Cutting Characteristics of Bulk Metallic Glass

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The establishment of appropriate machining techniques for bulk metallic glasses (BMGs), which exhibit excellent mechanical, physical and chemical properties, is required to apply the BMGs. In this report, the cutting characteristics of BMGs were examined by turning with different tool materials, nose radii (Rn) and cutting speeds (V). Round bars of Zr₆₅Cu₁₅Ni₁₀Al₁₀ and Pd₄₀Cu₃₀Ni₁₀P₂₀ at% BMGs were used as the workpieces. In order to compare the cuttability of the BMGs with that of crystalline alloys, steel (JIS SGD-400D) and free-cutting brass (JIS C3604) were used. The principal cutting force (Fh) and surface roughness (Rn) of the machined surfaces were measured. X-ray diffraction patterns were also obtained from the machined surfaces. The value of Rn in the BMGs exhibit the upper end of precise finishing level (i.e., Rn = 0.2 μm), and was remarkably lower compared with the steel and a little lower compared with the free-cutting brass in spite of the value of V. The value became smaller with increasing values of Rn, exhibiting a very low value of 0.08 μm for an Rn value of 1.2 mm. The values of Fh in both BMGs did not show a clear difference and were half that of the steel for a V value less than 40 m/min, even though the tensile strength of the BMGs was twice as large as the steel. The chip of the BMGs showed an ideal flow type with very short and regular intervals, formed by planar slip, and revealed very homogeneous, flat and featureless back surfaces. From these observations of chips, it is presumed that the reason for the excellent cuttability of BMGs is due to a slipping-off mechanism at planes of very short intervals decided only by the maximum shear stress and non-built-up edges caused by a low glass transition temperature.

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1. Introduction

The establishment of suitable machining techniques is fundamental for application of bulk metallic glasses (BMGs) with excellent mechanical, physical and chemical properties to structural, magnetic and other materials. Until now, reports on methods for the mechanical working of BMGs have been mainly related to plastic deformation at temperatures under the supercooled liquid temperature range (ΔTg = Tg − Tc, where Tg is the crystallized temperature and Tc is the glass transition temperature). BMGs exhibited ideal superplasticity and ultra-precise formability in stamp forging with accuracy in the order of nano- or micro-meters at these temperatures. It is also reported that the electron beam welding and friction pressure welding have been easily performed with maintaining a good glass phase.

The cutting is considered one of the most basic methods in the mechanical working. Recently, Bakkal et al. had reported the chip light emission and morphology, cutting forces, surface roughness and tool wear through the investigation of the turning of Zr-based BMG together with an Al alloy and SUS304 stainless steel under the same cutting condition using the different tool materials. Authors also had presented the cutting force, surface roughness, and cut surface and chip morphology through the investigation of the turning of not only the Zr-based BMG having the large toughness but also Pd-based BMG having the small toughness together with a steel and free-cutting brass under the same cutting conditions using the different tool materials and nose tip radii.

The results of the author’s presents are summarized in this paper. Although the comparison between the results of Bakkal and authors is not altogether possible because the work materials, tool materials and cutting conditions are different, this paper also takes up an important common and different points in both Bakkal and our results and presumes the cause.

2. Experimental Procedure

The BMG workpieces were round bars of Zr₆₅Cu₁₅Ni₁₀Al₁₀ at% alloy with 16 mm in diameter fabricated using a powder extrusion method (commercial material made by YKK Corp.) and round bars of Pd₄₀Cu₃₀Ni₁₀P₂₀ at% alloy with 13 mm in diameter made by a water quenching method. In order to compare the cuttability of the BMGs with that of crystalline alloys, a steel (JIS SGD-400D) and free-cutting brass (JIS C3604) were also used as representative of the crystalline alloys. The mechanical and physical properties of these materials are shown in Table 1.

Cutting tool tips of diamond, cubic boron nitride (CBN), ceramics and cermet were used. The corner nose radius of the cutting tool tips (Rn) was 0.4 mm. Rn values of 0.8 and 1.2 mm were also used in the cutting tests when using the cermet tool tips. The mechanical and physical properties of these tool materials are shown in Table 2.

Turning was carried out on a numerically controlled lathe that had a uniform cutting speed control function (SL-25Y, Mori Seiki Corp.). The cutting depth (d) and feed speed (f) were kept constant at 0.05 mm and 0.05 mm/rev., respectively, and the cutting speed (V) was varied between 5 and 150 m/min. Here, the value of d and f was decided from the cutting conditions beautifully finished under a light cut in order to maintain a good amorphous level using limited BMGs. Cutting conditions of the BMGs, steel and brass were the same. Coolants were not used during cutting.
The principal cutting force \( F_H \) was measured by using strain gauges that were attached to the shank of the cutting tool holder. The surface roughness of the machined surface was measured with a contacting stylus-type surface roughness tester (SV-3000 M4, MITSUTOYO Corp). X-ray diffraction measurements (XRD) were performed on a facing surface. The turned surface and chips were observed using a metallurgical microscope and scanning electron microscope (SEM).

3. Results and Discussion

3.1 Cutting force

Figure 1 shows the relationship between the principal cutting force \( F_H \) and cutting speed \( V \) when using the cermet tool tip. The value of \( F_H \) for both BMGs was approximately half of that for the steel for a \( V \) less than approximately 30 m\( \cdot \)min\(^{-1} \), although the tensile strength of the BMGs is approximately twice that of the steel. For the middle- and high-speed ranges of \( V \), the values of \( F_H \) for the BMGs and steel were constant and almost identical. Concentrated slip in the workpiece near the tool tip was induced by shear stresses even for the low-speed range of \( V \). The temperature increase in the BMGs is induced by structural relaxation due to slip in addition to the slip itself and BMGs have a \( T_g \) and the \( T_g \) is enough lower (\( T_g \)s of Zr- and Pd-based BMGs are 680 and 580 K, respectively, see Table 1) than the melting temperature of the steel. It is added that BMGs do not generally cause work hardening and the steel causes it. Therefore, the BMGs might have lost strength at lower temperatures and exhibited slip with smaller shear stresses in comparison with the steel, even though the strength of the BMGs was twice that of the steel. This presumption indicates that there is a possibility that BMGs generally have low \( F_H \) even for the low speed range of \( V \) in spite of its high strength, comparing with the case of cutting of high strength crystalline alloys.

With increasing values of \( V \), it is presumed that the difference between values of \( F_H \) was small as a result of softening of the steel with increasing temperature. The \( F_H \) of the free-cutting brass might be the lowest of all the materials tested due to the strength of brass being very small compared with the other materials (i.e. one fifth of the BMGs as shown in Table 1).

When the \( F_H \) values of both BMGs are compared more carefully, the \( F_H \) of the Pd-based BMG was slightly smaller than that of the Zr-based BMG. The \( T_g \) of the Pd-based BMG is 100 K lower than that of the Zr-based BMG as shown in Table 1. Thus, the Pd-based BMG might have lost strength at lower temperatures during cutting compared with the Zr-based BMG. As a result the \( F_H \) of the Pd-based BMG appeared to be slightly lower than that of the Zr-based BMG.

Figure 2 shows the results of \( F_H \) as a function of the tool tip material for the BMGs. The \( F_H \) value is the largest for both BMGs when using the diamond tool. It is thought that softening due to the heat generated by cutting is the least for the diamond tool tip since the thermal conductivity (\( \alpha \)) of...
diamond is very large compared with that of other tool tip materials (see Table 2). For \( V > 50 \text{ m/s} \), the chips from the Zr-based BMG were often burnt except when diamond tool tips were used as shown in Fig. 3.

### 3.2 Surface roughness

Figure 4 shows the relationship between the arithmetical mean deviation \((R_a)\) of the workpieces and \( V \) when using the cermet tool tip. Regardless of the value of \( V \), the value of \( R_a \) in both BMGs was almost constant and found to be about 0.2 \( \mu \text{m} \); that is, at the upper end for precise finishing level \((R_a \approx 0.013-0.2 \mu \text{m})\). Comparing in detail the values of \( R_a \) on the turned surfaces of both BMGs, it can be seen that the \( R_a \) value of the Zr-based BMG tended to be slightly smaller than that of the Pd-based BMG. The \( R_a \) value of both BMGs was significantly lower than that of the steel (1–1.8 \( \mu \text{m} \)) and slightly lower than that of the free-cutting brass (about 0.35 \( \mu \text{m} \)) which is well known to produce excellent cutting surfaces. It is not clear whether the \( f \) and \( d \), especially \( d \), used for cutting of the BGAs were optimal ones to obtain a good \( R_a \) for the steel and brass. However, the \( R_a \) almost achieved the fine finishing level \((R_a = 0.40–1.6 \mu \text{m})\), which is known to be an upper limit for the cutting of crystalline alloys. Bakkal et al. reported the similar result that the \( R_a \) of the turned surface of a Zr-based BMG was usually better than that of Al alloy and SUS304 stainless steel under the same cutting conditions as the BMG. Therefore, the result that the \( R_a \) value of both BMGs was lower than that of the steel and brass seems to be appropriate.

The best value of \( R_a \) in the turning of the Zr-based BMG obtained by Bakkal et al. was 0.35 \( \mu \text{m} \). The values of \( f \) and nose radius \((R_n)\) (0.4 mm) were equal to us, but the \( d \) (0.5 mm) was different from us (0.05 mm). Their larger value of \( R_a \) (more than 0.35 \( \mu \text{m} \)) compared with our value of \( R_a \) (less than about 0.2 \( \mu \text{m} \)) may be due to the effect of larger \( d \) compared with us.

Figure 5 shows the effect of the material and nose radius of tool tips on the \( R_a \) value of both BMGs. The diamond tip produced the smallest value of \( R_a \) in both BMGs. The diamond tip produced the smallest value of \( R_a \) in the Zr-based BMG. In the Pd-based BMG, there was no clear difference in the \( R_a \) values whether turning with diamond or cermet tips. The chips of the Pd-based BMG did not burn even when using a \( V \) of 80 \( \text{m/s} \) in conjunction with the cermet tool tip in contrast to those of the Zr-based BMG as mentioned section 3.1. This is due to Zr reacting more readily with oxygen than Pd. For the Zr-based BMG, the \( R_a \) values were lowest when using the diamond tips. One of the reasons is due to not burning of the chips that produces a vapor that adhere to the surface of workpiece. This is in contrast to the Pd-based BMG chips that do not burn even when turning with the cermet tool tip and no clear difference in the \( R_a \) values of the Pd-based BMG whether turning with diamond or cermet tips might occur.

Table 3 shows the relationship between the theoretical...
is known to be not attained generally in the workpiece of usual crystalline alloys. Therefore, it is presumed that the BMGs are the materials that the precise finishing level is easily obtained by turning unlike usual crystalline alloys.

XRD measurements were performed on the facing surface of the Zr-based BMG turned at a $V$ of 80 m/min in conjunction with the cermet tool tip as shown in Fig. 6. The diffraction pattern indicated that the facing surface remained a glassy phase even for conditions that lead to burning of chips.

### 3.3 Observations of the turned surface

Figure 7 shows photographs of the turned workpieces. In Fig. 7(a), the left-hand region of the Zr-based BMG workpiece exhibits a slightly dulled metallic luster. This was due to the burned chips coiling up and then adhering to the workpiece. Other regions on the workpieces of both the Zr- and Pd-based BMGs show greater metallic luster when compared with the brass.

Figure 8 shows micrographs of the turned workpiece surfaces. As mentioned above, the Pd-based BMG tended to show a slightly larger value of $R_a$ compared with the Zr-based BMG. The surface of the Zr-based BMG workpiece was also very smooth as shown by the microscopic observations in Fig. 8(a). There was slight fraying in regions between the 50 $\mu$m streak intervals, indicating feed speed ($mm/rev$) on the surface of the Pd-based BMG as shown in Fig. 8(b).

The Pd-based BMG, consisting of metal and metalloid atoms, is considered to be slightly more brittle than the Zr-based BMG, which consists of only metal atoms. This may be related to the difficulty of slip in the Pd-based BMG compared with the Zr-based BMG and slight fraying in some regions appeared to occur on the turned surface of the Pd-based BMG. The turned surface of the free-cutting brass was considerably rougher than the BMGs as shown in Fig. 8(c). As shown in Fig. 8(d), the steel surface exhibited many tear-off marks and the surface is rougher than that of the brass.

### 3.4 Observation of the chips

Figure 9 shows macrographs for the side, front and back surfaces of the chips for all of the turned material. The back surface refers to the surface in contact with the tool tip face. Although the chips from the steel were of the flow type, wavy slip lines with irregular amplitude and period were observed.
Fig. 7 The morphology of the macroscopic machined surface of the BMGs and crystalline alloys using the cermet tool tip.

Fig. 8 Micrographs of the morphology of machined surface of the BMGs and crystalline alloys using the cermet tool tip.
The chips produced by cutting the BMGs were more of an ideal flow type, exhibiting planar and evenly fine spaced slip lines. The chips from the free-cutting brass showed an intermediate morphology between the chips of the steel and BMGs, and exhibited wavy slip lines of irregular period and small amplitude.

The back surfaces of steel chip showed many tear-offs and adhesions, indicating the repeated initiation, growth and falling of the built-up edge. On the other hand, observations of the BMG's revealed very homogeneous, flat and featureless back surfaces, indicating that built-up edges had not occurred. The free-cutting brass chip showed an intermediate morphology between the steel and BMG's chip even in observations of the back surface. It is presumed that a lack of built-up edge in the BMGs was due to the BMGs becoming softer than crystalline alloys with increasing temperature by cutting as the BMGs have the enough lower $T_g$ values (see Table 1) compared with the melting temperatures of the crystalline alloys.

From the chip observation results, the mechanisms that the roughness on the turned surface of the BMGs exhibited the precise finishing level, which cannot be attained generally in usual crystalline metals, were presumed as follows. The chips slipped off at planar and evenly fine spaced slip planes controlled only by a maximum shearing stress. As the result, the cutting force became constant and chattering was not easily generated. As the BMGs are generally difficult to produce the plastic deformation in addition to the slipping off behavior of the BMGs, the BMGs were easily cut off along the shape of the tool tip. A built-up edge did not occur in the BMG workpieces as the $T_g$ is low.

The presumed above all generation mechanisms achieving the precise finishing level in both BMGs are connected with
the general characteristics of BMGs. Therefore, it is anticipated that the surface roughness of other metal based BMGs by turning are also excellent. The future confirmation is expected.

The report of Bakkal et al. investigated the turning of a Zr-based BMG showed the chips morphology with melting or large deformations, as the shear might be large in comparison with us. Therefore, our result of slipping off generation mechanism of the chips obtained from the observation on side and front surfaces of the chips and the result of no built-up edges obtained from the observation on the back surfaces of the chips had not been mentioned in their report. Rather, they had shown the result that the periodically shear band formation deteriorated the surface roughness and the best Ra had obtained when the chips had burned most severely. It is necessary in the future that BMGs are turned under various cutting conditions including different d values.

4. Conclusions

The cuttability of Zr- and Pd-based BMGs by lathe was examined using different tool tip materials (diamond, CBN, ceramics and cermet), nose radii of the tip (Rn = 0.4, 0.8 and 1.2 mm), feed speed (f = 0.05 mm/rev) and cutting speeds (V = 5–150 m/min). The results that were obtained are as follows:

(1) In spite of the tensile strength of the BMGs being twice that of the steel, the value of the principal cutting force (FH) of the BMGs was half that of the steel in the low V region. For the medium and high V region, no significant difference in the value of FH for the BMGs and steel could be observed, while the value of FH was observed to be constant. The value of FH in the Pd-based BMG was slightly larger than that of the Zr-based BMG. The lowest value of FH when turning the Zr-based BMG was found on using the diamond tool tip. No difference in FH was observed when turning the Pd-based BMG with either diamond or cermet tips.

(2) The surface roughness (arithmetical mean deviation (Ra)) of both BMGs was constant regardless of the value of V. Ra of both BMGs was much lower than that of the steel and slightly lower than that of the free-cutting brass, and exhibited values at the upper end of the precise finishing level (Ra <= 0.2 μm). The value of Ra of both BMGs was inversely proportional to Rn. For Rn = 1.2 mm, Ra was 0.08 μm (maximum height, Rz = 0.5 μm). The ratio of Rz to the theoretical surface roughness (Rth) showed low values in the range of 1.4 to 2.2. The Ra of the Zr-based BMG was slightly larger than the Pd-based BMG. The value of Ra of the Zr-based BMG was lowest for the diamond tip when compared with all the other tip materials. Differences in the values of Ra for turning by the diamond and cermet tips was not observed for the Pd-based BMG.

(3) The X-ray diffraction pattern on the facing surface of the Zr-based BMG with V = 80 m/min showed still the glassy phase.

(4) The excellent cuttability of the BMGs (i.e. very low surface roughness in comparison with the crystalline metals) is thought to be due to the BMGs having no built-up edges derived from a low glass transition temperature and small chattering derived from the fact that the BMGs show ideal flow type chips, formed by planar, parallel and very small spaced slip, which is only controlled by the maximum shear stress, as the BMGs do not have slip systems as in crystalline metals.

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