The appearance of wave patterns tends to destroy the machined surfaces, and the worst quality was obtained at the speed of 250 m/min. The free surface morphology of the chips, with cutting speed smaller than 150 m/min, show obvious serration and molten droplets between shear bands. With the increase of cutting speed, oxidation on the chip surfaces occurred, and the chip surface was gradually covered by powder particles due to the melting of Zr57 BMG workpiece materials. The machined surfaces of Zr57 BMG maintain amorphous structures after high-speed machining, which shows excellent application potential for the processing of Zr57 BMG.

Introduction

Significantly different from traditional alloys, bulk metallic glasses (BMGs) are a new kind of metallic materials, which have unique mechanical and physical properties and a wide range of application prospects [1]. Machining has been used extensively for the machining of metals and alloys in industry, where the cutting performance and mechanisms were also studied for the structural applications of new class of alloys [2–5]. The machining of BMGs therefore attracted a great deal of research attention [6]. For example, Bakkal M. et al. studied the cutting performance of Zr-based BMG by turning, drilling, milling and grinding [7–10]. The results showed that excellent dimensional accuracy and surface quality can be obtained with conventional machining processes. Fujita et al. [11] also found that BMGs have excellent machinability due to the absence of built-up edges (BUG) during machining. Bakkal et al. [12] found that the chip crystallization behavior was intensified with the increasing of cutting speed. The chip crystallization was followed with light emission during machining. However, different from chip crystallization, no crystallization occurred on the machined surface of BMG at different cutting speeds. It also indicated that the machining processing of BMG was feasible. Then the influence of cutting temperature on the generation and propagation of shear band was studied [13]. The results showed that the thermal instability of the shear band was the main reason for the plastic deformation behavior of BMG. The BMG can exhibit excellent plastic deformation performance during machining.

However, due to the necessities to achieve rapid cooling rate to form glassy atomic structures, BMGs are known to have limited sample dimensions, and the studies of BMG machining mainly focused on low-speed and micro machining. Micro grinding of Zr-based BMG was conducted by Gong et al. [14]. The results showed that the material removal mode of Zr-based BMG was plastic and brittle with CBN

abrasive micro grinding wheel, and the material removal mode was brittle with the diamond abrasive micro grinding wheel. At the same time, the grinding temperature was simulated and the maximum value was 288 °C within the range of experimental parameters. Chen et al. [15] studied the cutting performance of a $\text{Zr}_{55}\text{Cu}_{30}\text{Al}_{10}\text{Ni}_5$ (at.%) BMG with ultra-precision cutting, and found that BMG showed excellent plasticity during the cutting process. The best surface roughness can reach 100 nm, and a mirror surface cannot be obtained because of the viscous flow during the machining. Zhu et al [16] studied the nano cutting process of a $\text{Cu}_{50}\text{Zr}_{50}$ (at.%) BMG with molecular dynamics simulation, and found that the material removal mechanism of BMG was mainly based on nanoscale extrusion instead of macroscale shear deformation.

Previous studies on micro turning of BMG also revealed that the variation of cutting speed had little effect on cutting force at low liner velocity [17]. At the speed of 1.52m/s, the extremely high temperature during the machining will induce the oxidation of BMG chips accompanied with light emission. On the contrary, no chip oxidation and light emission occurred when cutting speed decreased to 0.38m/s [18]. Because of the low thermal conductivity of BMG [19], the generated cutting heat was difficult to be transferred, which would lead to the temperature rise in the cutting zone. Besides, serrated chips are typical features during the cutting of BMG. Jiang et al [20] recognized that the formation of serrated chips was mainly due to the repeated shear band formation in the primary shear zone (PSZ). Maroju et al [21] found that the inhomogeneous deformation of BMG chips was mainly influenced by the cutting temperature and free volume. Dhale et al [22] found that with the increase of cutting speed, the individual serrated region of chips will gradually form cracks due to the propagation of shear bands.

In recent years, although many studies were carried out on the machining of BMG, and fruitful achievements were made, the studies on the cutting performance of BMGs at speed larger than 150 m/min have rarely been reported under regular cutting condition due to the sample size limitation. A higher cutting speed will produce a higher cutting temperature during the machining, which will have a significant impact on the cutting force, chip morphology and surface quality. The deformation characteristics and amorphous structure of BMG at high-speed machining should also be different from low-speed machining. In this work, high-speed turning of a Zr-based BMG was conducted, with cutting speed ranging from 100 m/min to 350 m/min. The cutting force, surface morphology and chip deformation during the high-speed machining of BMG were examined and discussed, giving more insight into the high-speed machining performance of BMGs.

Methodology

$\text{Zr}_{57}\text{Cu}_{20}\text{Al}_{10}\text{Ni}_8\text{Ti}_5$ (at.%) BMG (noted as Zr57 BMG) was used as the workpiece material for high-speed machining. The as-cast BMG rods with sizes of 90 mm × Φ5 mm were produced by suction casting. Industrial pure Zr (Zr702) rods with same sample dimensions were used for comparison. The mechanical and physical properties of two workpiece materials are presented in Table 1.

Table 1
Mechanical properties of two kinds of workpiece materials

Materials	Yield strength (MPa)	Elastic modulus (GPa)	Thermal conductivity (W/m·K)	Hardness (HV _{0.5})	Melting point (°C)
Zr57 BMG	1635	82.0	7.1	537.7	822
Zr702	205	99	22	189.9	1852

The turning process was carried out on a CA6140 lathe with maximum spindle speed of 1440 r/min. The lathe was equipped with a three-dimensional dynamometer Kistler 9257B and a frequency converter (3G3RV-A4075-ZV). The axial force F_x , radial force F_y and main force F_z were recorded by the dynamometer. In order to achieve high-speed machining of BMGs with limited sample diameters, a special fixture device was designed, as shown in Fig. 1. The fixture was a 45-steel bar with a diameter of 90 mm. Three arc slots of 5 mm diameter were machined on the end face of the bar. A cover plate and bolt were then used to fix the workpiece material rods in the arc slots along the axis direction. High-speed machining of BMG was realized by means of intermittent turning, and the maximum cutting speed can reach 350 m/min, which was only 150 m/min in previous researches [11]. The experimental setup as well as the use of fixture device is shown in Fig. 1. During the intermittent turning of BMGs, the actual cutting distance of BMG specimen was short and the corresponding machining time was also short. In order to ensure that there were enough sampling points, the sampling frequency of the dynamometer was set as 5000 Hz.

During the cutting process, the cutting parameters used in this research were 100 m/min to 350m/min for cutting speed v , 0.2mm for cutting depth a_p , and 0.08mm/r for feed rate f , respectively. Cemented carbide inserts (YBG302 with TiAlN coated) were used for the high-speed machining, and the cutting condition was dry cutting. The geometric parameters of the cemented carbide inserts are showed in Table 2. The surface roughness of the machined surface was examined with the JH-340 roughness measuring device. The surface morphology and chip morphology were inspected using scanning electron microscopy (SEM) and energy dispersive spectrometer (EDS) on an SU8020 field emission scanning electron microscope. The machined surfaces were inspected using standard X-ray diffraction (XRD) analysis to study the possible change of amorphous microstructures.

Table 2
Geometric parameters of the cemented carbide inserts

Rake angle γ_0	Clearance angle α_0	Major cutting edge angle κ_r	Inclination angle λ_s	Corner radius r_ϵ	Coating
0°	0°	91°	0°	0.8mm	TiAlN

Results And Discussion

3.1 Cutting force

The cutting forces of machining Zr57 BMG and Zr702 are shown in Fig. 2. It shows that the cutting forces of F_x , F_y and F_z increased with the cutting speed ranging from 100 m/min to 350 m/min. For the machining of Zr57 BMG, radial force F_y was larger than F_x and F_z . Significantly different from the machining of Zr57 BMG, the main cutting force F_z was the largest one for Zr702. The extremely high yield strength and hardness of Zr57 BMG could be the main reason for the high radial force. Besides, the absence of corner radius of 0.8 mm obviously reduced the actual major cutting edge angle, which would also result in the increase of radial force F_y . However, the difference between the main cutting force (F_z) of Zr57 BMG and Zr702 was small. The cutting temperature of Zr57 BMG would be high because of its low thermal conductivity. Then it can cause the thermal softening effect during machining and the decrease of main cutting force F_z to some extent.

3.2 Surface roughness and morphology

The surface roughness of Zr57 BMG and Zr702 on machined surfaces is presented in Fig. 3. With the cutting speed ranging from 100 to 350 m/min, surface roughness of Zr 702 decreased gradually from 3.6 to 1.5 μm . For Zr57 BMG, the surface roughness first increased and then decreased, and it reached the highest value of 2.4 μm at the speed of 250 m/min. The surface quality of Zr57 BMG was better than that of Zr 702 when the cutting speed was smaller than 250 m/min. When the speed was larger than 250 m/min, the difference of surface roughness between Zr57 BMG and Zr702 was reduced.

In order to further study the variation trend of the surface roughness of Zr57 BMG, the machined surface morphology is presented in Fig. 4. Generally, the surface morphology can reflect the characteristics of material deformation process [23]. Groove marks along the cutting direction of the insert and adhesions were observed on the machined surface when the cutting speed was less than 150 m/min (Fig. 4(a,b)). Here, the appearance of groove marks was mainly due to the combination effect of extrusion stress on tool-workpiece interface and cutting temperature, which would cause the plastic deformation of the material. The adhesions on the machined surface was mainly caused by the debris of workpiece material during machining. It indicates that the machined surface of Zr57 BMG shows certain plasticity and viscosity, and finally generates groove marks and adhesions when the speed is less than 150 m/min.

With the cutting speed increasing to 200 m/min (Fig. 4c), the groove marks and adhesions on machined surface began to gradually disappear, and were replaced by wave patterns and molten droplets. Here, the cutting temperature increases with the increase of speed. When the temperature on the machined surface increases to the glass-transition temperature (T_g), the material will undergo thermal softening, show excellent liquidity and poor viscosity. The excellent liquidity and poor viscosity could be the main reason for the disappearance of groove marks and adhesions, and the appearance of wave patterns and molten droplets. When the cutting speed increased to more than 200 m/min, the wave patterns and molten droplets were more obvious, as shown in Fig. 5. The wave patterns were formed due to the liquid flow of melted workpiece material under the combined action of extrusion stress and temperature. At the

speed of 250 m/min (Fig. 5a), the flow of wave patterns was irregular, which may be due to that the cutting temperature and liquidity of melted material was not high enough. When the cutting speed increased to 300 (Fig. 5b) and 350 m/min (Fig. 5c), the flow of wave patterns became more and more regular. This could be attributed to the liquidity increases of the Zr57 BMG material with the increase of cutting temperature. It was also found that the molten droplets were always concentrated near the wave patterns. The scale of molten droplets increased with the increase of cutting speed, and it could evolve to wave patterns when the local temperature and stress was high enough. When the cutting speed increased to 350 m/min, the number of molten droplets decreased, but the sizes increased. The machined surfaces of Zr702 at the cutting speeds of 100 and 350 m/min were also shown in Fig. 6. Similar to Zr57 BMG, groove marks and adhesions were found on machined surfaces at relatively low cutting speed. However, when the speed increased to 350 m/min, different from that of Zr57 BMG, the adhesions began to disappear, but groove marks were still observed. No wave patterns and molten droplets occurred on the machined surfaces, as shown in Fig. 6b. This phenomenon may result from the high thermal conductivity and melting point of Zr702 material.

For Zr57 BMG, temperature plays an important role for the forming of machined surface morphology. With the increase of cutting speed, the surface morphology showed certain plasticity and viscosity firstly, and then showed excellent liquidity and poor viscosity. The morphology of groove marks and adhesions also evolved to wave patterns and molten droplets. The surface roughness reached the highest value of $2.4 \mu\text{m}$ at the speed of 250 m/min (Fig. 5a), at which irregular wave patterns started to form. As compared with the surface roughness results and morphology of machined surfaces, wave patterns affected on the surface roughness. The results showed that the appearance of wave patterns was more likely to destroy the surface quality, and it reached the poorest value when the wave patterns distribution was irregular at the cutting speed of 250 m/min. With the cutting speed increasing to 350 m/min, the distribution of wave patterns became regular, and the surface quality was also improved. Therefore, the variation of surface quality mainly depended on the material properties, such as plasticity, viscosity and liquidity, which would change with the rise of temperature.

Amorphous atomic structures make Zr57 BMG have excellent mechanical performance, while crystallization will destroy the amorphous structures and affect the material mechanical performance. During the high-speed machining Zr57 BMG, the extremely high temperature may cause the crystallization of material. In order to confirm whether crystallization occurs on the machined surfaces, the microstructure of Zr57 BMG at different cutting speeds was characterized using standard X-ray diffraction (XRD) analysis and compared with as-cast Zr57 BMG specimen, as shown in Fig. 7. There is a diffuse reflection peak at $2\theta = 38^\circ$, for both the as-cast and machined surfaces of Zr57 BMG at different cutting speeds. And no sharp crystalline peak for crystals was observed. It indicates that although wave patterns and molten droplets occurred on the machined surfaces, which were formed by a combined effect of extrusion stress and high temperature, there was no crystallization during the high-speed (100 m/min-350 m/min) machining of Zr57 BMG. Thus, despite with the generation of a large amount of heat during high-speed cutting, Zr57 BMGs can still maintain the amorphous atomic structures on machined surfaces, which shows excellent application potential for the processing of BMGs and BMG components.

3.3 Chip morphology

During machining, the formation of chips also affects the stability of cutting process. In order to study the chip morphology of Zr57 BMG at high-speed machining, SEM micrographs of chips were analyzed detailly, as shown in Fig. 8(a-e). Due to the low thermal conductivity of Zr57 BMG, light emission was likely to occur during machining. Similar to the chip morphology of low-speed machining Zr57 BMG, the free surface morphology of the chip with cutting speed smaller than 150 m/min showed obvious serration, as presented in Fig. 8(a,b). And molten droplets between shear bands were observed, which were formed by the melting of material on the surface of shear bands during the shear deformation process of chips. The appearance of molten droplets indicates that the temperature between two shear bands was close to the melting point of Zr57 BMG material during machining. With the cutting speed increasing from 250 to 350 m/min (Fig. 8(c-e)), powder particles began to appear on the serrated chip surfaces, and finally the surfaces were completely covered by powder particles. The chips still maintained the serrated shapes even when the speed increased to 250 m/min. When the cutting speed increased to 300 and 350 m/min, the chip shapes became irregular, and the chips were completely covered by powder particles. Here, the temperature rise was the main reason for the variation of chip morphology. The powder particles were the products of chip surface oxidation, and the degree of chip surface oxidation increased with the increase of cutting speed. Therefore, the chip surface was completely covered by powder particles when the speed increased to 350 m/min.

Different from Zr57 BMG, Zr702 is a traditional crystalline metal material, which has better plasticity and higher thermal conductivity. The SEM micrographs of Zr702 chips are presented in Fig. 9 (a-c). Serrated chips were also observed for Zr702, while the serrations were not obvious when compared with Zr57 BMG. This may be mainly due to that the plasticity of Zr702 is better than that of Zr57 BMG. Besides, no molten droplets were found on the chips because the thermal conductivity and melting point of Zr702 is higher than those of Zr57 BMG. Generally, Zr702 has higher thermal conductivity and the rise of temperature is smaller than that of Zr57 BMG. Therefore, differing from Zr702, oxidation occurs on the chip surface, which will be covered by powder particles for high-speed machining Zr57 BMG.

As a new kind of metallic materials, BMGs have unique mechanical and physical properties and a wide range of application prospects [24–26]. Although the strength of Zr57 BMG is high, the main cutting force is relatively small, as compared with conventional Zr702. The surface morphology of Zr57 BMG is obviously influenced by the temperature during machining, where groove marks and adhesions were formed initially and then evolved to wave patterns and molten droplets. The appearance of wave patterns tends to reduce the surface quality. Therefore, although high-speed machining Zr57 BMG is feasible, the cutting parameters should be optimized to improve the surface quality in future. Although a large amount of heat will be generated during high-speed cutting, the machined surfaces of Zr57 BMG specimen still maintains the pure amorphous atomic structures during high-speed machining (100–350 m/min). The present findings have shown that the high-speed machining can be used to process BMG and BMG components for widespread engineering applications [24]. Moreover, the high-speed machining can also be used to improve the machining efficiency of BMGs by not altering the material properties.

Conclusions

High-speed machining Zr57 BMG was carried out in this research. The effect of cutting speed on cutting force, surface roughness, surface morphology and chip morphology was investigated and discussed, and the conclusions are summarized as follows:

- (1) The extremely high yield strength and hardness of Zr57 BMG could be the main reason for the high radial force. However, although the strength of Zr57 BMG is much higher than that of conventional Zr702, the difference in main cutting force was small, which could be mainly attributed to the thermal softening of Zr57 BMG material during machining.
- (2) For Zr57 BMG, with the cutting speed increasing from 100 m/min to 350 m/min, the surface morphology showed certain plasticity and viscosity initially, and then showed excellent liquidity and poor viscosity. The machined surface morphology of groove marks and adhesions evolved to wave patterns and molten droplets with the increase of cutting speed.
- (3) The appearance of wave patterns tends to destroy the surface quality, and the worst value was obtained at the cutting speed of 250 m/min, where the wave patterns distribution was irregular. With the cutting speed increasing to 350 m/min, the distribution of wave patterns became regular and the surface quality was also improved. The machined surfaces of Zr57 BMG still maintain the amorphous structures after high-speed machining (100–350 m/min).
- (4) The free surface morphology of the chips, with cutting speed smaller than 150 m/min, showed obvious serration and molten droplets between shear bands. Different from Zr702, oxidation occurred on the chip surfaces, which was gradually covered by powder particles when the cutting speed increased from 250 m/min to 350 m/min.

Declarations

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Declarations of interest: The authors declare no conflict of interest.

Data Availability

The raw/processed data will be made available on request.

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Figures

Figure 1

The experimental setup and fixture device used in this research.

Figure 2

The cutting forces of machining Zr57 BMG and Zr702.

Figure 3

Surface roughness of Zr57 BMG and Zr702 at different cutting speeds.

Figure 4

Machined surface morphology of Zr57 BMG at the speed of (a) 100, (b) 150 and (c) 200 m/min.

Figure 5

Machined surface morphology of Zr57 BMG at the speed of (a) 250, (b) 300 and (c) 350 m/min.

Figure 6

Machined surface morphology of Zr702 at the speed of (a) 100 m/min and (b) 350 m/min.

Figure 7

XRD patterns of the machined surfaces of Zr57 BMG at different speeds.

Figure 8

SEM micrographs of the Zr57 BMG chips at different speeds.

Figure 9

SEM micrographs of the Zr702 chips at different speeds.