



## Bulk Metallic Glasses and Composites for Optical and Compliant Mechanisms

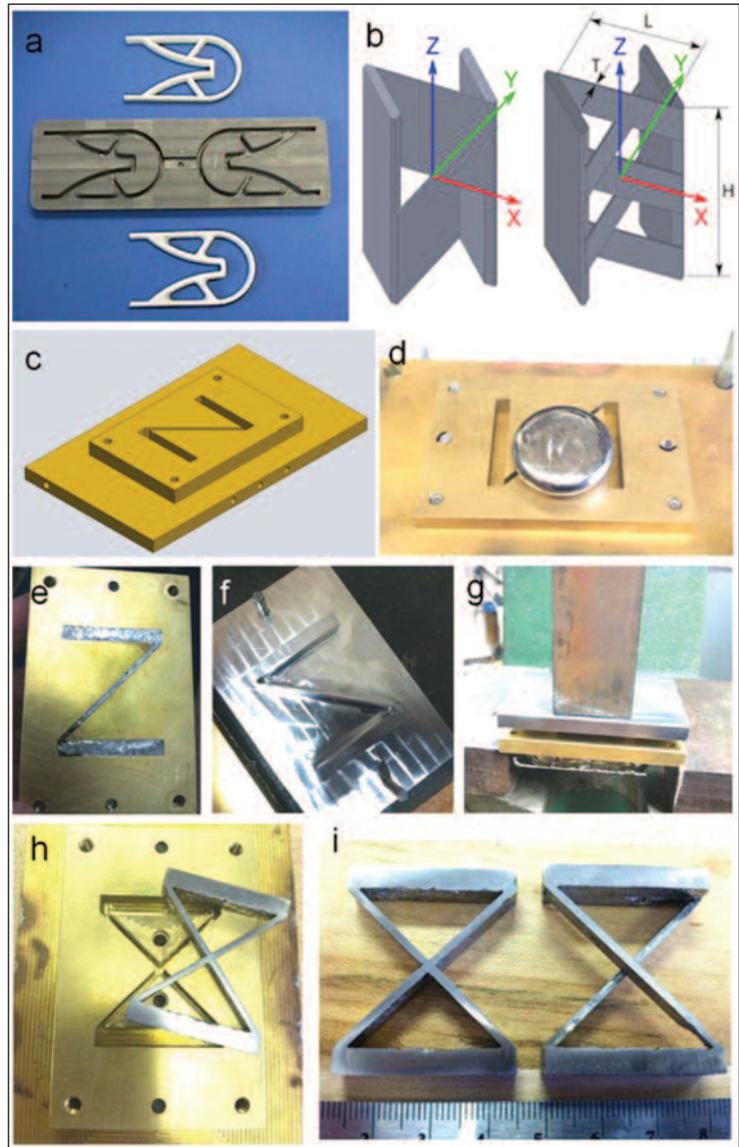
This innovation has uses in the aerospace, optics, bio-implants, spacecraft, and sporting equipment industries.

NASA's Jet Propulsion Laboratory, Pasadena, California

Mechanisms are used widely in engineering applications due to their ability to translate force and movement. They are found in kinematic pairs, gears, cams, linkages, and in flexure mechanisms (also known as compliant mechanisms). Mechanisms and flexures are used widely in spacecraft design, especially in the area of optics, where precise positioning of telescope mirrors requires elastic flexing of elements. A compliant mechanism is generally defined as a flexible mechanism that uses an elastic body deformation to cause a displacement (such as positing a mirror). The mechanisms are usually constructed as a single monolithic piece of material, and contain thin struts to allow for large elastic bending with low input force. This creates the largest problem with developing precise mechanisms; they must be fabricated from a single piece of metal, but are required to have strict accuracy on their dimensions. They are generally required to have high strength, elasticity, and low coefficient of thermal expansion.

The two biggest problems with conventional mechanisms are fabrication and materials selection. Plastic prototypes can be readily produced at low cost using 3D printing or molding, and utilize the large elasticity of polymers, but the mechanisms are unsuitable for structural applications due to their low strength and degradation, especially in spacecraft (polymers degrade in space due to the high UV exposure). A compliant mechanism used in a real engineering application must typically be made of metal, and must be fabricated either by machining or by an additive manufacturing process for metals. They are generally made from aluminum (low density and high machinability) or titanium (high strength and large elasticity). However, since the struts of the mechanism must be very thin (typically less than one mm thick), traditional machining is difficult to use because the struts bend during machining.

The use of amorphous metals (AMs) and their composites is ideal for both the mechanical properties and processing of compliant mechanisms and flexures. AMs have high strength, the elasticity of polymers, and the processability of plastics. They can be easily fabricated into monolithic mechanisms at significantly lower cost than machining, and exhibit performance better than many crystalline material in the same application. Since they can be fabricated using reusable steel or brass molds, many parts can be fabricated using only the initial material cost and the initial mold cost. This allows for many mechanisms to be made cheaply.



**Some Examples of Processing and Products:** (a) Compliant mechanisms can be fabricated easily from plastics by pressing them into heated molds. (b) Examples of cross-blade flexures often used in optics to support mirrors. (c) Design of multi-piece, water-cooled brass molds for casting amorphous metals and (d) an ingot of amorphous metal before heating and forging. (e) Once forged, the amorphous metal or composite fills the small features of the mold. (f) A steel ejector that snugly fits into the brass mold is used to push out the amorphous metal mechanism from the mold. (g) The amorphous metal flexure is pressed out of the mold with a press. (h) In another geometry, a cartwheel flexure can be fabricated from amorphous metal, seen here after trimming, and the undamaged mold from which it was cast. (i) Side-by-side amorphous metal flexures; cartwheel (left) and cross-blade (right).

AMCs (amorphous metal composites) are composite alloys that exhibit similar properties and processing ability to monolithic AMs, but also have the ability to be much tougher (to avoid brittle failure), have much higher fracture toughness and fatigue life, and also can be tuned to have low coefficient of thermal expansion (CTE) by utilizing low CTE inclusions. These combinations of properties (mechanical performance and processing ability) have not been utilized for compliant mechanisms until now.

AMs (which are also known as bulk metallic glasses or BMGs) and their composites can be fabricated into optomechanical, compliant, or flexure mechanisms easily and at low cost. To accomplish this, a selected composition of AM or AMC is fabricated into a feedstock material that is heated (using radio frequency heating or resistance heating)

and forged into a final part with either net or near-net shape. Because AM alloys have low melting temperatures, they can be melted and forced into a very complex mold, just like a plastic, but form a glass under the high cooling rate obtained by cooling lines in the mold. The quenched part does not react with the mold and is mechanically robust enough to survive the ejection process. The final part has the same tolerances as the mold (since there is very little shrinkage when forming a glassy metal) and yet can be removed without damaging the mold. This offers the potential to develop mechanisms that outperform currently available metals (aluminum, titanium, and steel) but that also can be fabricated in a low-cost, repeatable process. The resulting mechanisms, demonstrated here for Ti-Zr-Be alloys, have 2% elastic limit, up to 2 GPa yield strength, hardness >50 R<sub>c</sub>,

fracture toughness >100 MPa m<sup>1/2</sup>, and excellent fatigue limit. Prototypes have been developed into two common mechanisms, a crossblade, and a cartwheel flexure (see figure).

*This work was done by Douglas C. Hofmann and Gregory S. Agnes of Caltech for NASA's Jet Propulsion Laboratory. For more information, contact [iaoffice@jpl.nasa.gov](mailto:iaoffice@jpl.nasa.gov).*

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*Innovative Technology Assets Management  
JPL*

*Mail Stop 321-123*

*4800 Oak Grove Drive*

*Pasadena, CA 91109-8099*

*E-mail: [iaoffice@jpl.nasa.gov](mailto:iaoffice@jpl.nasa.gov)*

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