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Pulsed laser micromachining of Mg–Cu–Gd bulk metallic glass

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ABSTRACT

Micromachining of Mg-based bulk metallic glasses (BMGs) is performed using two kinds of pulsed nanosecond lasers: a 355 nm ultraviolet (UV) laser and a 1064 nm infrared (IR) laser. Precision machining on the micrometer scale and the preservation of amorphous or short-range order characteristics are important for the application of BMGs in micro-electro-mechanical systems. A higher micromachining rate is achieved using the UV laser than using the IR laser due to a better absorption rate of the former by Mg-based BMGs and a higher photon energy. The cutting depth of Mg-based BMGs ranges from 1 to 80 μm depending on the laser parameters. By appropriate adjustment of the laser power and scan speed, successful machining of the Mg-based BMG with preservation of the amorphous phase is achieved after the laser irradiation process. Short-pulse laser cutting represents a suitable alternative for machining of micro components.

1. Introduction

Bulk metallic glasses (BMGs) are disordered materials that lack the periodicity of crystalline structures. BMGs exhibit many exceptional physical, chemical, and mechanical properties that differ markedly from those of crystalline metals, and thus, BMGs have attracted considerable attention as structural materials [1–4]. It is difficult to fabricate nanometer-sized (on the scale of several hundred nanometers) components using crystalline alloys given that their grain size falls in the range 10–100 μm. However, the short-range atom clusters and viscous flow in the supercooled liquid region of BMGs allow the formation of BMGs with sizes as low as 10–100 nm [3]; thus, BMGs exhibit good potential as materials for micro-electro-mechanical systems and functional applications.

Conventional cutting tools [5,6] and focused ion beam (FIB) milling [7] offer certain advantages for the machining of micro components made from BMGs. For example, FIB allows precision machining on the nanometer scale and preserves amorphous or short-range order characteristics. Nonetheless, its relatively low machining rate and high cost make it unsuitable for mass production. With the development of laser micromachining techniques, diode-pumped Q-switched lasers have been applied to the patterning of various materials, including ceramics, metals, polymers, and semiconductors [8–13]. The morphology and microstructure of the patterned materials depend on the laser parameters. The traditional laser machining process employing long-pulse (ms) lasers is not appropriate for the manufacture of micro components, given that shorter pulses are needed to minimize crystallization [14]. The use of ultrashort-pulse (fs or ps) lasers is desirable because the short pulse preserves the amorphous characteristics of metallic glasses (MGs) [10,12,13,15] after laser ablation due to the fact that the irradiation time during a single pulse is shorter than electron cooling and lattice heating times, which prevents materials from accumulating heat and thus suppresses microstructural changes. However, the high cost of ultrashort-pulse lasers has limited their application to laboratory research. Consequently, current industrial applications mainly employ short-pulse lasers with nanosecond pulse rates. Short-pulse laser cutting is a good choice for machining of micro components given that the spot size of the laser beam can be reduced to several micrometers via an optical system.

There are three main BMG alloy systems with a low glass transition temperature (T_g). These can be classified as Au-based [16], Mg-based [17,18], and Ce-based [19] MGs. Of these three systems, the Mg-based MGs are most suitable for industrial purposes given that the use of Au-based MGs are limited by their high cost and the high oxidation rate of Ce-based MGs make them unsuitable for mass production. Mg-based MGs have a low T_g (130–140 °C), close to that of poly(methyl methacrylate), meaning that they have good forming ability and good strength. Therefore, to minimize the heat-affected zone (HAZ) and crystallization and maintain an amorphous structure in BMGs, the present study investigates the effects of various laser parameters

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such as laser fluence and scan speed on the micromachining of a Mg–Cu–Gd ($Mg_{65}Cu_{25}Gd_{10}$) BMG using 355 nm ultraviolet (UV) and 1064 nm infrared (IR) pulsed nanosecond lasers.

2. Experimental procedure

A Mg-based BMG alloy comprising $Mg_{65}Cu_{25}Gd_{10}$ (atomic %) was selected as the test material. The alloy was injection-casted into a water-cooled Cu mold with an internal cylindrical-shaped cavity measuring 3 mm in diameter. X-ray diffraction (XRD) and differential scanning calorimetry (DSC) measurements were performed to verify the amorphous nature of the cast alloy. The 3 mm-diameter BMG rod was sliced into disks of 1.5 mm height using a diamond cutter, and the disks were subsequently ground using SiC papers of grades ranging from 1200 to 4000. Finally, the disk surfaces were polished to a mirror finish with a diamond polish paste with grit sizes ranging from 0.25 to 1 μm, prior to the laser micromachining.

The system for laser micromachining consisted of two laser sources with a stability greater than 90%, a scanner (Scanlab), and an XYZ stage. The laser experiments were performed using a UV laser (Coherent AVIA 355–7000) with a wavelength of 355 nm, a repetition rate of 40 kHz, and a pulse duration of 30 ns, and an IR laser (SPI SP-20P) with a wavelength of 1064 nm, a repetition rate of 25 kHz, and pulse duration of 30 ns. Micromachining of the Mg-based BMG was carried out at a laser power of 3–6 W; the scan speed was varied from 30 to 400 mm/s.

To increase the resolution of the micromachined pattern, the size of the laser spot was decreased. The diameter of the laser spot, D_0, is expressed as:

$$D_0 = 1.22 \times \left(\frac{\lambda \times F}{n \times W_d}\right) \times M^2 \quad (1)$$

where λ is the laser wavelength, F the focal length, n the refractive index, W_d the diameter of the incident laser, and M^2 the laser-quality factor. Eq. (1) indicates that the diameter of the laser beam is directly proportional to the wavelength and focal length. For the experiment, the spot size was 40 μm. The absorption spectrum and crystalline structure of the Mg-based BMG specimens before and after micromachining were measured using grazing incidence in-plane X-ray diffraction, a surface profiler (α-step, Tencor), and a UV–vis-IR spectrophotometer (Jasco V-750). The morphology and component ratios of machined samples were examined by scanning electron microscopy and FIB.

3. Results and discussion

To examine the rate of absorption of various irradiation wavelengths by the Mg-based BMG specimens, the reflectivity of the disk specimens was measured using a UV–vis-IR spectrophotometer. Fig. 1 shows the reflectivity of the Mg-based BMG specimens for wavelengths in the range 200–1400 nm. Due to a change in the incident light source, the reflectivity spectrum exhibits discontinuities at wavelengths of 350 and 900 nm. Reflectivities of 23% and 55% were obtained at 355 and 1064 nm, respectively. From the equation of absorption, $(A)=1$ reflectivity (R), the absorption rate of Mg-based BMG at a wavelength of 355 nm is found to be 1.7 times higher than that at 1064 nm.

Table 1 lists the micromachining depth, measured using a surface profiler, of Mg-based BMG specimens obtained using various laser cutting parameters. For the UV laser with a fluence of 6 J/cm^2, increasing the scan speed from 30 to 300 mm/s resulted in a decrease in the cutting depth from 30 to 7.2 μm.

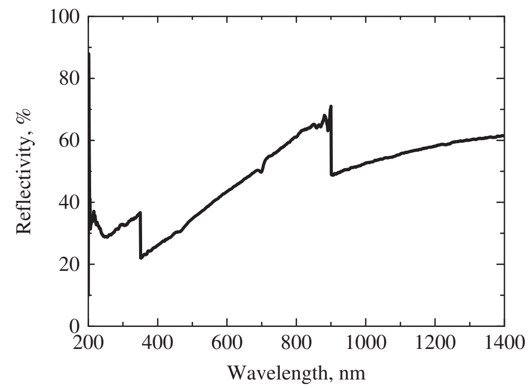

Fig. 1. Optical reflectivity spectra for wavelengths from 200 to 1400 nm for Mg-based BMG.

Table 1
Micromachining depths of Mg-based BMG after being laser processed with various parameters.

Scan speed	30 mm/s	200 mm/s	300 mm/s
UV laser, 6 J/cm^2	~30 μm	~11.2 μm	~7.2 μm
UV laser, 12 J/cm^2	~80 μm	~15.2 μm	~8.8 μm
IR laser, 9.5 J/cm^2	0 μm	–	–
IR laser, 19 J/cm^2	~0.9 μm	0 μm	–

The laser power affects the micromachining depth at a given scan speed; the cutting depth increases with increasing laser power and decreasing scan speed. In addition, the wavelength is a key parameter in the machining of Mg-based BMG specimens. For the IR laser with a fluence of 19 J/cm^2 and a scan speed of 30 mm/s, the cutting depth was only ~0.9 μm.

Fig. 2 shows the top and cross-sectional views of the laser-machined Mg-based BMG specimens obtained with various laser sources, irradiation energies, and scan speeds. The surface morphology of a groove machined using the UV laser with a fluence of 12 J/cm^2 and a scan speed of 30 mm/s is characterized by small ridges with a height of 50 μm on either side of the groove, as shown in Fig. 2(a) and (d). A large number of re-deposited materials or particles are observed between the ridges close to the groove; outside of the ridges, away from the groove, a number of wrinkles appear after plastic deformation. This phenomenon implied that the inner region between the ridges contained some deposited materials due to plasma cloud induced by the UV laser irradiation of 12 J/cm^2, and the HAZ, outside of the irradiated area, exhibited plastic wrinkles due to heat accumulation caused by a slow scan speed of 30 mm/s. The heat accumulation and thermal diffusion has the effect of softening the materials located within the HAZ because of temperatures exceeding the temperature T_g. On the other hand, the materials within the irradiated region undergo melting and vaporization to generate volume expansion. Plastic deformation is induced in the soft HAZ owing to the volume expansion of the irradiated region. When the scan speed was increased to 200 mm/s or above, the HAZ became smaller due to faster thermal dissipation, and the deformed wrinkles decreased in number or disappeared. The sprayed materials on either side of the machined grooves are shown in Fig. 2(b) and (e).

No groove is produced in the surface of the Mg-based BMG specimens when the IR laser with a fluence of 19 J/cm^2 and a scan rate of 30 mm/s was used (Fig. 2(c) and (f)). Under these conditions, the surface was heated to achieve viscous flow (over the temperature T_g). It is suggested that the thermal heating and penetration effects of the IR laser (wavelength of 1064 nm) do not induce the ablation effect via material spray, even if a fluence of