



Investigating bulk metallic glasses as ball-and-cone locators for spacecraft deployable structures

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Abstract: Ball-and-cone locators are the standard latching mechanism for spacecraft with deployable structures. Similar to other spacecraft components, the locators require the use of materials with low density and high performance. Bulk metallic glasses (BMGs) and their composites are alloys with superior mechanical properties with potential for spacecraft applications. In this study, Ti-based BMGs and their composites were prototyped for next-generation ball-and-cone locator inserts.

Key words: Bulk metallic glasses, Spacecraft, Ball and cone locators, Titanium, Composites.

1. INTRODUCTION

Novel materials are being developed constantly to meet the de- mand for high-performance applications, such as spacecraft com- ponents. To deploy a spacecraft into service, it must be launched from Earth's surface to the desired orbit altitude or target trajec- tory. Consequently, the total mass of the spacecraft is limited by the amount of rocket fuel available for launch, which is deter- mined, in the simplest case (external forces absent), by the Tsi- olkovsky rocket equation [1]:





where m0 is the mass of the payload (spacecraft), rocket, and propellant prior to launch, mf is the remaining mass after propulsion, v is the change in speed required to reach the destination, and v_e is the speed of the exhaust. Accordingly, a lighter space- craft part allows for increased rocket payload capacity, lowered fuel consumption, lowered design burdens for other critical components, and load redistribution to tune the natural frequencies of the spacecraft [2].

In addition to lower mass density, another criterion for space- craft materials selection is public safety. To reduce the quantity of space debris from artificial objects in Earth orbit, decommissioned satellites are designated to deorbit and reenter the Earth's atmosphere, if the risk of harm is sufficiently low [3,4]. To minimize this risk, components should possess sufficiently high mechanical performance while in service but should ablate quickly when ex- posed to the heat during reentry. The rate of ablation depends on the material's density, thermal conductivity, heat capacity, melting temperature, heat of fusion, heat of oxidation, and heat of ablation [5].

Ball-and-cone locators are a standard latching mechanism of deployable structures aboard spacecraft. The current state-of-the- art consists of a cylindrical 440 stainless steel insert with a machined concave cone, which is aligned against a Si3N4 ball that is restrained onto the concave cone of another identical insert (Fig. 1). Such a design allows for self-correction of the orientation of the structure and is sufficiently mechanically robust for space- flight. A typical spacecraft with deployable structures could have over fifty ball-and-cone locator inserts. At 24.4 g per insert, the inserts contribute over 1 kg of payload mass. Therefore, substituting a lower density material for the insert is highly beneficial for the spacecraft design. Ideally, the material used to produce the loca-





tors should possess low density, high hardness to avoid damage to the cone surface, ductility in compression to prevent catastrophic failure, low melting point to properly ablate during atmospheric reentry, tolerance to cryogenic temperatures and cryogenic thermal cycling, and should be

compatible with flight grade epoxy used to mount the locator inserts onto the spacecraft.

Bulk metallic glasses (BMGs) have historically been a strong candidate for spacecraft components due to their exceptional prop- erties such as high specific strength, high elasticity, and corrosion resistance [6–10]. Most notably, a BMG was used as one of the materials for the solar wind collector plates for the NASA Gen- esis mission [11-13]. In addition, BMGs were demonstrated to be feasible for other spacecraft components such as gears [14, 15], compliant mechanisms [16], and micrometeorite shielding [17, 18]. BMGs, typically designed near deep eutectics for increased glass forming ability [19], possess low melting points and there- fore are prone to ablate during spacecraft reentry to the Earth's atmosphere, which ensures public safety when BMGs are used for Earth-orbiting satellites. Therefore, BMGs are highly befitting as the material for fabricating ball-and-cone locator inserts. The current standard ball-and-cone locator insert has a diameter of 15.9 mm (5/8 in), so the candidate BMG compositions must have critical casting thicknesses (dc), the maximum thickness such that the BMG could be made fully amorphous, of at least 16 mm or higher. Of the low density alloys (below 6.0 g cm-3), only Ti-based BMGs possess sufficient mechanical performance, chemical inert- ness, and respectable glass forming ability (GFA) to meet the size requirement [20]. Furthermore, Ti-based BMGs are tolerant to cycling between cryogenic temperatures [21], which is essential for spacecraft applications. Ti-based BMGs are widely studied in the scientific literature [20,22–30], but only a handful of specific compositions have a dc \geq 16 mm [25,31–34], with the largest reported dc as at least 50 mm [31,32].





In this study, we prototype ball-and-cone locator inserts fabricated from Ti-based BMGs with low density and dc \geq 16 mm. To reduce the density further and enhance the mechanical properties, a novel BMG matrix composite was also developed. In addition to the measurement of mechanical properties, specifically designed push-out tests were performed on the BMG and BMG composite inserts, with and without cryocycling, to evaluate their performance as well as demonstrate readiness for integration into spacecraft. Similar tests were performed on inserts fabricated from 440 stainless steel, and from Ti-6V-4Al.



Fig. 1. (a) Schematic of the ball-and-cone locator mechanism. Photographs of (b) the standard locator insert fabricated from 440 stainless steel (the green tint is from the applied flight epoxy primer), positioned next to the Si_3N_4 ball, (c) the insert mounted into a prototype metal (Al) frame with flight epoxy and anchored down with a socket head screw, (d) the insert mounted in a carbon fiber frame with flight epoxy and anchored down with a socket head screw, and (e) ball-and-cone locator mechanism in motion. The arrow indicates the restraining clip to secure the ball onto one of the inserts. (For interpretation of the colors in the figure(s), the reader is referred to the web version of this article.)

2. Alloy design, fabrication, and characterization

2.1. Sample fabrication and characterization





Fig. 2 summarizes the BMG and BMG matrix composite ball- and-cone locator insert production method. The constituent ele- ments of at least 99.99% purity, massed out to their respective compositions, were arc melted in a Ti-gettered, Ar atmosphere. The ingots were flipped and remelted at least three times to ensure sample homogeneity. The ingots were then suction cast in the arc melter to produce parts of the same geometry as the standard ball- and-cone insert made from 440 stainless steel. After demolding, flashing and excess material were removed, followed by surface grinding and polishing to produce the desired surface finish. Sub- sequently, a through hole and counter bore were machined onto the cast inserts to emulate the 440 stainless steel insert. X-ray diffraction (XRD) and Vickers hardness measurements were per- formed on cross sections from the as-cast parts, which were cut with a precision diamond saw with the surfaces ground and polished.

2.2. Alloy selection and development

From reviewing the scientific literature, the Ti-based BMG with the lowest density for $dc \ge 16$ mm is Ti40 Zr20 Cu10 Be30 [15]. Inserts fabricated from Ti40 Zr20 Cu10 Be30 are fully amorphous (Fig. 3a). For comparison, inserts fabricated from (Ti36.1 Zr33.2 Ni5.8 Be24.9)91 Cu9, the alloy with the highest reported dc of over 50 mm [31], were also produced and characterized (Fig. 3b). Attempts to reduce the density by partially substituting Al for Ti or Cu in Ti40 Zr20 Cu10 Be30 resulted in a diminished GFA resulting in semi-crystalline sam- ples (Fig. 3c, d). Crystallization of the monolithic BMG dramati- cally embrittles the part [35], and therefore should not be used for load-bearing applications. The density of Ti40 Zr20 Cu10 Be30 (5.04 gcm–3) is less than that of the majority of Ti-based BMGs in the literature [20,36]. The low density coupled with high hard- ness of Ti40 Zr20 Cu10 Be30 makes it a prime candidate for producing ball-and-cone locator inserts since it will resist and wear on the cone surface by the ball during the latching process. Ti-6Al-4V, Please cite the article as: A. Desai, M.L. Auad, H. Shen, and S.R. Nutt, "Mechanical Behavior of Hybrid Composite Phenolic Foam," J. Cellular Plastics 44 [1] (2008) 15-36. DOI: 10.1177/0021955X07078021





de- spite having lower density, is much softer than Ti-BMGs and 440 C stainless steel, and therefore are not suitable for this intended ap- plication. Density and Vickers hardness of alloys discussed in this work are summarized in Table 1.

Apart from monolithic BMGs, Ti-based BMG matrix composites could also be utilized for the ball-and-cone locator inserts. Starting from the Ti44 Zr20 Cu5 V12 Be19 composite (DV2), designed for low density [38], and partially replacing V with Al to further decrease the density led to the development of Ti44 Zr20 Cu5 V5 Al7 Be19. For this system, V is known to soften while Al is known to harden the composite. Hence, Ti44 Zr20 Cu5 V5 Al7 Be19 is substantially harder at 534 HV than DV2 at 451 HV, while being less dense at 4.91 versus 5.13 gcm–3, respectively (Table1). XRD measurements of the cross section (Fig. 3e) depict prominent peaks attributable to the dendritic body-centered cubic (BCC) phase, with the broadening of the base of the primary peak confirming the presence of the amorphous phase. A scanning electron microscope (SEM) image of the microstructure is included in Fig. 3 inset, where the darker contrast depicts the BCC phase within an amorphous matrix of lighter contrast. The volume ratio between the matrix and the BCC phase remains close to 70:30, as reported for DV2 in [38], due to limited solubility of V in the matrix and Cu and Zr in the BCC phase [38,39]. This novel Ti44 Zr20 Cu5 V5 Al7 Be19 BMG matrix composite has a lower density and higher hardness than Ti40 Zr20 Cu10 Be30, a monolithic BMG.

Ti-based BMGs and their composites also possess low liquidus temperatures (TL), ranging approximately 1000–1300 K [36]. When alloyed with Be, the TL range narrows to 1000–1200 K [36,38]. The TL for the Ti-based BMGs and associated composites span 950–1100 K (Table 1). For reference, the TL for conventional al- loys used in this study is around 1900 K for Ti-6Al-4V and 1750 K for 440C stainless steel [37]. The much lower TL of Ti-based BMGs and composites allows





for ease of materials processing as well as ensuring that the inserts safely ablate away in the event of spacecraft reentry into the Earth's atmosphere.



Fig. 2. Flow chart of the BMG ball-and-cone locator insert fabrication. (a) High purity elements were massed out to their corresponding weight fraction and placed in a crucible in the water-cooled Cu hearth of the arc melter. (b) Then the elements were arc melted together. The ingot is flipped and remelted multiple times until (c) a homogeneous ingot was made. Then, the ingot is suction casted in the arc melter to produce (d) the preform. Part of the mold is shown (right). Finally, the excess material is removed and the counter bores are machined to form the final part. (e) The photograph depicts (left) the standard 440 stainless steel insert positioned next to (right) the cast BMG insert after final machining.



Fig. 3. XRD performed on cross section of cast inserts made from (a) $Ti_{40}Zr_{20}Cu_{10}Be_{30}$ (b) $(Ti_{36.1}Zr_{33.2}Ni_{5.8}Be_{24.9})_{91}Cu_9$ (c) $Ti_{40}Zr_{20}Cu_5Al_5Be_{30}$ (d) $Ti_{35}Zr_{20}Cu_5Al_{10}Be_{30}$ and (e) $Ti_{44}Zr_{20}Cu_5V_5Al_7Be_{19}$. The arrows indicate the dendritic BCC phase. The inset is a SEM image of the microstructure present in (e). The regions with darker contrast are BCC dendrites and the lighter contrast is the amorphous matrix.





Table 1

Summary of some key materials properties of the alloys discussed in this work. The Vickers hardness was measured using 2000 gf and 10 s dwell time. The density was measured by the Archimedes method. Replicating the exact dimensions from the standard ball-and-cone locator insert, the density fraction of the candidate material compared to 440 stainless steel is determined, which is used to calculate the expected mass per insert. Liquidus temperatures were taken from references or measured using differential scanning calorimetry.

Material	Hardness (HV)	Density (g cm ⁻³)	Density fraction	Mass per insert (g)	Liquidus temperature (K)
Standard alloys					
440 C Stainless Steel (State-of-the-art)	660	7.65	1.000	24.4	1753 [<mark>37</mark>]
Ti-6Al-4V	358	4.41	0.576	14.1	1923 [37]
Ti-based BMGs					
(Ti _{36.1} Zr _{33.2} Ni _{5.8} Be _{24.9}) ₉₁ Cu ₉	504	5.51	0.720	17.6	961 [<mark>31</mark>]
$Ti_{40}Zr_{20}Cu_{10}Be_{30}$	527	5.04	0.659	16.1	1050 [15]
Crystalline Ti-based BMG alloys					
$Ti_{40}Zr_{20}Cu_5Al_5Be_{30}$	731	4.76	0.622	15.2	~1050
$Ti_{35}Zr_{20}Cu_5Al_{10}Be_{30}$	650	4.66	0.609	14.9	~1050
Ti-based BMG matrix composites					
$Ti_{44}Zr_{20}Cu_5V_{12}Be_{19}$ (DV2)	451	5.13	0.671	16.4	~1100
$Ti_{44}Zr_{20}Cu_5V_5Al_7Be_{19}$	534	4.91	0.642	15.7	~1100

3. Part performance and feasibility

3.1. Four-point bending and ultrasonic measurements

Four-point bending experiments were carried out on Ti40Zr20 Cu10Be30, the best performing BMG, and Ti44Zr20Cu5V5Al7Be19, the developed BMG matrix composite with low density. As a com- parison, DV2 was also characterized. Similar to the casting process outlined above, 3.5 mm square beams of at least 50 mm in length were cast via arc melting in a Ti-gettered, Ar atmosphere. Flashing and surface casting defects were removed by grinding. Then, the beams were bent using the four-point bending fixture mounted to a universal testing machine (UTM). The loading span length is 15 mm and the supporting span length is 45 mm. When the loading span length is 1/3 the support span length, the flexural stress (σ f) is calculated using:

$$\sigma_{\rm f} = \frac{FL}{bh^2}$$





where F is the force, L is the support span length, b is the beam width, and h is the beam thickness. The results are summarized in Fig. 4.

From the four-point bending results, it is apparent that Ti44 Zr20 Cu5 V5 Al7 Be19 has a similar flexural yield strength to Ti40 Zr20 Cu10 Be30, but with much larger plasticity. Ti40 Zr20 Cu10 Be30 is stiffer than Ti44 Zr20 Cu5 V5 Al7 Be19, which is confirmed with ultrasonic measurements (Table 2). DV2 had much lower yield strength, stiffness, and hardness (Table 1) compared to Ti44 Zr20 Cu5 V5 Al7 Be19, indicating that the mechanical properties of the developed composite are superior than the parent material. Therefore, the most promising material in terms of material properties for producing next generation ball-and-cone locator inserts is the Ti44 Zr20 Cu5 V5 Al7 Be19.

3.2. Cryocycling and push-out tests

To evaluate the practicality of the selected materials be- yond measurements of mechanical properties, push-out tests were specifically designed. Ball-and-cone locator inserts made from 440 stainless steel, Ti-6Al-4V, (Ti36.1Zr33.2Ni5.8Be24.9)91Cu9, Ti40 Zr20 Cu5 Al5 Be30, and Ti44 Zr20 Cu5 V5 Al7 Be19 were bonded to Ti-6Al-4V sleeves using Hysol EA 9394 (Henkel Corporation Aero- space Group) epoxy adhesive (Fig. 5a).

Inserts and sleeves were cleaned for bonding by initially wip- ing acetone using a clean room wiper until no further discoloration appeared on the wiper. The parts were then immersed for 10 min- utes in a heated ($170 \circ F \pm 10 \circ F$, $77 \circ C \pm 5 \circ C$) tap water solution of Oakite 61B (120 g/L) and transferred immediately to a hot tap water to rinse (1 min minimum) to remove the Oakite solution. Demineralized water at ambient temperature was used for the fi- nal rinse. Following cleaning, the inserts and sleeves were prepared for bonding by immersion for 10 min (± 5 min depending on ob-Please cite the article as: A. Desai, M.L. Auad, H. Shen, and S.R. Nutt, "Mechanical Behavior of Hybrid Composite Phenolic Foam," J. Cellular Plastics 44 [1] (2008) 15-36. DOI: 10.1177/0021955X07078021





served reactivity) in a solution of 20 parts by volume of Sur Fin Ti-2 etchant to 100 parts by volume of 70 wt.% nitric acid. Follow- ing etching, the parts were rinsed in hot tap water for 2 minutes and then soaked in demineralized water for 2 min. Hysol EA 9394 epoxy adhesive, mixed at 100 parts by weight Part A to 17 parts by weight Part B and degassed, was hand applied to the mating surfaces of the etched inserts and sleeves. The epoxy-coated inserts were placed into the epoxy coated sleeves and excess epoxy was removed. The epoxy reached full cure after a minimum of 5 days at room temperature.

After bonding, push-out tests were performed on the insert- epoxy-sleeve system. Custom-made fixtures were designed and machined to function on a universal testing machine (UTM). The fixtures consist of a top plunger, with a ball tip, and a counter bored platen for the base (Fig. 5b). The samples are placed inside the counter bore, where the outer diameter is appropriately sized to house the sleeve and the inner diameter allows the insert to pass unobstructed during the test. Then, the top plunger is low- ered at a constant displacement rate and the force is recorded. The force will consistently increase with displacement until the insert starts to slip with respect to the sleeve. At that moment, the force will drop. The maximum force recorded and used as a metric for evaluating the performance of the insert.

In addition to mechanical forces, structural spacecraft compo- nents experience cyclic, cryogenic temperature profiles. To emulate the thermal conditions, inserts epoxied to the sleeves were cryocycled from room temperature to -150°C for five cycles in a cold chamber (Fig. 5c). Then, pushout tests were performed and compared to the control, where no cryocycling was applied. Pre- vious studies of cryocycling Ti-based BMGs showed no discernable change in mechanical properties after cycling [21], but more re- cent studies suggest that cryocycling may toughen BMGs of certain compositions [40]. BMG matrix composites also exhibit remarkable mechanical properties at Please cite the article as: A. Desai, M.L. Auad, H. Shen, and S.R. Nutt, **"Mechanical Behavior of Hybrid Composite Phenolic Foam,"** J. Cellular Plastics 44 [1] (2008) 15-36. DOI: **10.1177/0021955X07078021**





cryogenic temperatures, similar to mono- lithic BMGs [41,42]. The coefficients of thermal expansion of BMGs are on the order of $10-5 \circ C-1$ [43], which is comparable to most metals. Therefore, any deterioration in performance from the push- out tests of inserts fabricated from BMGs and their composites is attributable to changes in the epoxy from cryocycling. Figs. 5d, e and Table 3 summarizes the results from the push-out tests.

Without cryocycling, the ball-and-cone locator inserts produced from all the materials considered had maximum push-out forces that are comparable to or greater than that of the reference state-of-the-art 440 stainless steel inserts. After cryocycling, the maximum push-out force of Ti-6Al-4V, Ti40Zr20Cu5Al5Be30, and Ti44 Zr20 Cu5 V5 Al7 Be19 inserts increased and were greater than that of the 440 stainless steel inserts. However, the Ti-6Al-4V exhib- ited plastic deformation, resultant from the ball impinging onto the insert (Fig. 5f), prior to the failure of the epoxy and slipping. Ti-6Al-4V despite possessing low density, is not sufficiently hard to resist the wear that would be caused from Si3N4 ball and should not be selected for this application. The inserts fab- ricated from other materials had no evidence of surface damage, indicating that even the semi crystalline Ti40 Zr20 Cu5 Al5 Be30 in- sert is sufficiently robust. However, the brittle nature of crystal-lized BMGs poses too much of a risk for use for this application. The (Ti36.1Zr33.2Ni5.8Be24.9)91Cu9 inserts experienced a drop in the maximum push-out force post-cryocycling and underperforms the 440 stainless steel inserts. As seen in Fig. 5g, the low push-out force is due to the failure of the epoxy and not from the failure of the (Ti36.1 Zr33.2 Ni5.8 Be24.9)91 Cu9 insert. The insert itself experienced no plastic deformation as a result from the test.







Fig. 5. (a) Photograph of an insert that is bonded to the Ti-6Al-4V sleeve using flight grade epoxy. (b) Photograph of the push-out test fixture, mounted on a UTM, with a sample loaded. (c) Insert-epoxy-sleeve samples taken out of the cold chamber to warm up to room temperature for cryocycling. Compression force versus displacement curves of the push-out tests done for samples (d) without cryocycling and (e) after cryocycling. (f) Photograph of Ti-6Al-4V inserts (left) as-machined and (right) after cryocycling and the push-out test. The arrow indicates the dent formed by the ball during the push-out test. (g) Photograph of cryocycled (Ti_{36.1}Zr_{33.2}Ni_{5.8}Be_{24.9})₉₁Cu₉ insert after the push-out test. The arrow indicates the failed epoxy. The insert remains undamaged.

4. Summary and conclusions

Based on the results of the push-out tests and the measured mechanical properties, the Ti44 Zr20 Cu5 V5 Al7 Be19 composite devel- oped in this study has the highest potential to replace 440 stainless steel as the state-of-the-art for ball-and-cone locator inserts due to lower density,





sufficiently high hardness, high strength, high plasticity, and high push-out forces with and without cryocycling. Utilizing Ti44Zr20Cu5V5Al7Be19, 437 g would be saved for a space- craft with fifty inserts (35.9% lighter when compared to 440 stain- less steel). If a monolithic BMG be preferred over the BMG matrix composite, Ti40 Zr20 Cu10 Be30 should be used due to its high GFA and attractive mechanical properties. Also, both monolithic BMGs and BMG matrix composites possess low TL values, which is ben- eficial for ensuring public safety of spacecraft reentry. Thus, with the implementation of these newly discovered materials for next- generation ball-and-cone locator inserts, more efficient and flexible designs could be realized for future spacecraft.

Acknowledgements

This research was funded by NASA's Exploration Systems Mis- sion Directorate under Contract No. NNH10ZTT001N. DCH also ac- knowledges funding support from the Presidential Early Career Award. PB's research was supported by an appointment to the NASA Postdoctoral Program at the NASA Jet Propulsion Laboratory, California Institute of Technology. The program is administered by Universities Space Research Association under contract with NASA. Part of this research was done at the Jet Propulsion Laboratory, California Institute of Technology, under contract with NASA. Refer- ence herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not constitute or imply its endorsements by the United States Government or the Jet Propulsion Laboratory, California Institute of Technology.



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