New materials that enable mass production of high-strength micro-components of arbitrary geometry at extremely low cost are bulk metallic glasses. The successful development of micro-molding technology with these materials will revolutionize micro-systems and enable numerous wholly new classes of micro-devices. We have shown that certain bulk metallic glasses can be molded to produce micron sized or potentially sub-micron sized features at low temperatures (350ºC-400ºC), and retain their high strengths. Some of the existing bulk metallic glasses have yield strengths of approximately 1.5 GPa and elastic limits approaching 2%.

Proof of Concept

Preliminary experiments were carried out to evaluate the feasibility of molding micron sized features using an amorphous alloy. A mold was made from a block of polished, hardened steel with Vickers hardness indents ranging in size from 5-50 µm and heated in a small laboratory press. A strip of the amorphous alloy was placed in the mold, pressurized to 14MPa, and heated to 360ºC. After a short dwell time, the ram was released and the sample was removed and quenched in water.

Bulk metallic glass after pressing into hardness indents of various sizes (scale bars: 100 and 10 µm respectively).

Subsequent examination revealed that the filling of the indents is complete even with indent sizes approaching 5µm in depth. X-ray diffraction from this micro-molded surface revealed that the material did not crystallize during forming.

These results are encouraging and suggest that this material is ideally suited for mass production of three-dimensional geometries using a micro-molding process. It is expected that this process will produce high aspect ratio features with dimensions on the order of microns or less, combined with excellent surface finish and tight tolerances.

State of the Art in MEMS

Current MEMS fabrication is heavily influenced by, and largely dependent on, technologies and processes originally developed for microelectronics manufacturing. These processes impose severe limitations on the materials used, and are primarily limited to silicon in combination with sputtered and etched thin metallic coatings. The layered nature of the process imposes very severe limits on the types and range of component geometries which can be produced, and thus on the types of mechanical motion that can be realized. Further these processes are extremely slow and not amenable to mass production.

Potential Impacts on Device Components

If it were possible to fabricate miniature components with complex, three-dimensional geometries from high strength materials, one could envision fabricating: micro-resonators, high frequency microwave components such as waveguides, connectors, and enclosures, micro-flexures, micro-surgical devices, micro-motors, micro-transmission components, micro-fluidic arrays, and non-planar reflective micro-optics.

Advantages of Bulk Metallic Glasses

Many of the bulk metallic glasses have several fundamental characteristics which make them ideal for net-shape forming of micro-components. First are comparatively low glass transition temperatures (in some cases as low as approximately 350ºC). Above this temperature, the material becomes essentially a supercooled liquid, although it has not truly “melted” in the sense of a phase transformation. Second, since no phase change occurs when the material is cooled, the shrinkage is very small, on the order of 0.5% or less, compared to 4 to 8%
for conventional metallic alloys upon solidification. This gives exceptional tolerance control for the molded features. Finally, due to its lack of crystallinity, bulk metallic glasses exhibit excellent surface finish upon vitrification; this is important because of the difficulty in performing secondary surface finishing operations on micro-components.

The low molding temperatures and pressures required for forming these bulk metal glasses permits molds to be made of conventional materials such as tool steels or copper. This suggests that it may be possible to slightly modify conventional thermo-plastic molding equipment for this application, resulting in relatively low capital costs.

When molding fine features with high aspect ratios, where the high surface area to volume ratios lead to high heat transfer rates, the ability to control the viscosity of the material by controlling temperature should allow additional flexibility in optimizing processing parameters. The components made from the bulk metallic glasses will have exceptional mechanical strengths, high flexibilities, good fracture toughnesses and fatigue strengths, and will be both electrically and thermally conductive.

Research Challenges and Approach

We anticipate that the ability to flow the bulk metallic glasses in the supercooled liquid state is ideally suited for mass production using micro-molding processes. There are, however, a series of challenges that must be overcome before such a vision becomes a reality. These challenges and the innovative approaches to overcome these challenges are described in the following table.

### Key variables and technical challenges

<table>
<thead>
<tr>
<th>Key variables</th>
<th>Goal</th>
<th>Current practice</th>
<th>Associated barriers</th>
<th>Innovative approaches</th>
</tr>
</thead>
<tbody>
<tr>
<td>Material properties</td>
<td>Same properties as bulk material</td>
<td>LIGA – Ni, Cu MEMS - Silicon</td>
<td>Avoid oxide formation, &amp; crystallization</td>
<td>Inert gas atmosphere, active heating and cooling of dies.</td>
</tr>
<tr>
<td>Feature sizes</td>
<td>5 µm</td>
<td>LIGA - &lt; 1µm MEMS – 5µm typ.</td>
<td>Die manufacture, mold filling</td>
<td>LIGA or µEDM dies, temp. &amp; press. control, electro-statically aided mold filling and ejection.</td>
</tr>
<tr>
<td>Aspect ratio</td>
<td>5:1</td>
<td>LIGA – 10:1 or better</td>
<td>Predictable shrinkage</td>
<td>Low shrinkage of material if no crystallization</td>
</tr>
<tr>
<td>Relative tolerance</td>
<td>$10^{-3}$</td>
<td>$10^{-2}$</td>
<td>Poor without secondary polishing</td>
<td>Die manufacture, avoiding surface oxides</td>
</tr>
<tr>
<td>Surface finish</td>
<td>Optical quality as molded</td>
<td>Poor without secondary polishing</td>
<td>Die manufacture, avoiding surface oxides</td>
<td>LIGA or µEDM dies, inert gas atmosphere</td>
</tr>
<tr>
<td>Production rate</td>
<td>&gt; 1 part/minute</td>
<td>Days per batch</td>
<td>Molding equip.</td>
<td>Adapt current thermoplastic molding equipment</td>
</tr>
<tr>
<td>Cost</td>
<td>Inexpensive and low capital investment</td>
<td>High cost and high capital investment</td>
<td>Die cost, die durability, cycle time</td>
<td>LIGA or µEDM dies, adapt current thermoplastic molding equipment</td>
</tr>
</tbody>
</table>

### Personnel

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