University College Dublin

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Metallic Glasses for High Performance Mechanism Applications on Long Term Missions

Executive Summary Report

ESA Contract No. 4000127199/19/NL/AR/zk

September 2022

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1.1 Background

We hereby summarise the project: "Metallic Glasses for High Performance Mechanism Applications on Long Term Missions". The University College Dublin (UCD) team was assisted by a partnership, via subcontract, with Reliance Precision, headquartered in Huddersfield, UK, and with a manufacturing facility in Bandon. Co. Cork, Ireland.

The contract, 4000127199/19/NL/AR/zk, required a number of Technical Reports (TNs), and Final Report, all of which have now been delivered to ESA.

This Executive Summary Report (ESR) highlights some of the important details and findings of the project.

1.2 Introduction to Metallic Glasses

Metallic Glasses are a special family of metal alloys with unique properties. A glass is a solid with a non-crystalline structure, meaning the atoms are not arranged in a completely regular and repeating lattice pattern as is the case in most alloys such as steel. The metallic glass atoms are arranged in a random way: this is achieved by careful selection of the alloy composition – i.e. the elemental metals in the mixture – and fast cooling from the molten state. Solids with this random atomic arrangement are also known as amorphous solids. We are used to thinking of glass as the transparent material in windows or lenses or beakers ("glasses") to hold liquids, but this is just one form of glass – made of silicon dioxide. Metallic glasses, on the other hand, are not transparent – they look and feel like normal metals but they are very hard and wear-resistant and some are capable of handling the wide range of temperatures in outer space (-270°C to 400^{o}C).

Bulk Metallic Glasses (BMGs) are metallic glasses with smallest section size exceeding 1mm. BMGs exhibit relatively high strength, elastic limit, low Young's modulus, high elastic energy storage and good corrosion resistance.

The random atomic arrangement in the solid is similar to that in a liquid. Indeed these materials are sometimes referred to as supercooled liquids (SCLs). They undergo a hardening at the glass transition temperature (T_g) on cooling rapidly from the melt, but the atoms do not have time to arrange themselves into ordered crystals as they do in conventional alloys. Another feature is that BMGs do not crystallise on immediate re-heating above T_g, but rather crystal formation occurs at a higher temperature known as T_x, the crystallisation temperature. The temperature window $T_x – T_g$ is therefore known as the SCL range: the state of matter is a viscous liquid, and thermoplastic forming of BMGs can be carried out to large strains.

1.3 Stages of the Project

The project can be broken down into 4 main parts, each of which was reported on in the relevant TN. These are described in the contract, and can be summarised as follows.

TN1
We first conducted a literature review on space mechanism applications which can benefit from the use of metallic glasses. In this we identified Metallic Glass (MG) alloys with strong potential for application in mechanism parts. We also reported the outcome of a literature review on available processes for the production of MG specimens, from the perspective of application in mechanism parts.

TN2
We reported test matrices (combinations of mechanism application, MG material and production process) for the MG production process development.

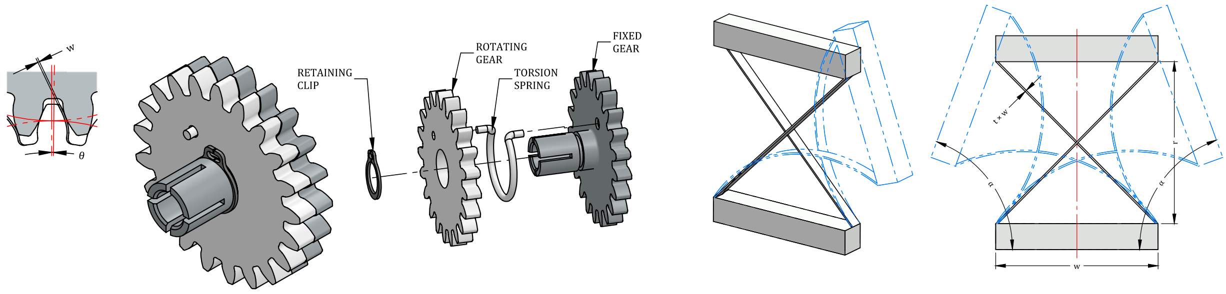
TN3
We presented test results and findings for all metallic glass process development activities. We compared key material property requirements for the relevant space application. We reported on the process parameters which allow production of material meeting the key material property requirements.

TN4
Here we reported the results and findings of material characterisation test activities, critically comparing the properties of the produced MG materials against the requirements. Implementation plan towards flight hardware was discussed.

In addition, although not called for in the contract, we have carried out materials characterisation on conventional (crystalline) alloys with space heritage, *viz.* Ti-6%Al-4%V and stainless steels 303 and 304. This was done to put into context the properties of the selected Bulk Metallic Glasses (BMGs). The results were included as an Annexe to TN4.

1.4 Summary and Key Findings

The project kicked off in summer 2019 when the UCD team met with the Reliance partners in Bandon. Here we agreed the approach to be taken. Reliance provided UCD with advice on the type of space-related products that should be the target of the work. UCD then started a two-year investigation in their labs in the Belfield campus, Dublin, to come up with the BMG alloys most suited to anti-backlash gears and large angle flexures (see Fig. 1).



(a) *(b)*

Fig.1: (a) Anti-backlash Gear (multi-component); (b) Large Angle Cross-axis Flexure

Following a very wide review of the existing literature (see TN1), a shortlist of 4 BMG alloys were selected for detailed investigation. The alloys were synthesised at UCD (see TN2 and TN3), in our Arc Melter (see Fig. 2) and suction casting into copper moulds. From these castings, samples were prepared for testing (Fig. 3).

The four alloy compositions were (with laboratory labels):

- $Zr_{53}Al_{16}Co_{23.25}Ag_{7.75}$ (C12)
- $Zr_{49}Ti_{1.96}Cu_{37.24}Al_{9.8}Y_2$ (C16)
- $Zr_{60}Ti_2Nb_2Al_{7.5}Ni_{10}Cu_{18.5}$ (C18)
- $Cu_{47}Zr_{46}Al_5Y_2$ (C35)

Fig. 2: Edmund Bühler AM 200 Arc Melter system

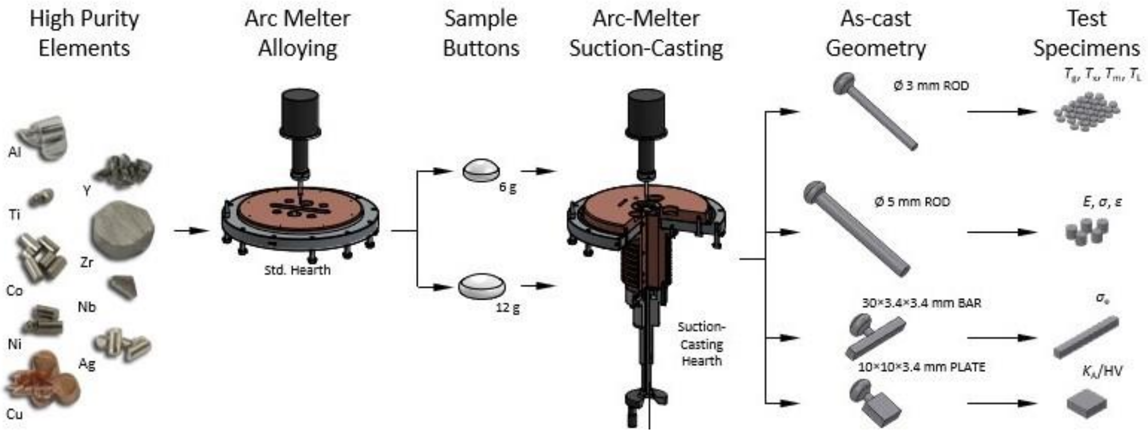


Fig. 3: Test sample manufacture

The principal tests carried out are shown in Fig. 4. Density measurements were carried out to assess if significant porosity was present. X-Ray Diffraction (XRD) was used to confirm that the samples were amorphous. Energy Dispersive X-ray (EDX) spectroscopy was used to check if the expected alloy composition (according to the relative amounts of each pure comment added in the arc melter; Fig. 3)) was achieved in the cast specimens.

Compression testing was used to assess the mechanical properties – in particular Young's modus, yield and failure strengths, and elastic & plastic strain. Fatigue testing was carried out to determine the life (number of cycles to failure) at various stresses. Hardness relates to the resistance to indentation at fixed normal applied loads, and may be relevant to wear resistance. The latter was measured using Ball-on-Disc (BOD) wear tests. The key thermal events for the BMGs were determined using Differential Scanning Calorimetry (DSC).

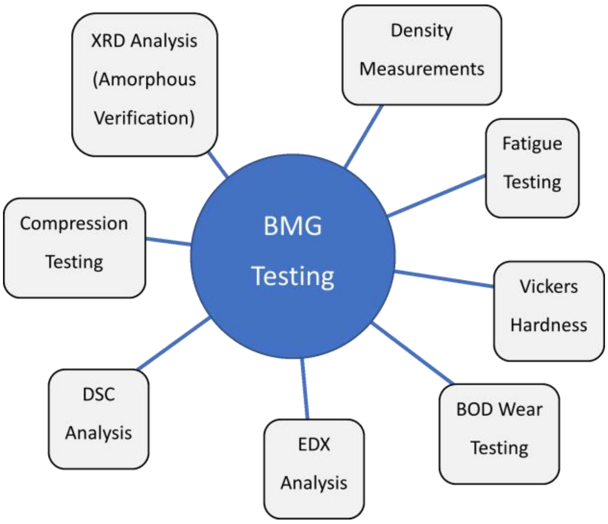


Figure 4: testing regimen for BMG alloys

Table 1 summarises the main properties of the 4 BMG alloys, as measured

C	*Composition* (at.%)	ρ (g/cm³)	E (GPa)	ε_e (%)	ε_p (%)	σ_y (GPa)	σ_f (GPa)	*HV* (*kgf/mm²*)	T_g (°C)	T_x (°C)	T_m (°C)	T_L (°C)	K_A	*σ_e (*MPa*)
12	$Zr_{53}Al_{16}Co_{23.25}Ag_{7.75}$	6.75±0.02	94±3	2.0±0.1	0.7±0.9	1.9±0.0	1.9±0.1	577±36	485	503	875	954	0.0019±0.0009	<200
16	$Zr_{49}Ti_{1.96}Cu_{37.24}Al_{9.8}Y_2$	6.76±0.03	87±3	1.9±0.1	0.5±0.5	1.6±0.1	1.7±0.1	527±51	399	429	787	858	0.0015±0.0009	<400
18	$Zr_{60}Ti_2Nb_2Al_{7.5}Ni_{10}Cu_{18.5}$	6.77±0.01	80±3	1.8±0.1	1.1±0.6	1.5±0.1	1.6±0.1	426±11	376	404	780	870	0.0036±0.0018	<400
35	$Cu_{47}Zr_{46}Al_5Y_2$	7.14±002	87±2	1.9±0.1	0.8±0.2	1.6±0.1	1.8±0.1	478±32	409	428	704	889	0.0008±0.0005	<400

*Table 1: Main measured properties of 4 shortlisted BMG alloys, where ρ is the alloy density, E is the Young's modulus, ε_e is the elastic strain limit, ε_p is the plastic strain limit, σ_y is the yield stress, σ_f is the failure stress, HV is the Vickers hardness, T_g is the glass transition temperature, T_x is the crystallisation temperature, T_m is the melting temperature, T_L is the liquidus temperature, K_A is the Archard's wear coefficient, and σ_e is the fatigue endurance stress limit. Note, * indicates values estimated based on experimental results. C12, C16, C14 and C35 are just labels used internally for alloy classifications in UCD.*

Apart from the key temperatures identified by constant-heating DSC for each alloy (see Table 1), we also performed tests at various constant temperatures, and measured the time taken for the first crystallization event to occur. The results are shown in Fig. 5.

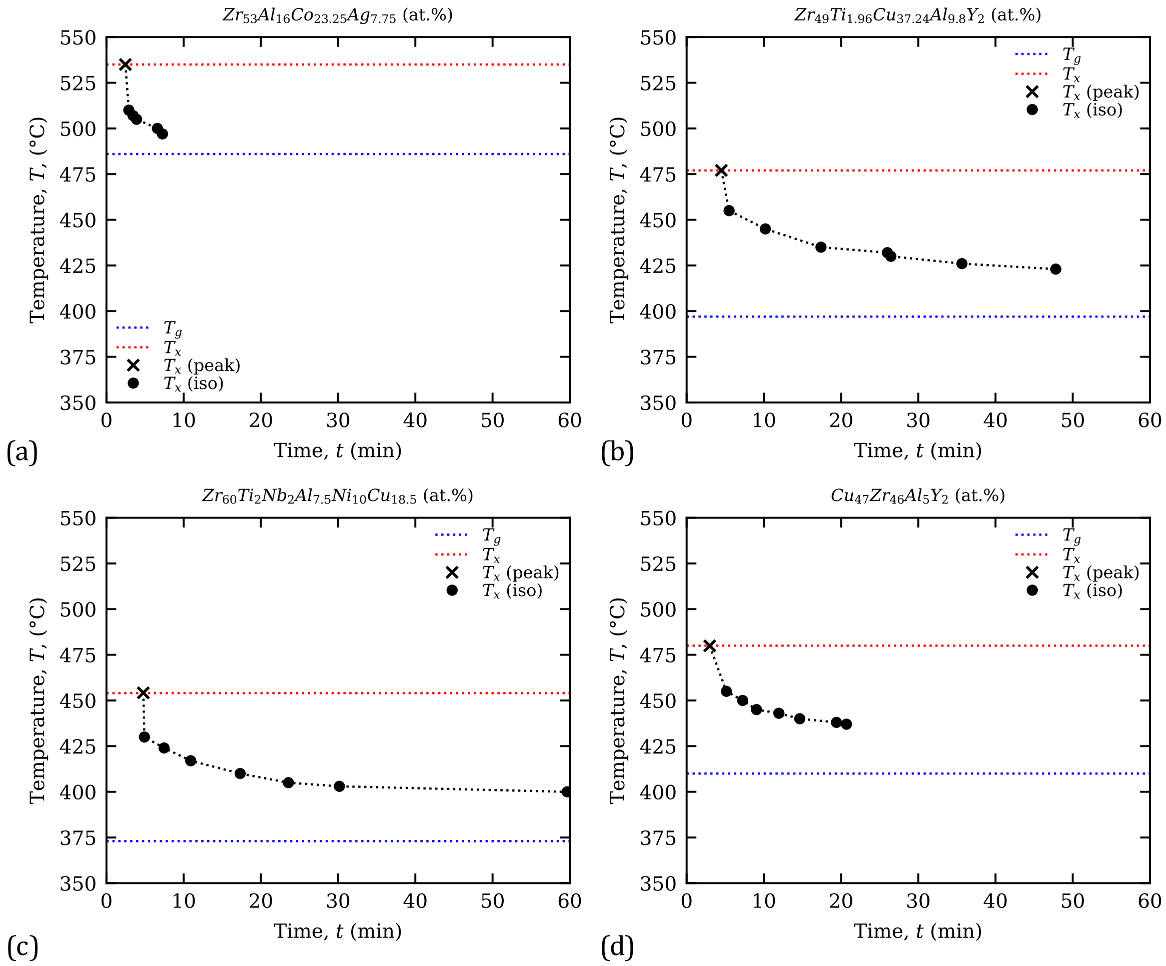


Figure 5: Experimentally determined time-temperature-transformation for each of the project compositions. (a) C12. (b) C16. (c) C18. (d) C35. The dot-markers indicate time to crystallisation at fixed T. The ×-marker indicates the crystallisation peak time recorded during the previous constant heating experiment. Alloy specific T_g and T_x temperature transitions shown in blue and red, respectively.

These tests are important as they indicate the time allowed if the BMG mechanisms exceed their glass transition temperate in service and enter the SCL stage, before crystallisation would destroy the material – it would no longer be a metallic glass.

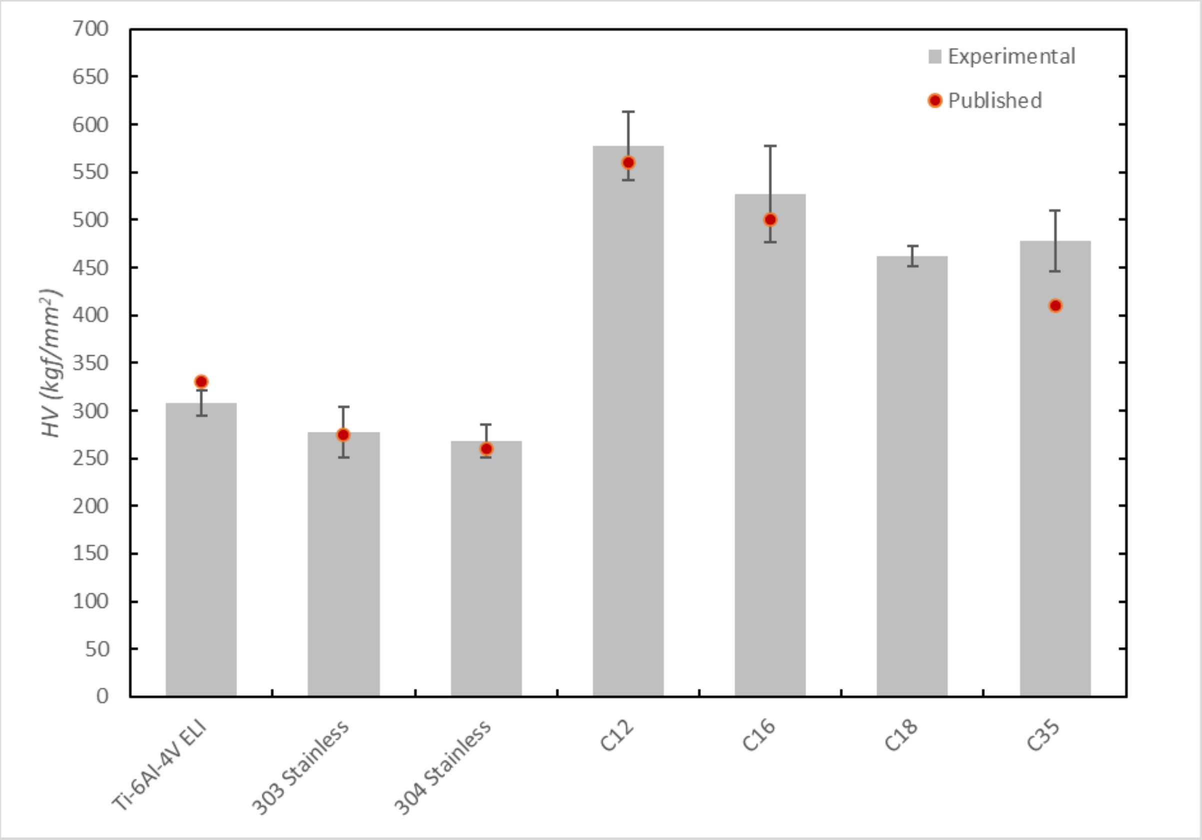


Fig. 6: Vickers hardness values for the 4 BMG alloys and 3 conventional ones.

The hardness of the BMG alloys is shown in Fig. 6, and shown for comparison purposes are the values measured for 3 conventional crystalline alloys: Ti-6%Al-4%V and cold-worked 303 and 304 grade stainless steels. The higher hardness of the BMG alloys is clear.

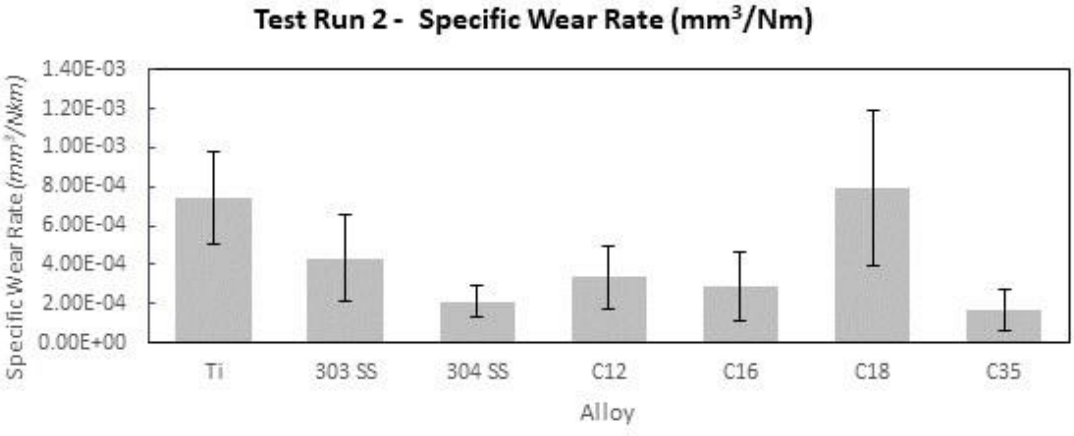


Fig. 7: wear rate normalized by applied load

From BOD wear tests, the normalised wear rate for the alloys is shown in Fig. 7. The BMG alloys are competitive with the conventional alloys under these wear conditions.

Fatigue testing showed that the BMG alloys could survive at least 10^5cycles at low stress levels (see Table 1). However the conventional alloys showed better fatigue properties.

Finally two BMG alloys were deemed the best fit, one for each of the target space mechanisms (see TN4).

From the four alloys studied in detail, recommendations are hereby made for both space mechanisms: $Zr_{49}Ti_{1.96}Cu_{37.24}Al_{9.8}Y_2$ (at.%), hereby called Alloy A, is very suited to gear applications, and $Zr_{60}Ti_2Nb_2Al_{7.5}Ni_{10}Cu_{18.5}$ (at.%), Alloy B, for compliant mechanisms. For the gears, Alloy A combined high wear performance with good processability. For the flexures, Alloy B demonstrated reasonable fatigue performance combined with good processability and the potential for thermoplastic forming. Machining trials carried out at Reliance in Bandon on Alloy A have confirmed suitability for precision rack, pinion and worm gear (see Fig. 8) manufacture.

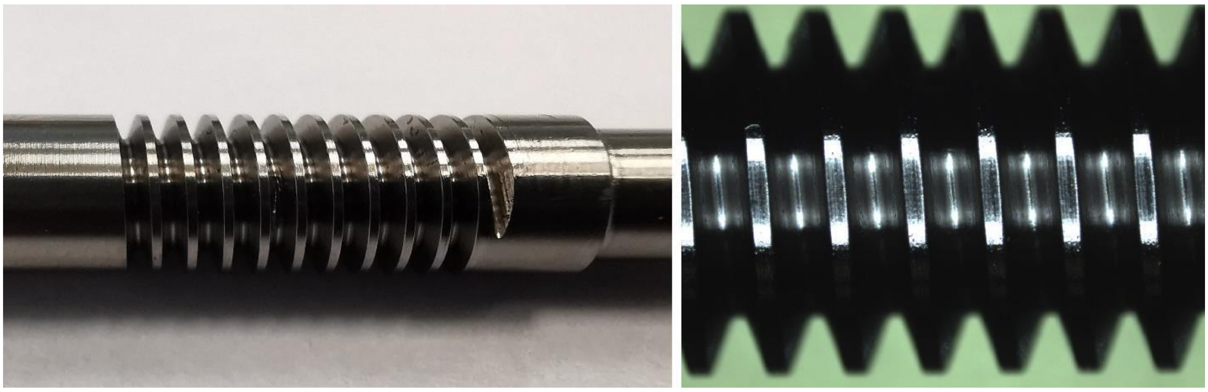


Fig. 8: worm gear machined from BMG Alloy A

In order to rank the identified BMG alloys against conventional alloys – grade 303/304 stainless steels and titanium alloy – which have space heritage, the latter alloys were tested under the same protocol as the BMGs (see TN4a). The BMG alloys score well under hardness and wear resistance when compared with the conventional alloys (Figs. 6 and 7), while one BMG alloy (B) demonstrates fatigue performance suggesting its use in flexural mechanisms. In conclusion, laboratory testing of has shown that two BMG alloys are promising candidates for space-mechanisms, but further work is needed to establish their performance in real-world applications and under space-simulated conditions, such as high vacuum and at various temperatures, both cryogenic and elevated.

1.5 Publications relevant to the project:

A number of papers were published or presented on the progress of the research. Two of the conference presentations were online, due to the Covid pandemic restrictions on travel at the time. The papers are listed below:

Conference:

- Murphy, A.G., Norman, A., Browne, D.J., "Metallic Glasses for Space Mechanism Applications", presented at TMS Annual Meeting & Exhibition, San Diego, CA, USA, 23-27 February 2020.

- Murphy, A.G., Norman, A., Browne, D.J., "Selection and testing of Bulk Metallic Glass alloys for space-based mechanisms", invited talk, presented at TMS Virtual Annual Meeting & Exhibition, online conference, 14-18 March 2021.

- Murphy, A.G., Norman, A., Meagher, P., Worsley, T., Browne, D.J., "Bulk Metallic Glasses for space mechanism applications: an experimental investigation", presented online at 1st ESA/NASA International Conference on Advanced Manufacturing for Air, Space and Land Transportation, 7-11 March 2022.

Journal:

- Murphy, A.G., Norman, A., Meagher, P., Browne, D.J., "Wear of Bulk Metallic Glass alloys for space mechanism applications", ASME Journal of Tribology, **144**, 2022, paper 091706; doi:10.1115/1.4054146.

- Murphy, P. Meagher, A.G., Norman, A., Browne, D.J., "Mechanical and thermal stability of Bulk Metallic Glass alloys selected for space mechanism applications", manuscript submitted and under review.

1.6 Conclusions

- A literature study identified BMG alloys suitable for synthesis in an arc melter but without toxic or prohibitively expensive elements.
- This work presents the findings from materials testing performed on four amorphous alloy compositions selected for potential replacement of traditional crystalline space-mechanism alloys.
- Based on the results, the BMG alloys selected exhibit favourable properties for the mechanisms of interest.
- Processing conditions play a significant role in the as-finished performance of each of the alloys. Casting conditions within the arc melter subject to significant operator influence.
- The BMG alloy C16 (hereby Alloy A) can be machined into precision gear shapes with existing tools, following parameter optimisation.
- The BMG alloy C18 (hereby Alloy B) is likely suitable for flexural space mechanisms, based on the measured properties.
- The BMG properties compare favourably with traditional alloys – stainless steels and Ti-6%Al-4%V.

1.7 Future Work

We propose expanding and extending the scope of the research to a higher TRL, enabling the design and production of working prototype mechanisms in BMGs. This would take the developed technology to a TRL6 demonstrator, at the cusp of industry take-up and commercialisation activities.

The advances foreseen include:

- Larger metallic glass test ingots.
- Extension to investigation of other promising alloy compositions (to include lower boiling point components).
- Moving from material testing to design and development of larger (sub-) systems for space mechanisms.
- Production of near net shapes from the melt (casting, squeeze casting) or supercooled liquid (thermoplastic forming).
- Possibility of BMG inserts (e.g. gear teeth) to a hub of conventional alloy, such as steel, which would be cheaper and tough, albeit with lower wear resistance.
- Mechanism testing under simulated service conditions, including dry (or no) lubrication.
- Technology demonstration
- Plan for industrial implementation for space missions.

The above approach was agreed at a meeting between UCD and Reliance at the Reliance manufacturing facility in Bandon, Co. Cork, on 16 June 2022.