COLD WELDING AND FRICTION IN VACUUM OF BULK METALLIC GLASS (BMG) MADE BY POWDER BASED PROCESSES FOR USE IN SPACE

A.Merstallinger (1), L. Baca(1), N. Stelzer (1), Z. Kovacova(2), E. Neubauer (2), A. Toufine(3), A. Makaya(4)

*(1) **Aerospace & Advanced Composites GmbH,** Viktor Kaplan Strasse 2, 2700 Wiener Neustadt, Austria*

EMail: Andreas.Merstallinger@aac-research.at

*(2) **RHP-Technology GmbH,** 2444 Seibersdorf, Austria*

*(3) **OPTALM,** 31240 l'UNION, France*

*(4) **ESA (ESTEC)**, 2200 AG Noordwijk, The Netherlands*

ABSTRACT

Bulk Metallic Glasses (BMGs) offer properties which make them interesting to tribological applications like gears or HDRMs (Hold Down and Release Mechanisms). Especially the low stiffness combined with reasonable hardness in comparison to steels is promising.

This paper reports on optimisation of the powder based processing routes using small specimens with subsequent characterisation of crystallinity, density, etc. This was followed by manufacturing of semi-components. Tribological testing was run on the specimens extracted therefrom.

Results presented herein show that friction and wear of pairing BMG-BMG is lower compared to steel-steel. However, the results do not indicate uniquely that they can be operated without additional lubrication, they may offer emergency lubrication (e.g. when during a low temperature cycle the fluid lubrication fails). Of high interest is their ability to avoid cold welding when pairing BMG to BMG. Tests under conditions of launch, show them to exhibit negligible adhesion (without additional coatings or lubricants). This makes them also interesting to components whose contact points are not accessible to coating processes (clock springs).

1 INTRODUCTION TO BMG

BMGs are metallic alloys, which – by extremely rapid cooling – stay amorphous, while conventional cooling leads to (poly)crystalline micro-structures. The absence of any crystallinity leads to different and interesting properties compared to classical metallic alloys.

The scientific progress has been made particularly during last 25 years, more extensively in last 5-10 years. Several compositions have been developed. The first glassy alloy was reported by Duwez at Caltech, USA, in 1960. Au – 25at% Si in the glassy state was prepared by rapid solidifying the liquid using cold metal plate at cooling rates approaching 10^6 K.s^{-1}. X-ray diffraction (XRD) analysis revealed the absence of all crystalline structure and the formation of a non-crystalline structure of the prepared droplets. Following this discovery, a large number of metallic glasses were found in various alloy systems and were produced in form of ribbons, wires or thin sheets. Formation, structure and investigation of properties of metallic glasses have attracted increasing attention because of their fundamental scientific importance and engineering application potential [1],[2],[3].

Development of various processing techniques allowed to access bulk metallic glasses of bigger dimensions. The first bulk metallic glass (BMG) was the ternary Pd-Cu-Si alloy prepared by Chen et al. in 1974. The millimeter diameter rods were prepared by suction-casting method at significantly lower cooling rate 10^3 K.s^{-1}. Few years later, in 1982, bulk glass ingot of centimeter size was prepared from Pd-Ni-P by solidification at cooling rates at 10 K.s^{-1} region. In the late 1980s, Inoue et al. in Tohoku University of Japan succeeded in finding new multicomponent alloy systems consisting mainly of common metallic elements with lower critical cooling rates. Having systematically investigated the glass forming ability (GFA) of ternary alloys of rare-earth materials with Al and ferrous metals, they observed exceptional GFA in the rare-earth-based alloys, for example, La–Al–Ni and La–Al–Cu. They obtained fully glassy rods and bars with thicknesses of several millimeters by casting the alloy melt in water-cooled Cu molds. Based on this work, the researchers developed similar quaternary and quinary amorphous alloys (e.g. La–Al–Cu–Ni and La–Al–Cu–Ni–Co BMGs) at cooling rates under 100 K/s and the critical casting thicknesses could reach several centimeters. Some similar alloys with rare-earth metals partially replaced by the alkali-earth metal Mg were also developed (such as Mg–Y–Cu, Mg–Y–Ni, etc.,), along with a family of multicomponent Zr-based BMGs (e.g. Zr–Cu–Ni, Zr–Cu–Ni–Al BMGs). The work of Inoue led to the design and investigation of new families of BMGs. Many kinds of BMGs have been developed including MgCuY, LaAlNi, ZrAlNiCu, ZrAlNiCu (Ti, Nb), ZrTiCuNiBe, TiNiCuSn, CuZrTiNi, NdFeCoAl, LaAlNi, FeCoNiZrNbB, FeAlGaPCB, PrCuNiAl, PdNiCuP, etc. [3]. The development of late transition metal (LTM)-based BMGs is strongly encouraged due to material costs and the availability of raw material deposits.

Therefore, a Fe-based BMG in the Fe–Al–Ga–P–C–B alloy system was successfully developed in 1995. Also, at that time, three empirical component rules for the stabilization of a super cooled metallic liquid were proposed. These rules stated that (1) the multicomponent system should consist of three or more elements, (2) there should be a significant difference (greater than ∼12%) in the atomic sizes of the main constituent elements, and (3) the elements should have negative heats of mixing. A variety of Fe-based, Co-based, Ni-based, and Cu-based BMGs have been synthesized in accordance with these rules and other topological and chemical criteria. As a result, various unique properties of LTM-based BMGs have been obtained. These properties have not been obtained in any crystalline alloys. Therefore, it should be possible to extend the range of applications [4].

2 STATE OF THE ART

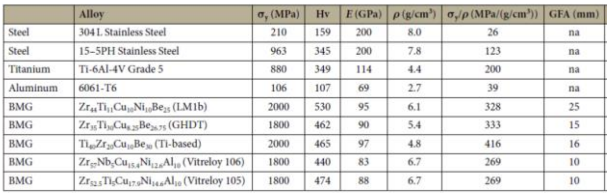
The Bulk Metallic Glass **Vitreloy 106a** (Zr58.5Nb2.8Cu15.6Ni12.8Al10.3) developed by Caltech in 1995 is one of the first examples of metallic glasses with flight heritage in space. The BMG was integrated into NASA's Genesis **mission as a solar wind collector [5].**

The use of conventional metals or ceramics for applications under prolonged movement, such as bearings and gears, come along with a number of short-comings. Crystalline metals tend to exhibit poor wear resistance whilst ceramics often suffer from brittleness.

BMGs offer wear resistance on par to ceramics but with up to two orders of magnitude higher toughness. In comparison the ceramics, the BMGS are much easier to fabricate due to a lower processing temperature, by using a variety of methods and better machinability.

Many of the properties of the metallic glasses are of high interest and desirable for space mechanism applications and are attributed to their homogenous and isotropic amorphous structure. In particular, metallic glasses have been extensively studied in bulk form and as coatings for their desirable wear and corrosion performance [6]. Thus, interesting space applications with enhanced lifetime, higher resistance to launch loads and possibly reduced dimensions, e.g. by using the geometrical freedom of Additive Layer Manufacturing techniques [7], [8] to support long missions are desired, especially for gears, e.g planetary gears (*Figure 1*) roller bearings, plane bearings [9], [10], [11].

Figure 1: Components made of BMGs: Planetary Gear: Housing (left) Gear wheels on carrier (Right)



	Alloy	σ_y (MPa)	Hv	E (GPa)	ρ (g/cm³)	σ_y/ρ (MPa/(g/cm³))	GFA (mm)
Steel	304 L Stainless Steel	210	159	200	8.0	26	na
Steel	15–5PH Stainless Steel	963	345	200	7.8	123	na
Titanium	Ti-6Al-4V Grade 5	880	349	114	4.4	200	na
Aluminum	6061-T6	106	107	69	2.7	39	na
BMG	$Zr_{44}Ti_{11}Cu_{10}Ni_{10}Be_{25}$ (LM1b)	2000	530	95	6.1	328	25
BMG	$Zr_{35}Ti_{30}Cu_{8.25}Be_{26.75}$ (GHDT)	1800	462	90	5.4	333	15
BMG	$Ti_{40}Zr_{20}Cu_{10}Be_{30}$ (Ti-based)	2000	465	97	4.8	416	16
BMG	$Zr_{57}Nb_5Cu_{15.4}Ni_{12.6}Al_{10}$ (Vitreloy 106)	1800	440	83	6.7	269	10
BMG	$Zr_{52.5}Ti_5Cu_{17.9}Ni_{14.6}Al_{10}$ (Vitreloy 105)	1800	474	88	6.7	269	10

Table 1: Comparison of properties between two common gear steels, conventional titanium and aluminum alloy, and five bulk metallic glass (BMG) alloys [11]. TN11

As reported by NASA [12] , metallic glasses can offer advantages for planetary and strain wave gearboxes to work with solid lubricants or even unlubricated (the latter must be taken with care, as the reported lifetime was close to zero!). They would then require no electrical power for the heaters to operate system and therefore the overall complexity of the system can be reduced. This leads further to an increased mission lifetime/science return. Metallic glasses or hybrids composed of steel and metallic glass gearboxes are candidate applications (e.g. using MoS_2 dry lubricated metallic glasses planet gears) which are screened for a drill application where only short life time is required [13]. The paper reports the success of functionality from low temperature (LN2) to ambient by a very first screening test. However, the transfer of these results to more general mechanisms is not possible. These test were done only in ambient (air), hence ice formation and oxidation is still covering the surface protecting them against adhesive seizure. Also no characterisation of the gears in terms of efficiency, stiffness, etc. was done. Hence they cannot be compared to data available at AAC. Hence, applicability to locomotion actuators in rovers would still to be assessed.

Anyway, the even more interesting outcome of this paper is an assessment by simulation of performance of a flex spline in a HD using the mechanical data of BMGs. Though some mechanical properties of BMG are inferior compared to reference steel, the working principle of a HD levels that out: BMG have a lower Young's modulus than steels, but as in a flex spline the deflection is fixed (not the load), hence the lower E causes less stress in the flex spline. Similar advantage is argued for the fatigue [8]. Hence the overall conclusion expects that " … the BMG flex splines should experience a similar or even longer fatigue life than steel due to their higher elasticity and yield strength, even though they are more brittle [8]". Of course, his expectation needs to be proven experimentally.

A third promising fact, is that the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration (NASA) has together with HDAG demonstrated that components for Harmonic Drive ® gears could be fabricated from metallic glasses [8]. In this case there is one of the drawbacks that the selected material was a Beryllium containing material. Although Beryllium is an excellent material, there are issues with the handling and machining of this material or alloys including Beryllium since it is toxic. Further, in case of sliding applications wear may occur, which will results in free debris. At first glance the high risk to health is not levelling out the small gain of mass saving by the Be-based BMG: the overall mass of larger flex spline ("size 20", is about 50mm diameter) is about 30g, mass saving by density would be ~30% of that –that is not significant compared to a gear box. Alternative BMGs mentioned are the Vitreloy105 and 106 (Zr-Nb-Cu-Ni-Al), at first glance these Non-Beryllium containing BMGs are also promising candidates.

Concluding the state of the art, a trade-off was performed considering not only material properties, but also manufacturing issues, e.g. the availability of raw materials or the probability of the manufacturing process to arrive at thick walled parts. The materials with higher priority (due to availability of suitable materials) are listed first:

C1: "ZrCu(23-25)Al(3-5)Nb(1-3) (AMZ4)"
C3: FeCrMoBWCMnSi
C2: Zr52.5Cu17,9Ni14,6Al10Ti5 (Vitreloy 105)
E2: Ti50Ni20Cu23Sn7 //Ti50Cu25Ni15Zr5Sn5
E3: Ni53Nb20Zr8Ti10Co6Cu3
E1: Fe41Co7Cr15Mo14Y2C15B6

C1-C3 are available as commercial powders while the experimental materials (E1-E3) were made by mechanically alloying. Based on an initial screening of the experimental grades, it was decided to continue only with commercial materials due to issues with the homogeneity of the powders. For the C3 powder the fabricated parts showed issues with corrosion and therefore this was also not further investigated.

3 EXPERIMENTAL - MANUFACTURING

3.1 SOLID STATE PROCESSING

RHP uses solid **compaction routes** included RSP (Rapid Sintering Process) and IHP (Inductive Hot Pressing). Rapid Sinter Pressing (RSP) enables high heating rates and applied pressure, but is limited in operation temperature (max. 950°C) and operating in ambient atmosphere. Secondly, Inductive Hot-Pressing (IHP) enables heating rates up to several 100°C/min, operation in vacuum or inert gas up to 2000°C. As first results were promising, these routes were continued for several BMGs.

3.2 LIQUID PHASE PROCESSING

Liquid phase processing was done at RHP by **Injection Moulding (IM)/casting** and was investigated for C1 and C2 materials. Commercially available AMZ4 (C1) and VIT105 (C2) ingots were purchased. This processing route was assessed for having great potential for direct realization of complex shapes. Various designs and processing conditions were used for preparation of samples. C2 material was selected for further development since fully amorphous samples were successfully casted.

3.3 ADDITIVE MANUFACTURING

OPT'ALM has implemented in industrial environment, the powder fusion Additive Manufacturing technology usually maned DED (Directed Energy Deposition). Samples and near shapes geometries for HDRM's and spring applications have been realized on plate and rod Titanium Alloy TA6V substrates.

Figure 2: Nozzle deposition during patches realizations.

TAGUCHI experimental plans allowed to investigate several sets of manufacturing process parameters (laser power, powder flow rate, speeds on trajectories) and geometries combined to deposition strategies. They were done on a MODULO 400 CNC DED machine. These TAGUCHI tests were performed on cube (1cm$^{3)}$, wall (5mm height, 40 mm length, 1 mm thick) and patch (between 0,3 to 0,6 mm thick, 20 x 20 mm) geometries, with 2 kind of BMG powders.

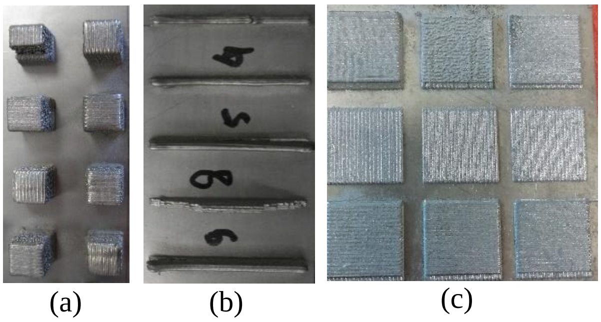


Figure 3: DED AM deposition strategies for cubes (a), walls (b), patches (c).

The best results were obtained on patches for material C1 powder. Because the amorphous microstructure of the deposited material is cooling rate dependant, additional works were performed on time between two successive weld beads. They permitted to get the greater cooling rate as possible combined to a very good adhesion of the material on substrate and no crack on BMG part.

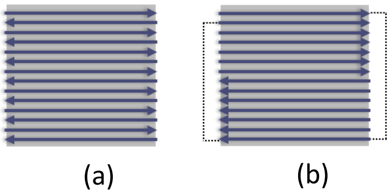


Figure 4: DED AM strategies (a) weld beads deposited side by side in zig-zag with a dwell time of 5 seconds; (b) weld beads deposited form external edge to the centre.

Typical set of parameters employed for HDRM application with the deposition strategy (b) is: Flow rate 5 g/min, Deposition speed 2200 mm/min, Laser power 150 W, Inter weld bead distance 0,1mm.

4 EXPERIMENTAL 1 – DOWNSELECTION OF CANDIDATES

Based on first iterations on manufacturing, following applications, sample geometries and processes were proposed for optimization towards application related semi-finished parts (*Table 2*).

Optimization of processing conditions for both, RSP and IHP, was done to prepare fully dense materials with amorphous structure. Finally, the optimal processing conditions were determined for C1.

Fully amorphous near net shape cups were successfully prepared by IM/casting of C2. However, it must be emphasized that the process is very sensible and there are many parameters affecting the final sample. Adjustment of processing parameters depends on specific tool design, quantity of material melted, processing conditions, especially temperature, cooling rate and temperature of tooling during injection/casting.

Application	Material / Process	Type of specimen (size)
Ball bearing race	C1 (RSP)	Ring DM
HD-gear “CS” Circular spline	C1 (RSP) C1 (IHP)	Ring DM30mm Cross section 5*4mm
HD-gear “FS” Circular Flex	C2 (IMcast)	Cup DM20mm Wall thickness 1mm
Wave Spring	C1 (LMD)	Wave-Ring DM25mm Cross section 1*2mm
HDRM, separable contact	C1 (LMD)	Discs/Cones: DM 30mm Thickness 3-5mm

Table 2: Survey of materials and processes selected for tribological applications

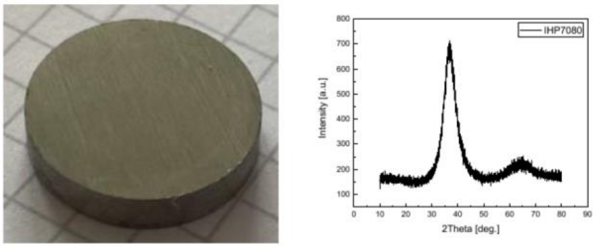


Figure 5: C1 (AMZ4) sample prepared by IHP (left) and XRD-patter confirming it to be amorphous.

Thick coatings of C1 (AMZ4) were prepared by LMD process on steel substrate for HDRM application. As coated quadratic areas are shown in *Figure 6*. Cylinders for machining of pins and discs were extracted (by eroding) for basic characterization such as XRD analysis, inspection of microstructure but also for tribological testing. XRD analysis showed for all samples semicrystalline structure typical for LMD processing of metallic glasses. XRD patterns of investigated samples are comparable for all measured samples.

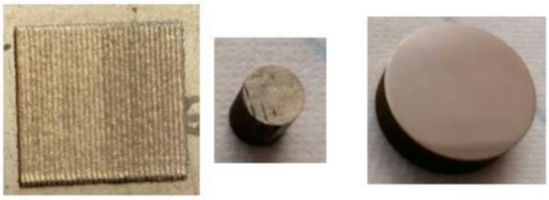


Figure 6: C1 (AMZ4) by LMD (as coated on steel, left), and machined pin (center) and disc (right).

5 EXPERIMENTAL 2 – TRIBO TESTING

To validate the new materials for use in mechanisms, two basic methods were selected:

Pin-On-Disc-Tribometer (PoD) enables to derive friction for gears, bearings and HDRM with sliding motion during release or for friction based HDRMs.

Cold welding (fretting) is primarily relevant to separable surfaces (HDRM): as the measured adhesion forces indicate the necessary opening forces of a HDRM. The term cold welding is linked to a failure to open. This happens, if the adhesion force exceeds the opening forces (provided e.g. by springs). As the stroke of the fretting motion ins in range similar to gears with small module, it can also be used to validate lifetimes for HD-gears.

For testing of friction and wear a High Vacuum Tribometer based on a Pin-On-Disc configuration was used (*Figure 7*). It enables temperatures from -100°C to +300°C. Finally, test atmosphere was ambient air and high vacuum both at RT. The software enables full control of the test as well as several motion types, like unidirectional or oscillating. Due to small specimens oscillating was selected with a stroke of approx. 10mm and speed of 0.01 m/s. The load was fixed to of 5N, which was related to 150-250MPa Peak Hertzian contact stress [14]. The friction forces could be resolved by +/- 0.02N.

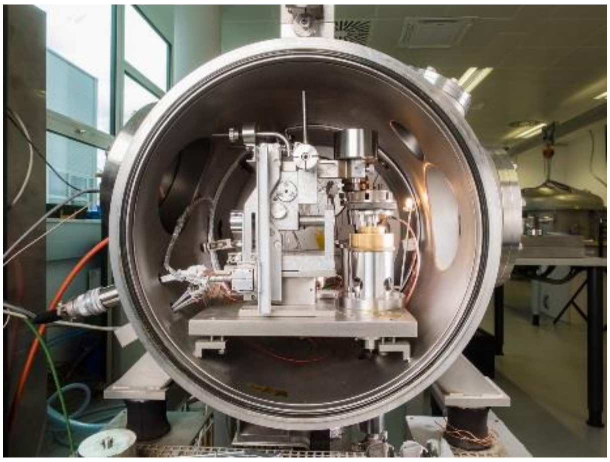


Figure 7: High Vacuum Tribometer (Inside view). Pin and disc holding, heating system not shown.

Besides friction, the adhesion / cold welding / stiction under fretting was investigated by a special test method developed by AAC together with ESA [15]. It uses a pin-on-disc-configuration similar to PoD-tribometers, but in an oscillating movement of only 50µm amplitude which referred to as “fretting”. Secondly, the main result is the force necessary for vertical separation (Not the friction force that acts in lateral direction). The aim was to assess materials and coatings for their ability to prevent cold welding (especially under upper stage during launch when strong vibrations may lead to fretting when the spacecraft is already exposed to space.) Based on the device a method was developed, agreed by ESA and published as STM paper [15]. In short, testing is done under fretting motion of 200Hz with an amplitude of 50µm. the loads are selected to achieve a maximum Hertzian pressure of 60% of elastic limit at begin of the test. Several studies on cold welding on typical space material combinations and coatings were performed. A summary is published in [15], but data is also available online [16]. Within this project, the loads were kept similar to friction tests at 5N.

Figure 8: Fretting device: Detail showing the fixation of pin (upper rod) and disc (mounted directly on a force transducer).

BMG-Disc and BMG-Pins were machined from semi-components by mechanical means (turning, milling) or by eroding. BMG-pins were designed with spherical tips of radius 30mm. The LMD-process revealed only thick coatings (300µm) on steel plate. After machining pins out of that plate, the presence of the BMG-coating on each pin curvature was verified by SEM/EDS.

For comparison to literature, also AISI440C-Steel was used as counterpart by commercial balls (radius 3mm). Surfaces were machined to Ra~0.1µm.

All samples were ultrasonically cleaned before testing.

6 RESULTS

6.1 Friction and Wear

As reference SS15-5PH was tested against AISI440C in air and vacuum. This PH-steel is typical for use in gears for space applications. *Figure 9* shows the output of the PoD-test: a plot of friction coefficient as function of revolutions is given: blue dots refer to the average of one revolution, red to the peak of each revolution. A typical range of friction coefficient for steel-to-steel in air is approx. 0,6-0,8 (without lubrication). In high vacuum the friction coefficient has significantly increased to 1,2-1,4 (on average) with peaks up to 2.3 ! (*Figure 9*). The wear mechanisms changed to “adhesive and ploughing”, i.e. the hard pin is ploughing through the softer disc creating reasonable but grooves. Secondly, part of the softer steel is transferred to the pin adhering there strongly (*Figure 10*).

The friction coefficient for the BMG-to-BMG is for all PoD-tests quite similar. The level may be rated as “medium”, with mean values in range of 0,6-0,8, and peak values up to 1,5. They are “noisy”, some being more some less, no clear tendency was identified. As promising is, that friction is constant up to 1000 revolutions. No difference between air and vacuum is identified. (*Figure 11*.)

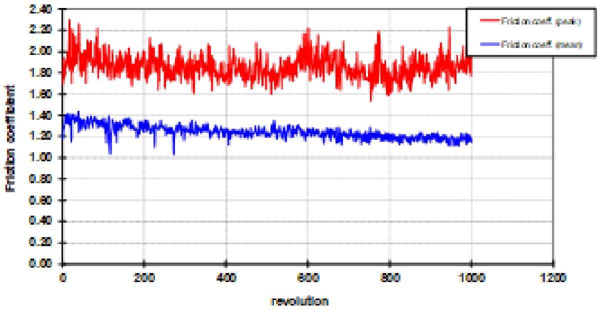


Figure 9 PoD-test Steel-to-steel Plot of friction

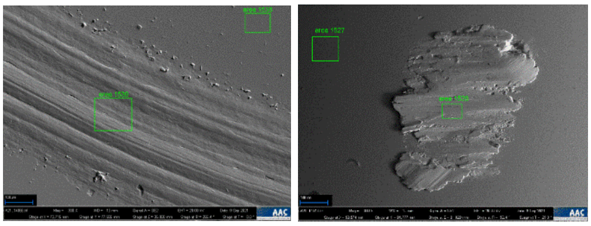


Figure 10 PoD-tests SEM analysis after test in vacuum: Left (SS15-5 disc): reasonable ploughing
Right (440C-ball): reasonable transfer from disc

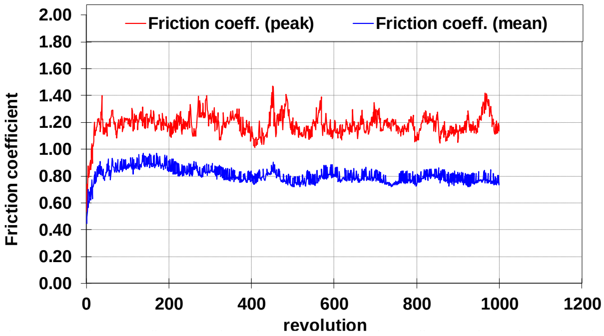


Figure 11 PoD-test (BMG-C2 versus BMG-C1): Plot of friction coefficient (typical for most promising combinations of BMG-to-BMG)

Post-investigations of the wear tracks show smooth grooves on the disc with hardly any free debris. That would be disadvantage as it reduces the risk of contamination to other instruments on the spacecraft (*Figure 12*, left). All the BMG-pins show hardly any wear, with some transfer from the disc (*Figure 12*, right).

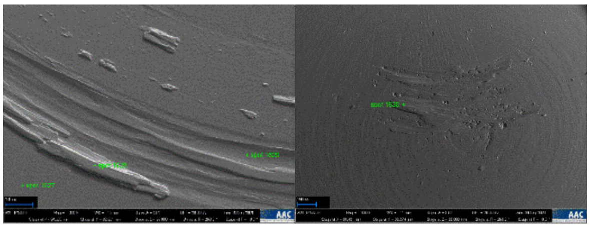


Figure 12 PoD-tests SEM analysis after test in vacuum: Left (Disc C2): BMG-discs show minor ploughing
Right (Pin C1): pin shows minor transfer from discs

6.2 Fretting and cold welding

To assess the applicability of BMGs to HDRMs, fretting tests were done in Launch mode: short tests running through air – low vacuum – high vacuum, simulating the environment from shaker (air) and launch (low and high vacuum). In each environment 30 cycles were done, after each separation was measured. The plots show the adhesion force of each separation (red for air, blue for low vacuum and green for high vacuum).

Very promising results were found for contact to BMG. As example the combination C2-IMCast-to-Ti-alloy shows almost no adhesion, with some spikes in between (*Figure 13*). Finally, best performance "no adhesion" is seen in tests F1B32 (C1-RSP vs C1-IHP) and F3B32 (C2-IMcast vs C1.IHP). However, for the latter repeatability needs to be proven, as the parallel test (F3B32) shows few adhesion spikes when starting high vacuum, but this vanishes with ongoing test.
Overall, compared to conventional metal-metal-contacts these results are really promising. It means that even in case of loss of lubrication by grease or coatings the risk of losing the mechanism is much lower!

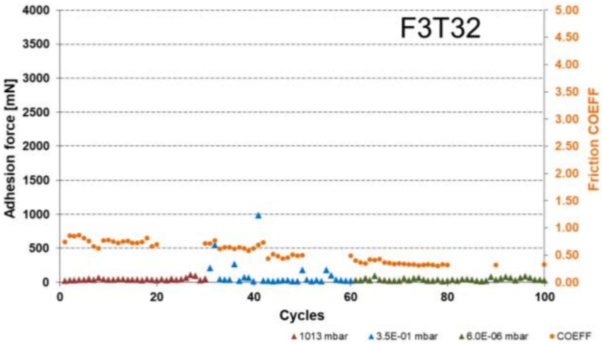


Figure 13 Launch-Test BMG-to-Ti6Al4V: separation force almost negligible (BMG C2-IMcast)

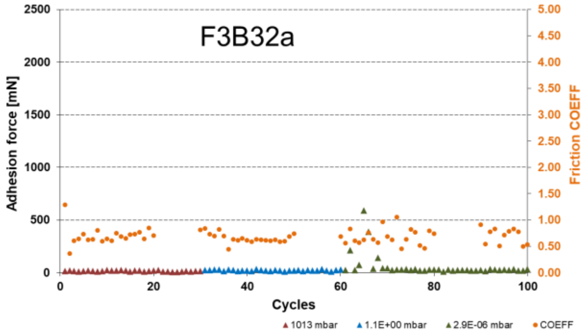


Figure 14 Launch-test BMG-to-BMG: separation force negligible (C2-IMcast <> C1-IHP)

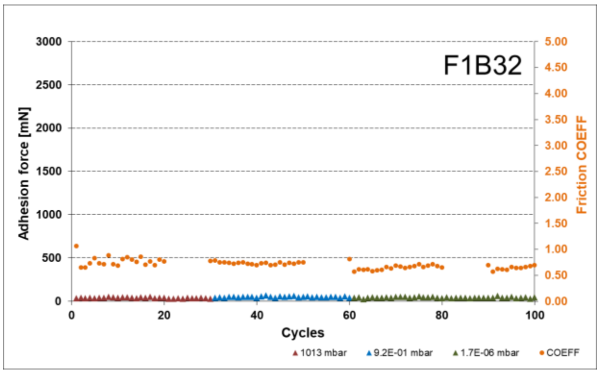


Figure 15 Launch-test BMG-to-BMG: separation force negligible (C1-RSP to C2-IMcast)

The most critical value is the single maximum adhesion force. *Figure 16* surveys these values via bars, each bar reflecting the maximum adhesion value per each environment for the said material combinations. (e.g. green bar is the maximum value of the adhesion forces in high vacuum). Surveying all the data, the combinations showing the most promising performance are C1-RSP-to-C1-IHP and C2-IMcast-to-C1-LMD (red circles *Figure 16*).

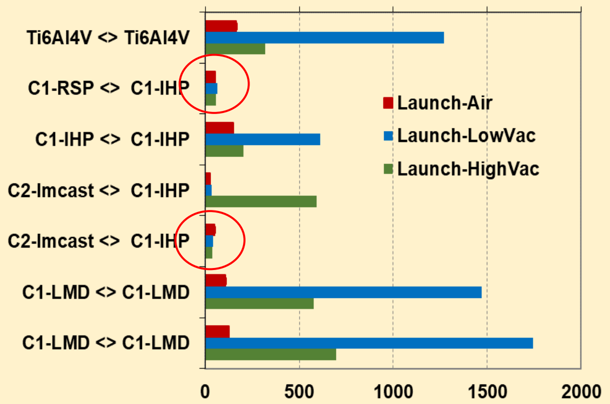


Figure 16 Launch-test BMG-to-BMG: max. separation force during launch tests for different combinations, 2 most promising combinations: red circle.

7 CONCLUSION

7.1 Conclusion towards manufacturing

Summarising the work, the first findings concerns its ***proper ability to machining*** (turning. Milling, eroding). Gluing of pins to support structures survived even turning of curvatures on the contact surfaces as well as all friction and fretting tests. Some BMG were found to shows low inter-granular strength, turning led to breaking out of grains. (This may be linked to failure of a few pins that were joining by laser point welding. It may also be seen as pre-indicator on the wear mechanism. Some specimens were manufactured by LMD, they offered about 300µm thick layers, which also could be machining to spherical tips.

An extremely important finding was, that with those production routes thick parts could be manufactured. Discs with diameter of 20mm had thicknesses of up to 6mm and were proven to be fully amorphous ! The processes enable also near-net-shape semi-finished parts, e.g. the circular spline of a HD-gear with a cross section of 5*4mm can be manufactured at typical diameters.

The powder based Directed Energy Deposition Additive Manufacturing technology (DED) has been successfully evaluated for HDRM applications. Parameter sets and strategies for the deposition were identified and were compatible with amorphous microstructure, very good adhesion on substrate and right construction geometry. Best results have been reached on coating patches performed with 1 and 2 deposition layers (between 0,3 and 0,6 mm thick) on Titanium alloy Ti6Al4V substrates. Works highlighted that the flowability of the BMG powder must be improved, by adding a special chemical component for example.

Heating of substrate helped to reinforce the dilution at the junction between substrate and BMG area, and consequently improved the adhesion with the substrate.

Based on these advances, other in-depth studies would allow to determine optimized DED Additive Manufacturing process parameters by investigating for example the impact of dwell time during deposition, remelting of the substrate, but also the way to machine the DED deposit on post-processing phases to obtained the final part functionalization (coating, tribology aspect).

7.2 Conclusion on tribological applications

Surveying the ***average friction coefficients***, all tests with BMG show lower average friction coefficients than for the reference combination of SS15-5PH (disc) to hard steel 440C in vacuum (benchmark µ=1,24). Combination of BMG to 440C revealed friction coefficient µ ranging from 0,51 to 0,64 in air. In vacuum µ ranges from 0,65 to 0,78 for BMG against steel, and from 0,61 to 0,82 for BMG against BMG. From current data, no tendencies could be deduced, as the scattering might simply reflect the repeatability from test to test. To elaborate tendencies, a higher number of tests would be needed. The friction is "noisy", i.e. friction coefficient during sliding scatters, but peak values are lower than for the reference steel-to-steel. (Please note, that these tests were done without any lubrication.)

Regarding the wear rate of the BMG (discs), the wear of the SS15-5PH disc to 440C-steel ball is taken as benchmark. In vacuum, wear rates of BMG-discs are about one order of magnitude lower than the benchmark.

Concluding results in friction and wear, it can be said that BMG-to-BMG is seen promising compared to current combinations based on PH-steels. Especially, C2 (VIT105) which was manufactured by a casting process would therefore become a candidate for the flex spline in a Harmonic Drive® gear. As opposite part, the circular spline could be manufactured by IHP out of C1 (AMZ4, a ring with cross section of e.g. 5*4mm).

Hence, **an outlook for many mechanisms** would be that a combination of BMG-to-BMG would offer less friction than steel-to-steel in case of emergency, when lubrication is lost. Such events occur e.g. when temperature get too low in fluid lubricated contact (e.g. planetary exploration during night), then the lubrication efficiency by the fluid is lost, and the material itself is driving friction, i.e. the torque in a gear. The lower wear rate between BMG-to-BMG would also increase the life of such a gear. Especially, if the gear is exposed during thermal cycles to very low temperatures, the grease may lose its lubrication and wear protection effect, then a lower wear rate of the substrate material would enable longer life compared to steel-to-steel contact.

Regarding **cold welding, the main findings are**:

BMG are basically subjected to cold welding (adhesion). Their metallic character enables that two BMG-parts moved/fretted against each other can weld together. The level differs strongly and testing for each case is strongly recommended (if funded by ESA, data can later on be added to the WEB-based data base on cold welding run by AAC [16]).

BMGs in contact to Ti6Al4V show high adhesion, when tested in high vacuum, hence no in-orbit operation is recommended. BGM in contact to BMG, can offer surprisingly low adhesion in launch conditions, for proper combination it may even vanish (i.e. below detection limit of the test device).

Some more work need to be done to confirm the data. But from current state of results, the best combination are C1-RSP (AMZ4) and C2-IMcast (VIT105) both against C1-IHP.

Hence, for an HDRM, selecting proper combination (and process) for BMG, a contact of BMG-to-BMG may offer promisingly low adhesion (cold welding). Although, in general grease or coatings are applied in contact surfaces to reduce risk of cold welding, the use of base material that is resistant to cold welding is a strong advantage in risk management.

8 ACKNOWLEDGEMENT

The presented results were achieved within a project financed by the European Space Agency (ESA): “METALLIC GLASSES FOR HIGH PERFORMANCE MECHANISM APPLICATIONS ON LONG TERM MISSIONS”, ESA Contract Nr. 4000126334/18/NL/Ar/zk.

9 REFERENCES

[1] C. Suryanarayana and A. Inoue, Bulk Metallic Glasses, Second edition, Boca Raton: CRC Press, 2018.

[2] M. Chen, “A brief overview of bulk metallic glasses,” Asia Materials, vol. 3, pp. 82-90, 2011.

[3] W. H. Wang, C. Dong and C. H. Shek, “Bulk metallic glasses,” Materials Scienece an engineering, vol. R44, pp. 45-89, 2004.

[4] M. Miller and P. Liaw, Bulk Metallic Glasses, NY: Springer Science+Business Media, LLc, 2008.

[5] D. C. Hofmann and S. N. Roberts, “Microgravity metal processing: From undercooled liquids to bulk metallic glasses,” npj Microgravity, vol. 1, no. January, pp. 1–10, 2015.

[6] and N. B. D. S.S. Joshi, S. Katakam, H. Singh Arora, S. Mukherjee, “No Title,” Crit. Rev. Solid State Mater. Sci., vol. 41, no. 1, 2016.

[7] S. K. M. S.V. Madge, A. Caron, R. Gralla, G. Wilde, “Hardness and wear resistance of Zr-based bulk metallic glass/Ti surface composites fabricated by highenergy electron beam irradiation,” Intermetallics, vol. 47, pp. 6–10, 2014.

[8] S. Pauly et al., “Processing metallic glasses by selective laser melting,” Mater. Today, vol. 16, no. 1–2, pp. 37–41, 2013.

[9] U. Jansson, “Additive manufacturing – development of processes and materials.” [Online]. Available: http://www.additivemanufacturing.se/additive-manufacturing-ssf/. [Accessed: 05-Apr-2019].

[10] G. G. J.H. Na, M.D. Demetriou, W.L. Johnson, “EP2748345B1.pdf.”

[11] R. P. Dillon et al., “Castable Bulk Metallic Glass Strain Wave Gears: Towards Decreasing the Cost of High-Performance Robotics,” Sci. Rep., vol. 6, no. 1, pp. 1–11, 2016.

[12] W. Vesta, “NASA Facts NASA Facts.”

[13] K. O. Connor, “NASA Tech Briefs,” Composites, vol. 5, no. 6, p. 239, Nov. 1974.

[14] Contact mechanics, Johnson, K. L., Cambridge University Press, 1985

[15] Merstallinger A., Sales M., Semerad E., Dunn B., “Assessment of cold welding between separable contact surfaces due to impact and fretting in under vacuum”, ESA-STM-279, Nov.2009.

[16] Online-data base “Cold-Weld-Data”, accessible via internet http://coldweld.aac-research.at/.