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Closed channel fabrication using micromolding of metallic glass

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ABSTRACT

Casting and molding are attractive options for low cost mass production. Metallic glasses may avoid many of the problems associated with micromolding of metals such as high temperatures and pressures, costly mold production, and shrinkage due to crystallization. In this study, we have produced 100 μm^2, enclosed channels in metallic glass using a novel multilayer Si stack micromolding process. Scanning electron microscope (SEM) images of the enclosed channels are provided to verify that the closed channels extended through the sample.

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1. Introduction

Phase change processes such as casting and molding are attractive options for low cost mass production. For polymer systems, molding of micro-scale components is routinely practiced. However, for metallic systems, crystallization during cooling induces shrinkage that can be on the order of several percent, making it difficult to hold tight tolerances. Additionally, it is necessary to fabricate the molds from materials capable of withstanding the high temperatures associated with melting of metals.

To enable molding of micro-scale devices, amorphous metals, or metallic glasses, offer the potential to avoid many of the problems associated with micro-scale molding of metals. Schoers has summarized the advancements in molding, forming and casting of metallic glass alloys in a recent review (Schroers, 2005). The atomic structure of these alloys differentiates them from typical metals. While ordinary metals have a crystalline structure, clear ordering is less discernible in the atomic structure of the amorphous alloys. This unique atomic structure (or the lack of crystalline structure) leads to characteristic properties that may include high yield strength, hardness, strength-to-weight ratio, elastic limit, and wear resistance.

2. Background

In a recent publication, Bardt et al. have reported on initial results for a simple approach to micromolding of complex, three-dimensional, high aspect ratio structures with non-line-of-sight features (Bardt et al., 2007). This was accomplished using expendable silicon molds and a metallic glass alloy (Vitreloy 1, commercially available from Liquidmetal Technologies), as the molding material. The sacrificial silicon molds were created using standard lithographic and deep reactive ion etching (DRIE) techniques. By observing appropriate heating and cooling rates, the use of amorphous metal enabled us to overcome the shrinkage issues typically associated with casting processes (the absence of a crystalline structure reduces shrinkage to ~0.2%). It was shown that multiple silicon layers could be stacked and the metallic glass forced into the cavities under modest heat and pressure levels in an open-air environment. Following cooling, the metallic structures were released by etching the silicon away in a potassium hydroxide (KOH) bath.

The processing steps for this micromolding are summarized in the following list: (1) fabricate the negative of the desired (metallic) features in silicon layers using standard lithographic techniques; (2) stack the silicon layers; (3) place a metallic glass blank on the silicon stack-up; (4) heat the stack-up to the glass transition temperature of the metallic glass; (5) apply pressure to force (flow) the metallic glass through the mold; (6) cool the metallic glass to retain its amorphous microstructure; and (7) etch away the silicon mold (expendable molding process).

These prior studies showed that temperature is the most significant variable governing successful mold filling. Additionally,

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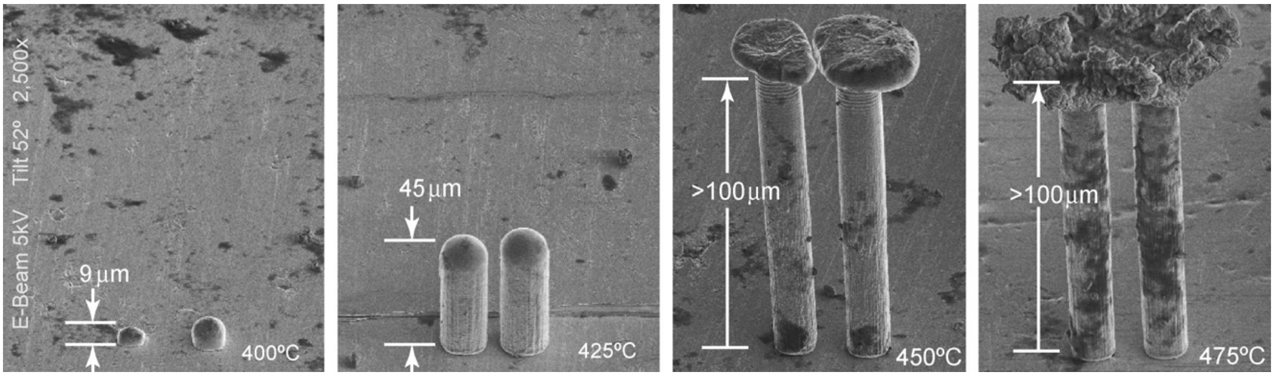

Fig. 1. SEM micrographs from twin 10 μm diameter post molding study. Processing conditions: (a) 400 °C, corresponding aspect ratio ∼1; (b) 425 °C, aspect ratio ∼ 4.5; (c) 450 °C, aspect ratio >10; and (d) 475 °C, aspect ratio ≫10.

transmission electron microscopy (TEM) sections of the mold/glass interface showed successful replication of features with characteristic dimensions on the order of 10 nm and no discernible gap between the silicon and the metallic glass.

Our initial tests focused on evaluating the process capability for high aspect ratio features. In one study, the metallic glass was forced through 10 μm diameter holes in a 100 μm thick silicon wafer at a macroscopic pressure of 115 MPa. It was found that a temperature increase from 400 to 475 °C (panels a–d in Fig. 1 show results for temperatures of 400, 425, 450, and 475 °C, respectively) increased the achievable aspect ratio from approximately unity to greater than 10:1 for twin 10 μm diameter posts. In panels c and d, the 'caps' on the posts occurred due to flow fully through the wafer (non-line-of-sight molding).

For these, and all subsequent, tests, we used a bulk metallic glass developed by Peker and Johnson with the composition: $Zr_{41.2}Ti_{13.8}Cu_{12.5}Ni_{10}Be_{22.5}$ (Peker and Johnson, 1993). This material has a glass transition temperature of approximately 350 °C. Above this temperature the material is viscous and the viscosity reduces rapidly with increasing temperature. The required cooling rate for retention of the amorphous structure is also low at ∼10 K/s. Johnson and Samwer have demonstrated that this material has a yield strength of 1.9 GPa and an elastic limit of approximately 2% strain (Johnson and Samwer, 2005).

Bardt et al. evaluated the capability to stack multiple wafer sections and flow through different cavity geometries to form three-dimensional structures (Bardt et al., 2007). Fig. 2 depicts a seven layer wafer stack-up on top of the metallic glass. The layer-to-layer misalignment is shown to emphasize the fact that strict control of their relative positions was not exercised (panel a). Panel b shows the flow progression through the wafer stack to form the final geometry. Panel c describes the processing conditions. After a 15 h etch in a 20% KOH solution, the silicon mold was consumed leaving only the metallic glass. Fig. 3 shows a scanning electron microscopy (SEM) image of the remaining metallic glass structure.

Following these initial tests, our next activity was to mold closed channels within a metallic glass structure using the techniques described in the previous paragraphs. Our approach and experimental results are provided in the following section.

3. Procedure

In this case, a four layer silicon stack-up was used. Each wafer section was 50 μm thick with appropriate features etched through. The stack-up was composed of wafer sections with the following geometries: (1) three 800 μm × 200 μm channels (100 μm spacing); (2) three 800 μm × 200 μm channels (100 μm spacing); (3) an open square (800 μm × 800 μm); and (4) no features (flat). Fig. 4 shows the geometry of each component of the stack. In an attempt to reduce mold misalignment discussed previously and illustrated in Figs. 2 and 3, alignment holes were patterned and etched in the Si channel molds as seen in Fig. 4. The overall stack-up, minus the top wafer and prior to molding, is depicted in the lower portion of Fig. 4. The shaded area represents the metallic glass mold charge. When heat and a compressive load are applied to the stack, the metallic glass flows into the mold cavities.

The same processing conditions depicted in Fig. 2c, followed by a KOH etch to remove the Si mold, were used to create the structure shown in Fig. 5.The bulk part was released from the silicon

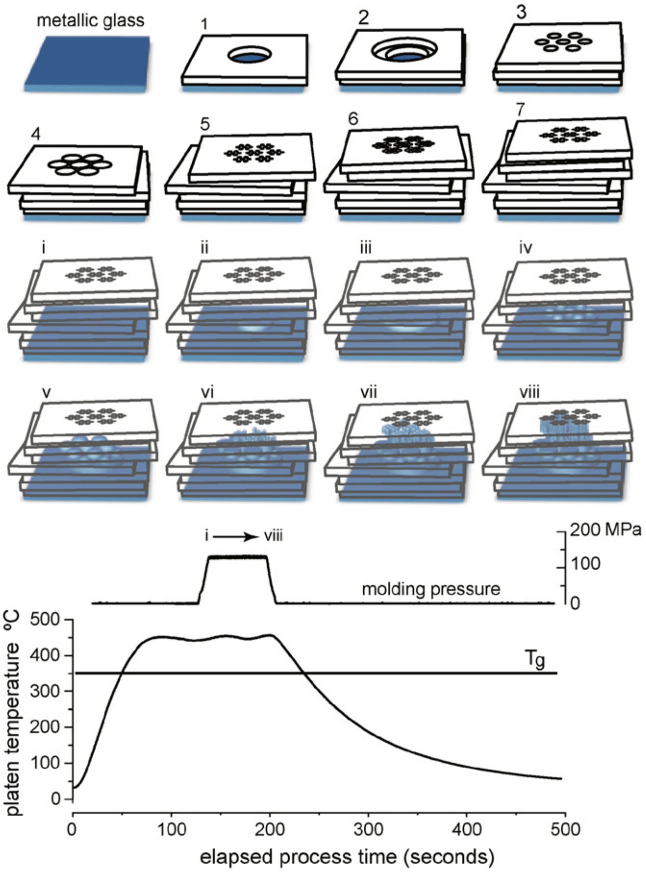

Fig. 2. Seven-layer mold stack to demonstrate non-line-of-sight fill capabilities. (a) Schematics of the stacking sequence with metallic glass shown as the shaded region. (b) Depiction of flow through the stack. (c) Processing conditions.

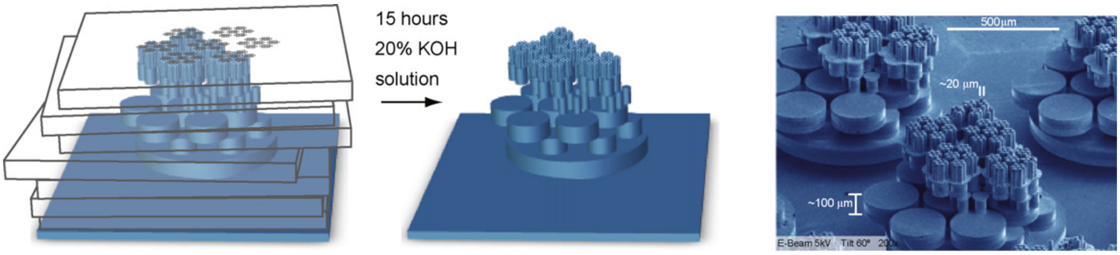

Fig. 3. Schematic representation of the seven-layer mold stack prior and post KOH etching followed by a SEM micrograph of micromolded metallic glass features removed from the mold.

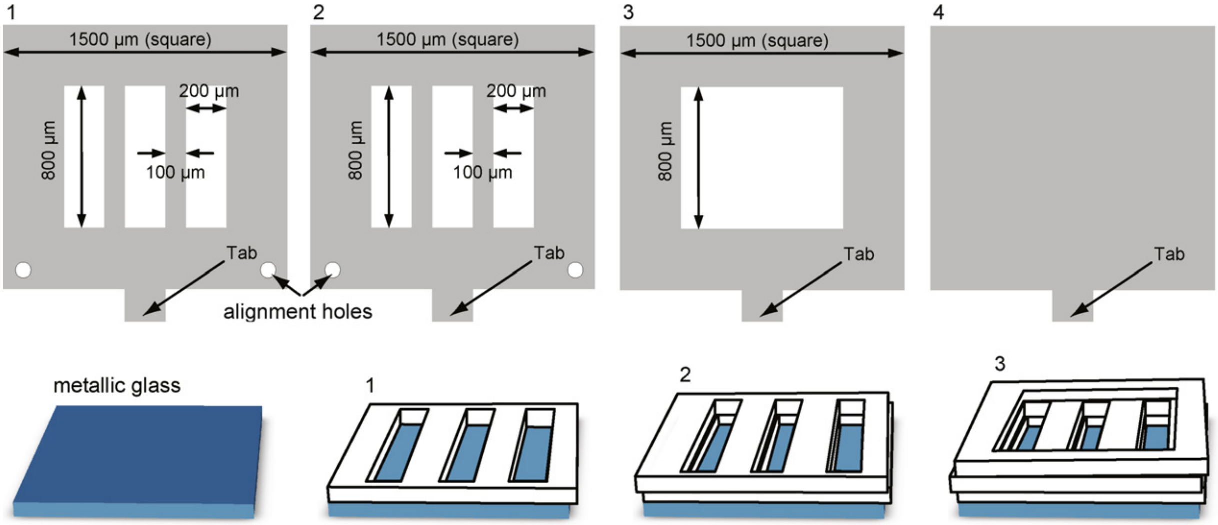

Fig. 4. (Upper) Schematics showing the dimensions of silicon wafers used to create the four-layer stack for closed channel fabrication. (Lower) Schematic of the stacking sequence minus the top layer for closed channel fabrication.

mold by stirring for 2 h in a KOH bath at 80 °C. An additional 16 h in the bath was required to fully etch the captured silicon within the 100 μm × 100 μm × 800 μm channels.

4. Results and discussion

In previous studies, stack alignment and registration was attempted using the edges of the Si wafer molds. This technique was inadequate. In the current study, pins were inserted in the alignment holes and then removed prior to molding in the first two wafers in the stack. As seen in Fig. 5, the first and second layers of the finished part have better alignment than the third layer, and better alignment than previously molded structures. The third layer in Fig. 5 has both translational and rotational misalignment, but the pins in layers 1 and 2 have virtually eliminated the rotational misalignment and reduced the translational misalignment to 15 μm as shown.

To verify that the enclosed channels indeed extended through the entire part and that the silicon mold had been completely etched away, the sample in Fig. 5a was sectioned with a diamond saw along the dashed line. Then, using a focused ion beam (FIB/SEM), an 'X' was milled in the metallic glass wall opposite the opening in the right channel; see Fig. 5b. The sample was then tilted so that the 'X' could be imaged through the channel with the SEM. Fig. 5c shows a clear continuous channel through the metallic glass. The sample was also scanned from 30 to 80° 2Θ in a Philips APD 3720 diffractometer using a Cu Kα radiation source. A plot of counts in arbitrary units (a.u.) versus degrees 2Θ exhibits the typical broad peaks associated with an amorphous structure; see Fig. 6.

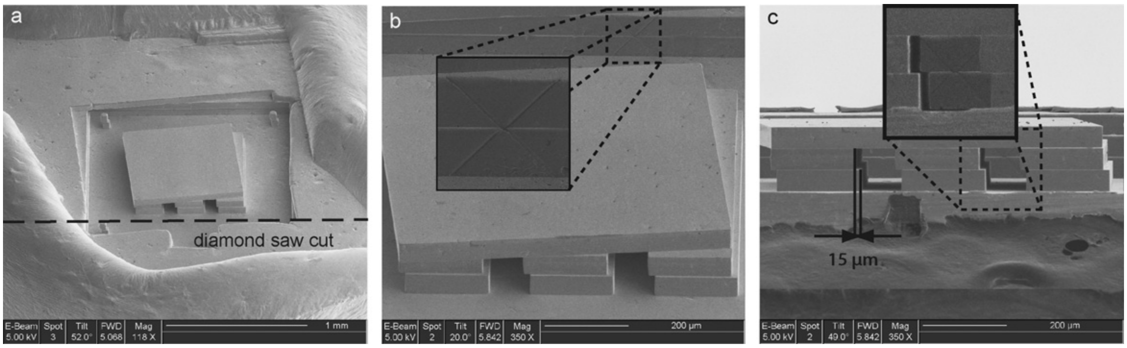

Fig. 5. SEM image of the closed channel structure after Si removal in KOH bath. (a) The sample was sectioned along the dotted line. (b) SEM image showing enlarged area where the FIB was used to mark an 'X'. (c) SEM micrograph of repositioned sample to image 'X' through the channel.

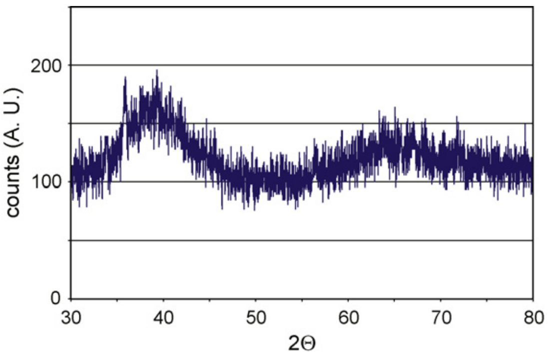

Fig. 6. X-ray diffraction scan of micromolded closed channel sample.

5. Summary

We have demonstrated the ability to create continuous enclosed channels from an amorphous metal alloy. The method uses existing well-developed silicon processing techniques and provides near net shape forming. The channels have been shown to be clear of mold material and debris. Future work will involve reducing the channel cross section for micro- and possibly nano-fluidic devices.

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