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Superplastic nanoforming of optical components of Pt-based metallic glass

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Abstract

Metallic glasses are useful for fabricating nanodevices due to their viscosity and homogeneity on nanometer scales. In this study, we developed optical components of metallic glasses by superplastic nanoforming. Metallic glasses exhibit Newtonian viscous flow in a supercooled temperature range between the glass transition temperature and the crystallization temperature. This study used Pt-based metallic glass with a glass transition temperature of 502 K. This material was applied to reflective interference optical components, and a diffraction grating (1 μm interval) and a hologram were fabricated by superplastic nanoforming. Dies were made by Ni-electroforming, with master models fabricated by photolithography of the interference pattern. The working temperature of Pt-based metallic glass was 540 K under a compressive stress of 10 MPa. The results demonstrated the advantages of the superplastic nanoforming technique on metallic glass and for mass production of optical components.

Keywords: Amorphous materials; Nanofabrications; Optical properties; Strain; Nanoimprint

1. Introduction

Many interference optical components are fabricated by molding plastics (polymer materials) or oxide glasses because of their precision formability. Reflective interference optical components, such as diffraction gratings or reflection holograms, are usually made by microforming plastics in low-cost mass production. However, the materials are not useable at elevated temperatures, and are poorer in mechanical properties and corrosion resistance than metallic materials. The micro- and nanoformability and mechanical and functional properties of metallic glasses are advantageous in the fabrication of reflective interference optical components.

A diffraction grating has a fine convex–concave pattern on the surface and is fabricated by precision forming with a die at low viscosity. The pattern interval is less than 1 μm, which is important in making such fine structured dies, as well as in transferring three-dimensional shape to the viscous materials, such as plastics [1] or metallic glass [2]. There are many ways to fabricate a micropattern, including electron-beam (EB)-lithography or micro- or nanomachining with a Focused Ion Beam [3]. Fig. 1 depicts the microstructure of SiO_2 on a Si wafer fabricated by EB-lithography and reactive etching with a cylindrical pit of 500 nm in diameter. Fig. 1(b) presents a full view of the structure fabricated in a 1 mm × 1 mm area. Drawing the micropatterns with the EB-drawing system is very time-consuming. In the present study, an interference optical system was used for lithography by one-shot exposure of micropatterns in a large area, and the microstructures were fabricated as models of microdies. A diffraction grating and a reflection hologram were fabricated with these dies by superplastic forming of Pt-based metallic glass.

2. Experimental

2.1. Pt-based metallic glass

Amorphous alloys are generally recognized as superior structural materials and functional materials. New amorphous alloys are called bulk amorphous alloys or metallic glasses because of their low-critical cooling rates for amorphization and the Newtonian viscous flow in the supercooled liquid temperature range [4]. These materials are also recognized as promising micromaterials and nanomaterials because of their homogeneity on micro- and nanometer scales [5]. The present study used $Pt_{48.75}Pd_{9.75}Cu_{19.5}P_{22}$ metallic glass. This material exhibits obvious glass transition behavior at the temperature $T_g = 502.3$ K, below

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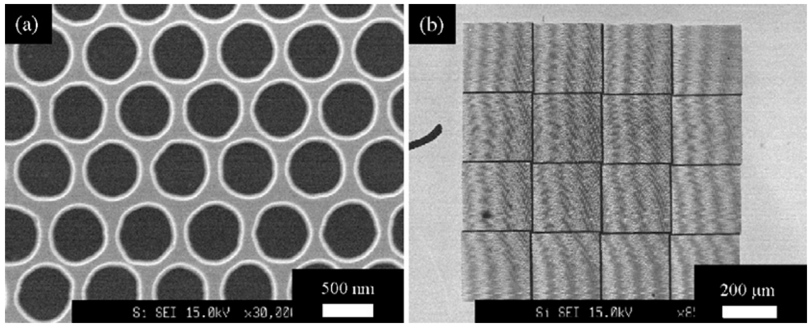

Fig. 1. SEM microphotographs of microstructured die of SiO_2 fabricated by EB-lithography and reactive etching processes. (a) Cylindrical pit of 500 nm in diameter; (b) full view of (a) in a 1 mm × 1 mm area.

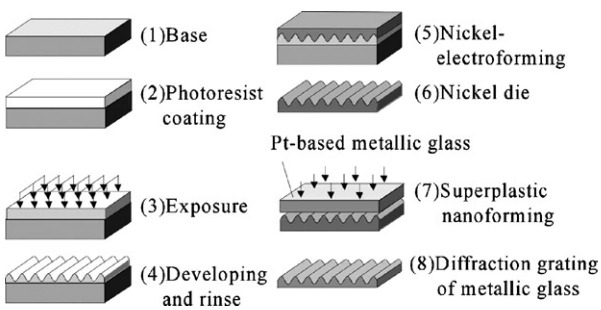

Fig. 2. Fabrication process of a diffraction grating.

the crystallization temperature $T_x = 587.7$ K, and develops a supercooled liquid state in a wide temperature range of $\Delta T_x = T_x - T_g = 85.4$ K. The micro- and nanoformability characteristic and application to micromachines were reported in previous papers [6,7].

2.2. Fabrication of microdies by an interference optical system

Fig. 2 depicts the diffraction grating die fabricated by lithography and Ni-electroforming processes. A positive resist was spin-coated on the substrate (Fig. 2-2) and exposed by an interference optical system. The light source for the optical system was a solid-state laser (375 nm wavelength), and the fringe pattern interval was determined by the angle theta, as depicted in Fig. 3. For example, the interval is 1 μm for theta of 22°. The fringe pattern was exposed to the spin-coated, photoresist and convex–concave patterns of 1 μm interval were fabricated after development and rinsing, as illustrated in Figs. 2-4 and 5(a and b) in the magnified images. The microshape of the resist on a substrate was transferred to a Ni-die by electroforming, as shown in Fig. 2(5 and 6). A sulfamate bath was used for Ni-electroforming. The fabricated microdie was observed by scanning electron microscope (SEM) and is presented in Fig. 5(c and d). The model shape (Fig. 5(a and b)) was precision transferred to the die shape (Fig. 5(c and d)). The fabricated microstructure's area is a 5 mm diameter circle. This one-shot exposure method has great advantages in manufacturing time and area compared with the EB-lithographic method.

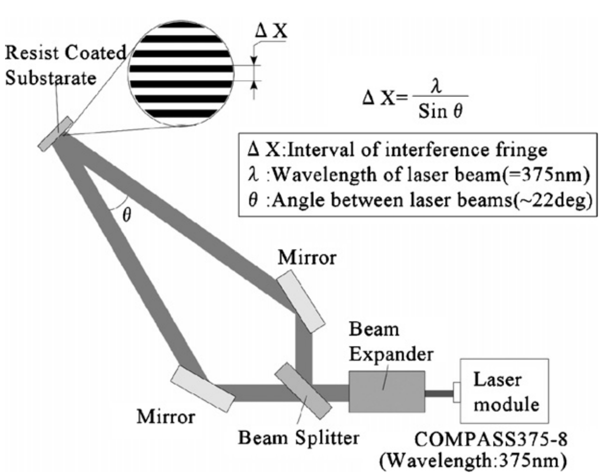

Fig. 3. Configuration of one-shot exposure by an interference optical system.

3. Results

3.1. Nanoforming of diffraction gratings of the metallic glass

Fig. 4 illustrates the configuration of the superplastic nanoforming apparatus. A specimen and a die are placed between two plates, and a compressive load is applied. The lower and upper plates are heated separately and controlled by PID controllers. The temperatures are measured by C.A. thermocouples with feedback to the controllers. A compressive load is generated by a linear actuator and controlled by a computer through a D/A converter. The apparatus has been designed as a microfactory cell, and is installed in a small vacuum chamber to eliminate the inclusion of air at the corner of a die and prevent oxidation of specimens. Superplastic nanoforging of Pt-based

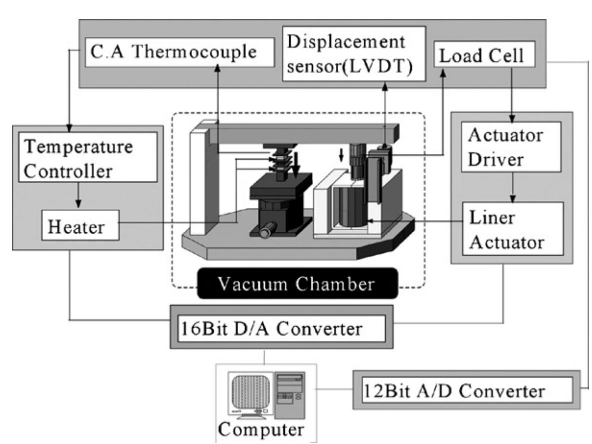

Fig. 4. Schematic illustration of superplastic nanoforming apparatus.

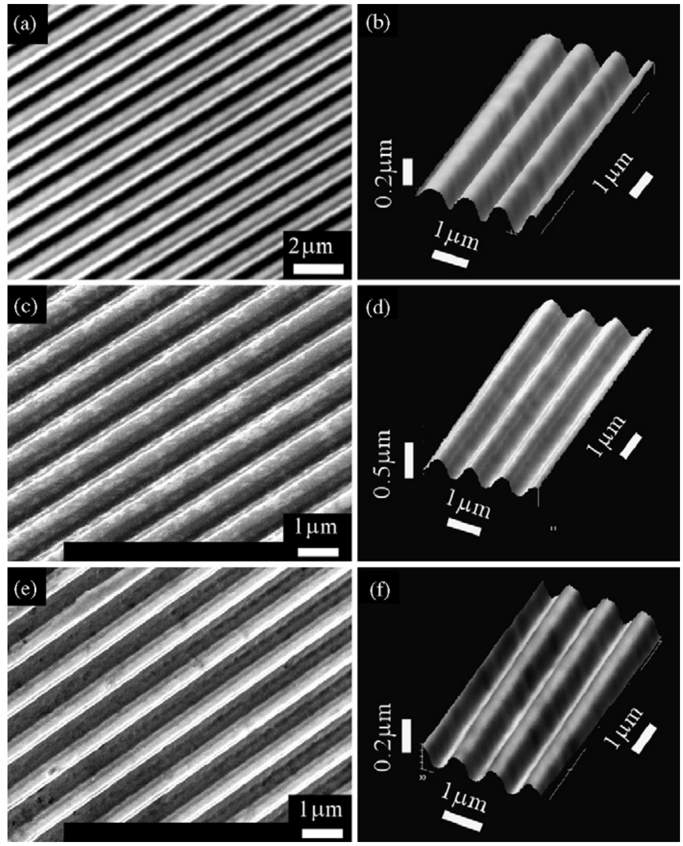

Fig. 5. Fabiricating process of diffraction grating of 1 μm interval. (a and b) Grating of resist; (c and d) die of electroformed Ni; (e and f) fabricated diffraction grating of Pt-based metallic glass.

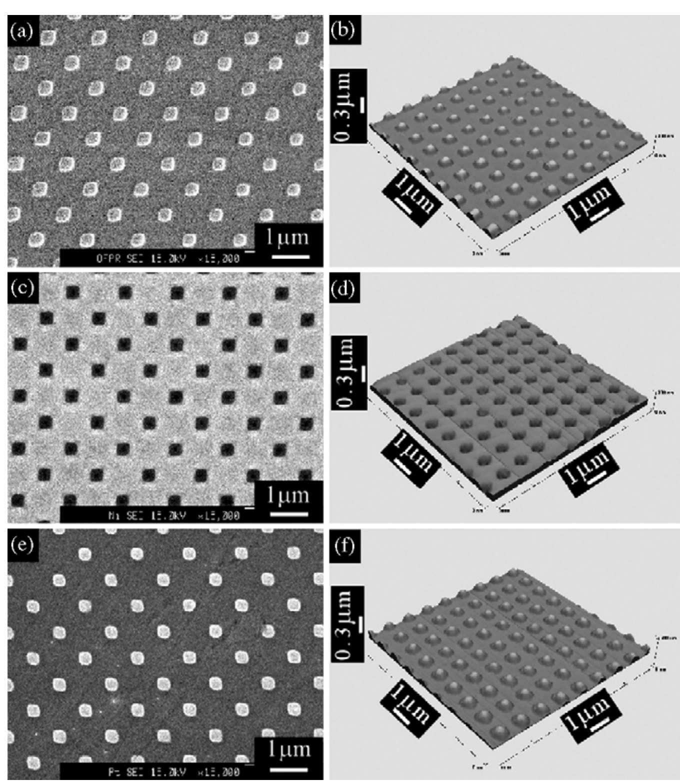

Fig. 6. Fabrication process of dot-pattern. (a and b) Resist of dot-pattern; (c and d) die of electroformed Ni; (e and f) fabricated dot-pattern of Pt-based metallic glass.

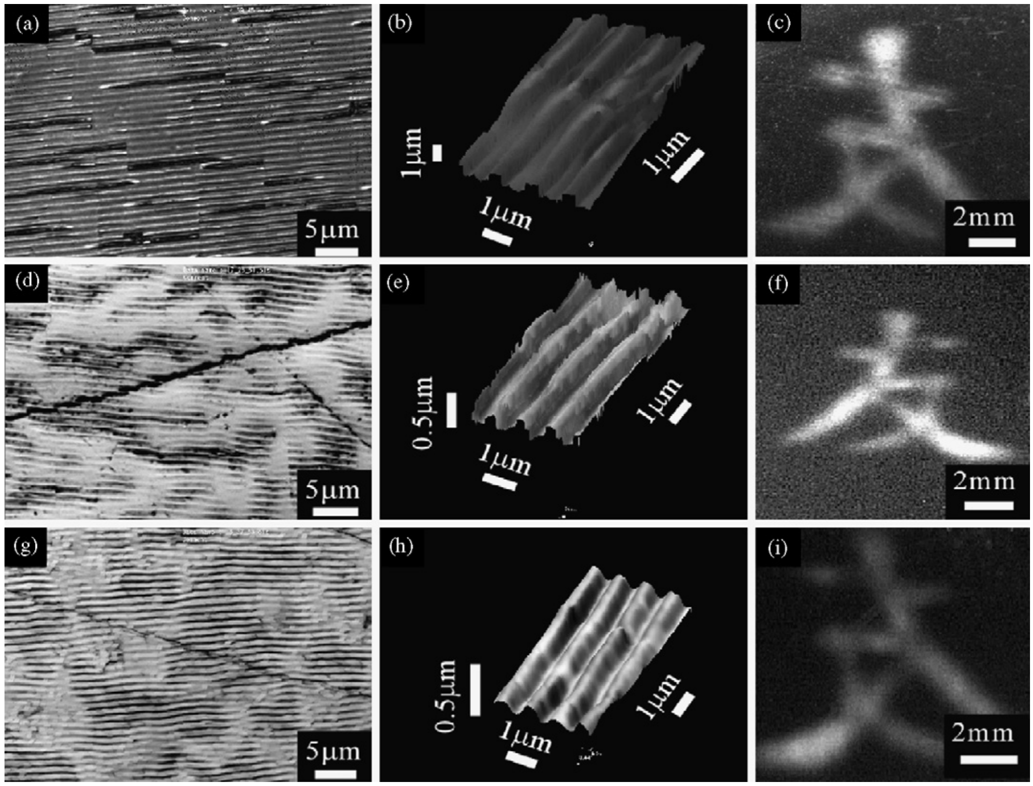

Fig. 7. Fabrication process of a hologram. (a–c) Hologram sticker; (d–f) die of electroformed Ni; (g–i) fabricated reflection hologram of Pt-based metallic glass; (c, f and i) holographic reflected image.

metallic glass was carried out; bird's-eye views of the forged specimen are presented in Fig. 5(e and f) . The applied initial mean stress was 10 MPa, forging temperature 550 K and working time 300 s. Fig. 5(f) presents the sine-wave shape of the resist structure replicated onto the metal grating.

The application of the one-shot exposure with the interference optical system results in the fabrication of a microdot-pattern. The interference fringe was double-exposed for a 90°-rotated photographic plate (resist-coated substrate). SEM microphotographs of the resist dot-pattern on the substrate after development and rinse are presented in Fig. 6(a and b). The die was fabricated by Ni-electroforming, and used for nanoforming of the metallic glass. The superplastic forming conditions were the same as those for making the diffraction grating. Fig. 6(e and f) presents microphotographs of the processing result.

3.2. Development of hologram of the metallic glass

Holographic interference is generated by two light beams (object light beam and reference light beam), and the fringes are recorded on photosensitive materials, such as a photographic plate. Reflection holograms are useful for the secure identification of various goods and are made of a reflection coating on a convex–concave surface structure of polymer film. Metallic glasses are useful for fabricating reflection holograms because the materials exhibit superior micro- and nanoformability, mechanical properties, and good corrosion resistance. Furthermore, the simple fabrication process does not require a reflection coating. In the present study, a hologram sticker was used as the master pattern for fabricating a die, as depicted in Fig. 7(a–c). The master pattern was replicated onto the three-dimensional surface microstructure of the die by Ni-electroforming (Fig. 7(d–f)). Fig. 7(g–i) presents SEM microphotographs of the fabricated reflection hologram of Pt-based metallic glass. Fig. 8 schematically illustrates the superplastic nanoforming apparatus. The compressive load was generated by a hydraulic actuator with a 2 kN capacity. The working condition of applied mean stress was 10 MPa for 300 s at a temperature of 550 K. Fig. 7(g–i) indicates the effectiveness in fabricating a reflection hologram.

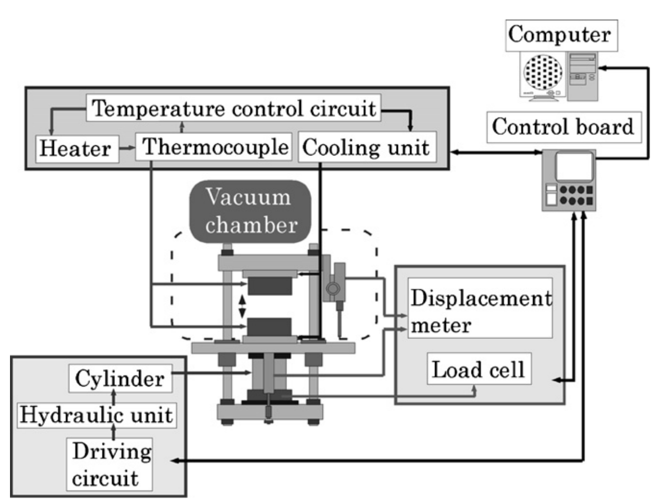

Fig. 8. Schematic illustration of superplastic nanoforming apparatus.

4. Conclusions

We have developed a superplastic nanoforming fabrication process for diffraction gratings and holograms using a metallic glass. The results obtained are summarized as follows:

1. An interference optical exposure system has great advantages over the fabrication of nanometer-scale dies by large-area lithography.
2. Metallic glasses are useful in fabricating reflective interference components such as diffraction gratings and holograms.

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