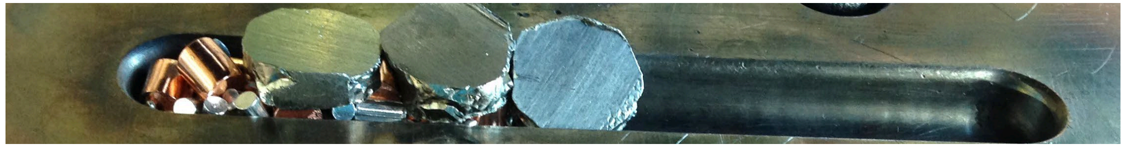

Bulk Metallic Glass Alloys for Space Mechanism Applications: an Experimental Investigation

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

*Andrew G. Murphy[1,4], Andrew Norman[2] , Philip Meagher[1], Tom Worsley[3], **David J. Browne[1]***

[1]
Phase Transformation
Research Group

[2]

[3]

[4]

Talk Outline:

- Project Introduction and Scope
- Mechanism, BMG, Processing Selection
- BMG Material Testing
- Conclusions & Future Work
- Acknowledgements/Questions & Comments

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Project Introduction and Scope: Space Mechanism Applications

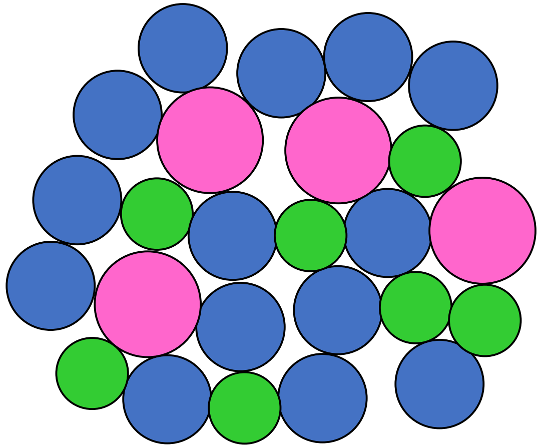
- Mechanisms and components for space applications must exhibit **exceptional performance in extreme environments**, while being virtually maintenance and failure free.
- **Materials selection** vital to achieve maximum performance and quality while reducing mass and costs.
- Key **materials selection criteria include**, specific stiffness, specific strength, corrosion resistance, fracture and fatigue resistance, thermal expansion coefficient and thermal conductivity for the temperature range $4\ \mathrm{K} \leq T \leq 675\ \mathrm{K}$, as well as ease of manufacture.
- Other factors that need to be considered included, **lubricant** compatibility/requirement, cold welding, galvanic compatibility, geometric accuracy, and surface finish.
- **Eliminate mass, complexity, and reduce maintenance** by reducing mechanism part count.

__Compliant flexure-based mechanisms__ can be used to replace hinges, linkages and potentially pyrotechnic actuators, increasing accuracy and performance, while reducing mass and manufacturing costs.

What are Glasses?

Glass

Solid composed of atoms arranged in a disordered way



Ceramic

Polymeric

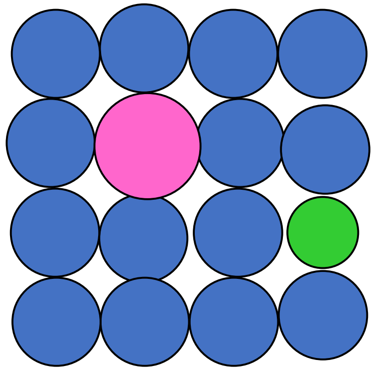
Metallic

Discovered in 1959

Naturally occurring

Crystal

Solid composed of atoms arranged in an ordered way



Ceramic

Polymeric

Metallic

What are Bulk Metallic Glasses?

Crystalline metal (First use: 6,000 BC)

Everyday metals are cast into shape by cooling the molten metal into a solid

The atoms order in a regular crystalline fashion.

The metal melts when heated above its melting point T_{melt}

Bulk Metallic Glass (First use: 1990 AD)

If section thickness > 1mm: **Bulk** Metallic Glass (BMG)

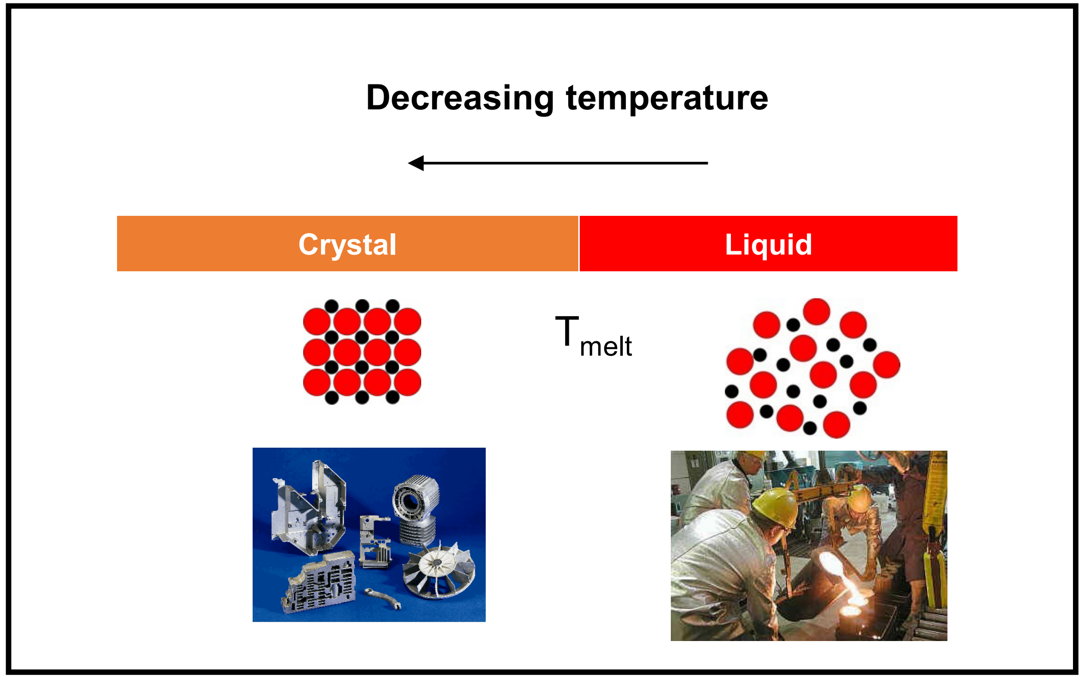
A metallic glass is made by cooling the liquid state of special alloys relatively rapidly.

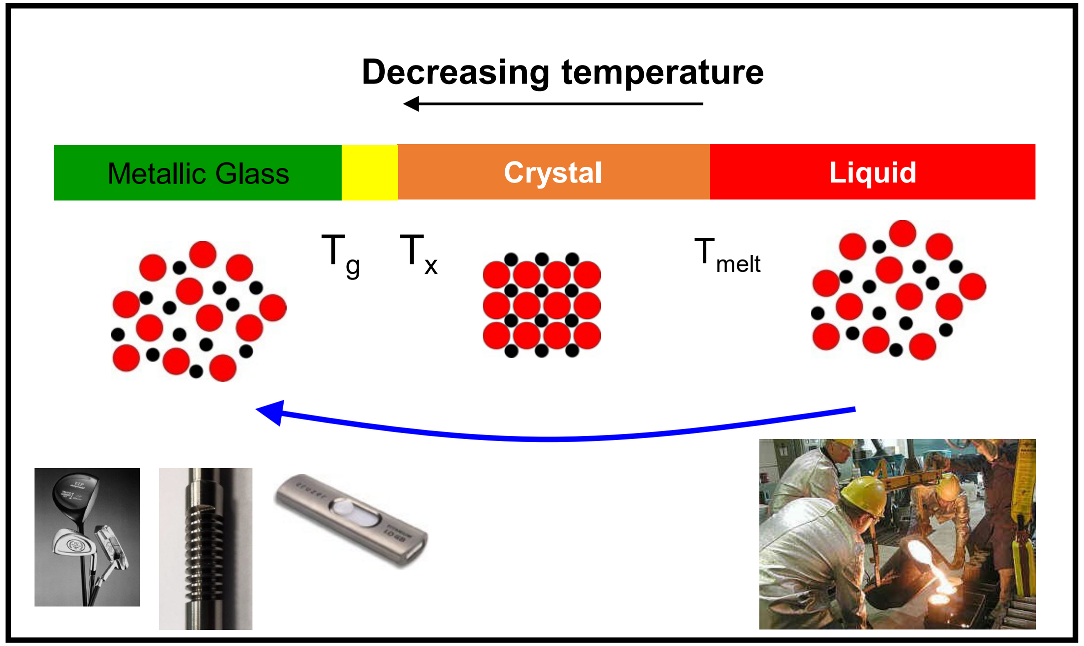
Because of the cooling rate and alloy composition, atoms do not get time to ‘re-order’ themselves into a crystalline state.

Between T_g and T_x is known as the supercooled liquid state, where material softens considerably (viscosity 10^4-10^7 Pa.s)

On re-heat, above a specific temperature T_x the material will crystallize.

Increasing the temperature above T_{melt} will melt the material.





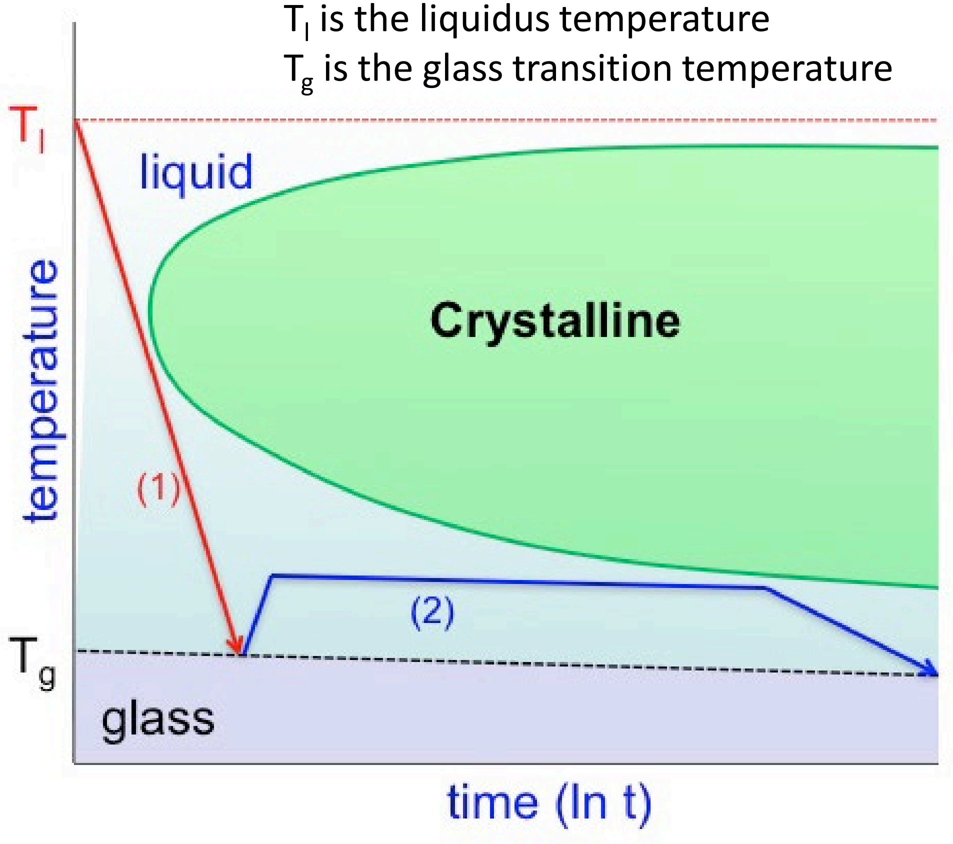
BMG properties

- Hard
- Strong
- Wear resistant
- Corrosion resistant
- Biocompatible (alloy-dependent)
- High precision replication – sharpness
- Tough in micro-parts
- Mouldable in Super-Cooled Liquid Range (SCLR)

TTT diagram

time-temperature transformation

T_l is the liquidus temperature
T_g is the glass transition temperature



path (1) shows critical cooling rate needed to form a metallic glass.

Perfume bottle made by blow moulding – thermoplastic forming – following path (2) in TTT

Source: Jan Schroers Lab, Yale University

Project Introduction and Scope: Bulk Metallic Glasses

- ✓ High strength (5 GPa ≥ σ_y ≥ 1 GPa)
- ✓ High elastic strain ($\varepsilon_y \approx 2\%$)
- ✓ Low Young's modulus ($E \approx 100$ GPa)
- ✓ High hardness ($HV \approx 500 \pm 100$)
- ✓ Corrosion resistance
- ✓ Thermoplastic formability (SCLR, T_g)
- ✓ High resilience, energy storage (σ_y^2/E)
- ✓ Low mechanical damping (Loss coefficient, η)
- ✓ Low wear loss
- ✓ Excellent soft magnetic properties
- ✓ Large range of BMG composition families (Zr, Ti, Cu, Fe, Pd, Pt)
- ✓ Limited solidification shrinkage giving excellent mould filling

- ✗ Can be macroscopically brittle. Shear localisation into thin bands leading to catastrophic failure
- ✗ Limited-to-no tensile ductility (ε_p)
- ✗ Low fatigue strengths ($\sigma_e = 0.15\sigma_y$)
- ✗ Difficult to maintain amorphous structure during processing
- ✗ Expensive, high purity, atomic elements (Pt, Pd, Au)
- ✗ Toxic elements (Be)
- ✗ Difficult to manufacture in large volumes
- ✗ Trial and error approach to BMG synthesis (no GFA predictability)
- ✗ Lab-to-lab performance variation for the same composition

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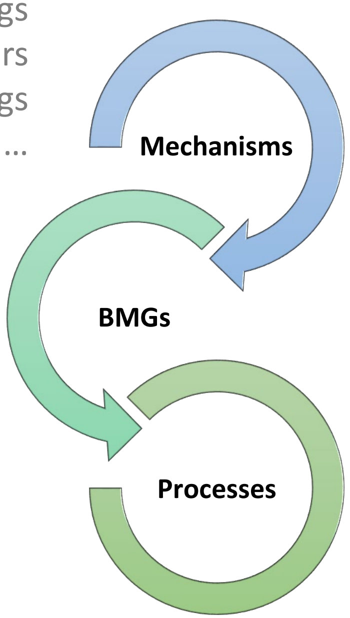
Project Introduction and Scope:

Identify and characterize specific **Bulk Metallic Glass** (BMG) alloys suitable for **space mechanism** applications, providing significant **performance improvements** over current state-of-the-art metals as well as possible **alternative manufacturing routes**.



Bearings
Gears
Springs
…

Mechanisms

Compliant
Mechanisms

$Zr_{35}Ti_{30}Be_{27}Cu_{8}$
$Cu_{47}Zr_{46}Al_{5}Y_{2}$
…

BMGs

Processes

Direct Casting
Thermoplastic Forming (TPF)
Electrical Discharge Machining (EDM)
…

Technology Readiness Level 3 (**TRL3**): Analytical and experimental critical function and/or characteristic **proof-of-concept.**

Talk Outline:

- Project Introduction and Scope
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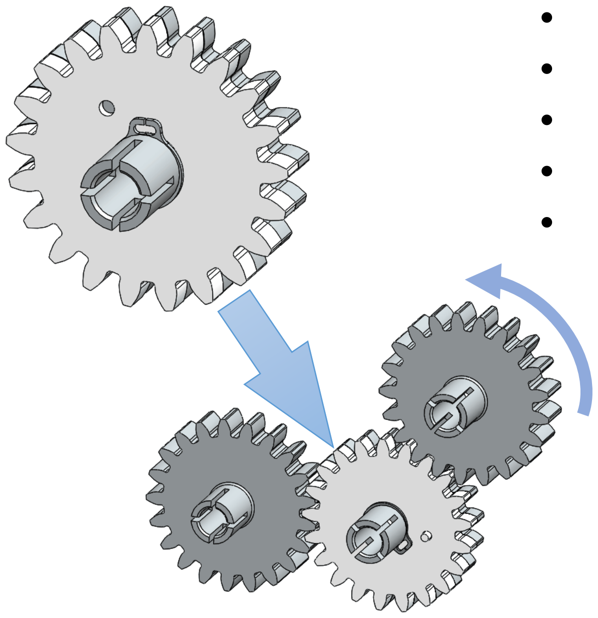
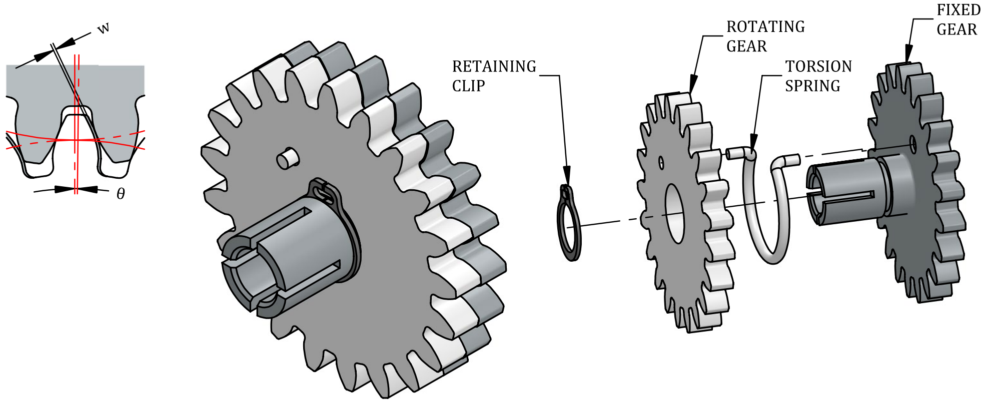
Bulk Metallic Glasses for Space Mechanism Applications

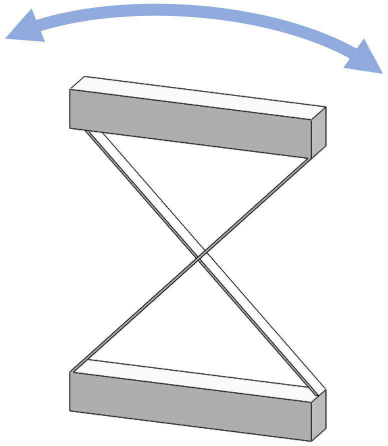
Mechanism Selection:



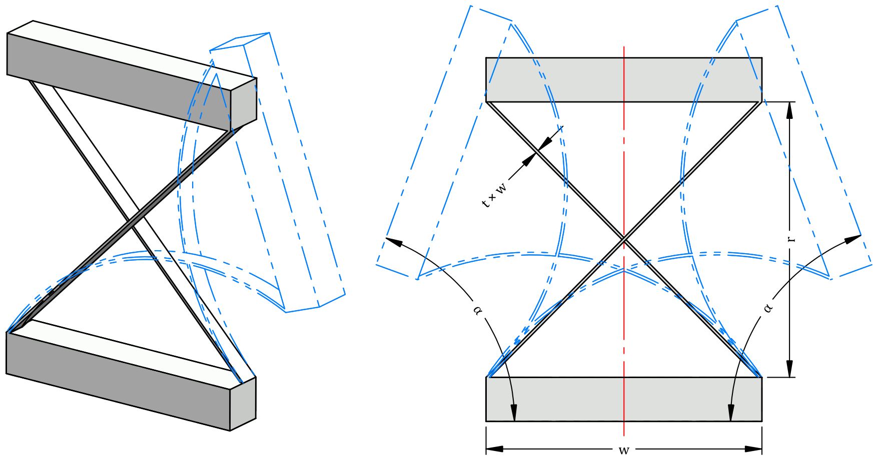
- High strength
- Wear resistant
- Low surface roughness
- High hardness
- High toughness



Anti-backlash Gear (multi-component)



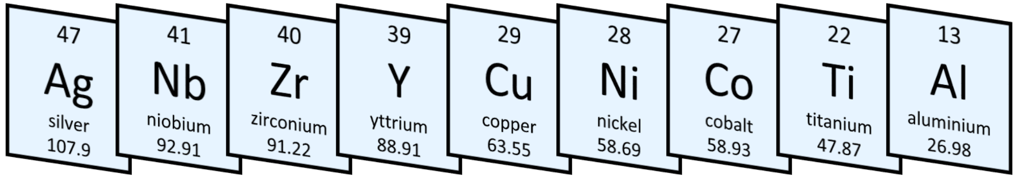
- High strength
- High fatigue endurance
- High elastic strain
- Low surface roughness
- Very high elastic energy storage



Large Angle Cross-axis Flexure

Bulk Metallic Glasses for Space Mechanism Applications

BMG Alloy Selection:



- $Zr_{53}Al_{16}Co_{23.25}Ag_{7.75}$

N. Hua, S. Pang, Y. Li, J. Wang, R. Li, K. Georgarakis, A. R. Yavari, G. Vaughan, and T. Zhang, '**Ni- and Cu-free Zr–Al–Co–Ag Bulk Metallic Glasses with Superior Glass-forming Ability**', Journal of Materials Research, vol. 26, no. 4, pp. 539–546, 2011.

- $Zr_{49}Ti_{1.96}Cu_{37.24}Al_{9.8}Y_{2}$

K. Zhou, Y. Liu, S. Pang, and T. Zhang, '**Formation and Properties of Centimeter-Size Zr–Ti–Cu–Al–Y Bulk metallic Glasses as Potential Biomaterials', Journal of Alloys and Compounds**, vol. 656, pp. 389–394, 2016.

- $Zr_{60}Ti_{2}Nb_{2}Al_{7.5}Ni_{10}Cu_{18.5}$

Inoue, Q. S. Zhang, W. Zhang, K. Yubuta, K. S. Son, and X. M. Wang, '**Formation, Thermal Stability and Mechanical Properties of Bulk Glassy Alloys with a Diameter of 20 mm in Zr-(Ti,Nb)-Al-Ni-Cu System**', Materials Transactions, vol. 50, no. 2, pp. 388–394, 2009.

- $Cu_{47}Zr_{46}Al_{5}Y_{2}$

D. C. Hofmann, L. M. Andersen, J. Kolodziejska, S. N. Roberts, J.-P. Borgonia, W. L. Johnson, K. S. Vecchio, and A. Kennett, '**Optimizing Bulk Metallic Glasses for Robust, Highly Wear-Resistant Gears**', Advanced Engineering Materials, vol. 19, no. 1, p. 1600541, 2017.

BMG Testing Regime: Key Material Properties

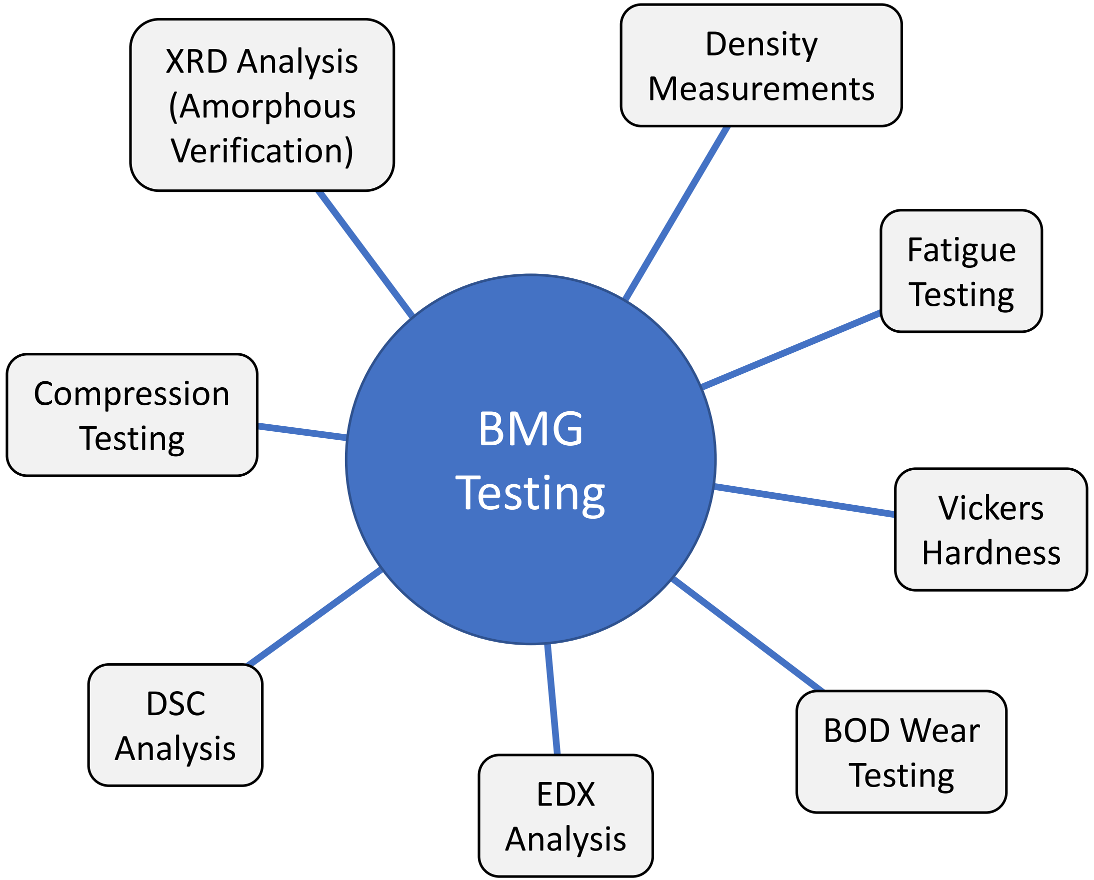
Class	*Property*	*Symbol*	*Units*	*Preference**
General	Cost	C_m	€/kg	Low
	Density	ρ	kg/m^3	Low
Mechanical	Young's modulus	E	GPa	Low
	Shear modulus	G	GPa	High
	Bulk modulus	K	GPa	High
	Yield strength	σ_y	MPa	High
	Ultimate strength	σ_f	MPa	High
	Fracture strength	σ_f	MPa	High
	Toughness	G_c	kJ/m^2	High
	Fracture toughness	K_{1c}	$MPa\ m^{1/2}$	High
	Damping capacity (loss coefficient)	η	-	Low
	Fatigue endurance limit	σ_e	MPa	High
	Hardness	Hv	N/mm^2	High
	Surface Finish	R_a	µm	Low
Thermal	Thermal conductivity	λ	W/mK	High
	Thermal diffusivity	a	m^2/s	High
	Specific heat	C_p	J/kgK	High
	Melting point	T_m	K	High
	Glass temperature	T_g	K	High
	Thermal expansion coefficient	α	K^{-1}	Low
	Thermal shock resistance	ΔT	K	High
	Creep resistance	-	-	High
Wear	Archard wear constant	k_A	MPa^{-1}	Low
Corrosion/ Oxidation	Corrosion rate	K	mm/year	Low
	Parabolic rate constant	K_p	m^2/s	Low

$Zr_{53}Al_{16}Co_{23.25}Ag_{7.75}$

$Zr_{49}Ti_{1.96}Cu_{37.24}Al_{9.8}Y_2$

$Zr_{60}Ti_2Nb_2Al_{7.5}Ni_{10}Cu_{18.5}$

$Cu_{47}Zr_{46}Al_5Y_2$



BMG Testing

XRD Analysis (Amorphous Verification)

Density Measurements

Fatigue Testing

Vickers Hardness

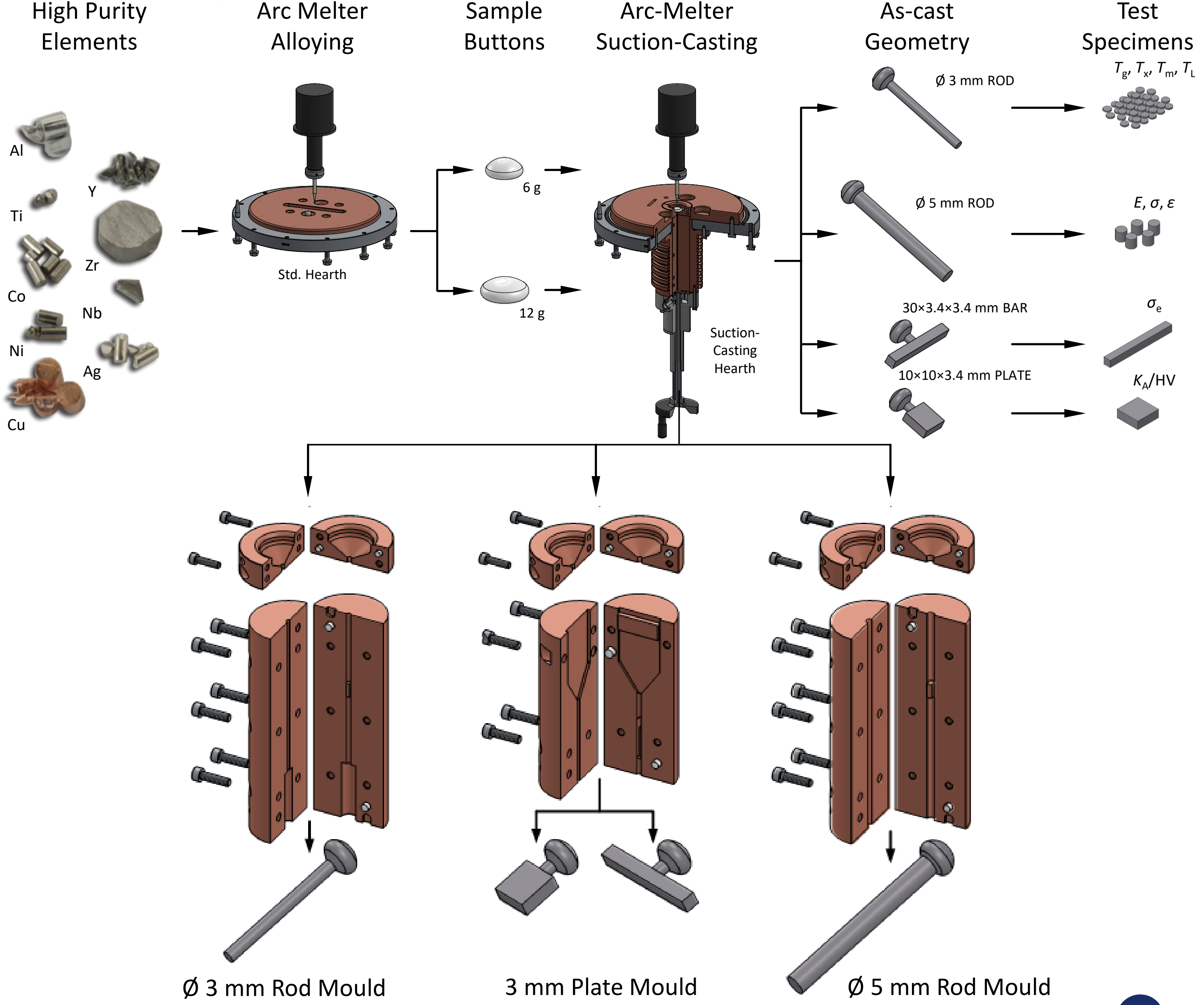
BOD Wear Testing

EDX Analysis

DSC Analysis

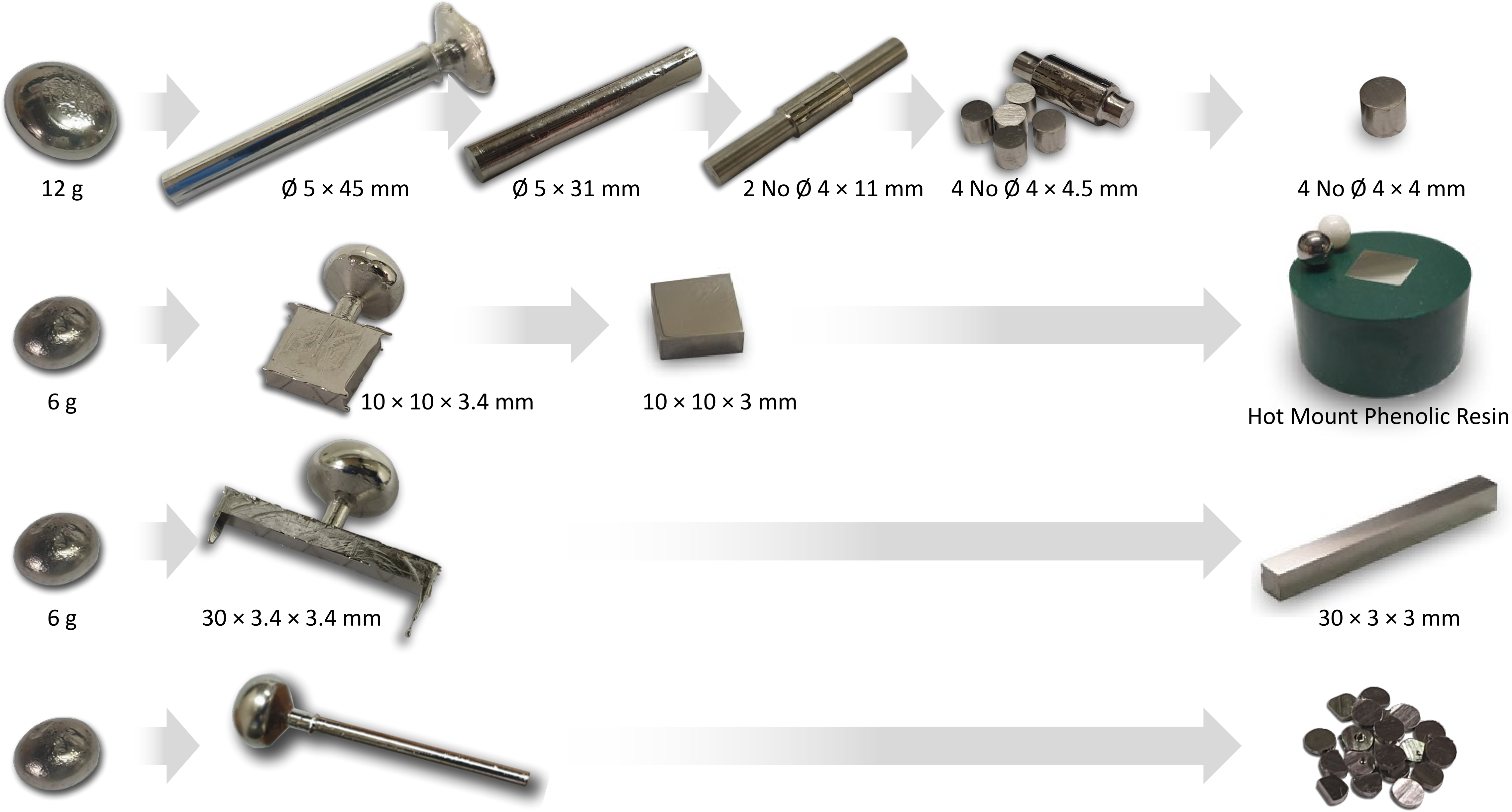
Compression Testing

Processing Route: Arc Melting/Suction Casting



- Edmund Bühler AM 200 Arc Melter system
- Vario Hybrid 400 DC HF generator
- Argon Atmosphere (99.98%)
- Suction Casting into Cylindrical Copper Moulds

Processing Route: Summary



12 g → Ø 5 × 45 mm → Ø 5 × 31 mm → 2 No Ø 4 × 11 mm → 4 No Ø 4 × 4.5 mm → 4 No Ø 4 × 4 mm

6 g → 10 × 10 × 3.4 mm → 10 × 10 × 3 mm → Hot Mount Phenolic Resin

6 g → 30 × 3.4 × 3.4 mm → 30 × 3 × 3 mm

6 g → Ø 3 × 45 mm → 20 No. Ø 3 × 28 mg

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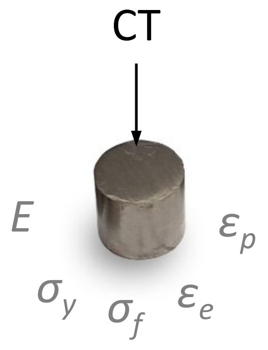
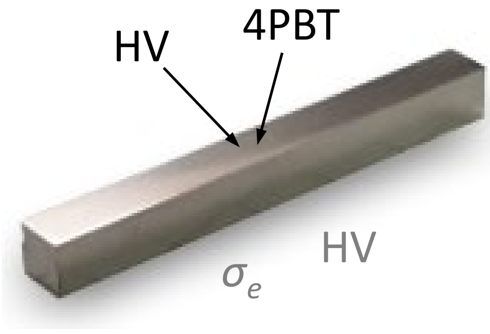
Test Specimen & Testing Equipment:

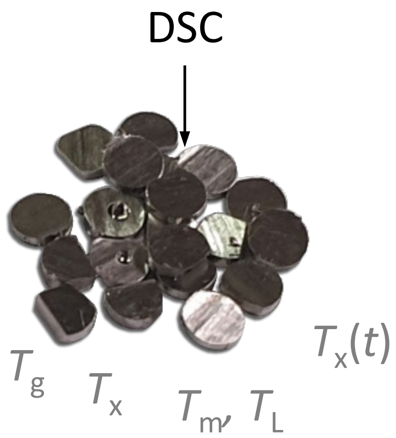


Ø 4 mm × 4 mm

10 mm × 10 mm × 3 mm



30 mm × 3 mm × 3 mm



Ø 3 mm × 28 mg

Testing:

- Density Measurements
- XRD Analysis (Amorphous Verification)
- EDX Analysis
- DSC Analysis
- Compression Testing
- Hardness Testing (HV)
- Fatigue Testing
- Ball-on-Disc (BOD) Wear Testing

Testing:

- Density Measurements (QA and porosity check √)
- XRD Analysis
- EDX Analysis
- DSC Analysis
- Compression Testing
- Hardness Testing (HV)
- Fatigue Testing
- Ball-on-Disc (BOD) Wear Testing

Testing:

- Density Measurements
- XRD Analysis (amorphous verification √)
- EDX Analysis
- DSC Analysis
- Compression Testing
- Hardness Testing (HV)
- Fatigue Testing
- Ball-on-Disc (BOD) Wear Testing

Testing:

- Density Measurements
- XRD Analysis (Amorphous Verification)
- EDX Analysis (confirm apportioned chemistry √)
- DSC Analysis
- Compression Testing
- Hardness Testing (HV)
- Fatigue Testing
- Ball-on-Disc (BOD) Wear Testing

Testing:

- Density Measurements
- XRD Analysis (Amorphous Verification)
- EDX Analysis
- DSC Analysis
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- Hardness Testing (HV)
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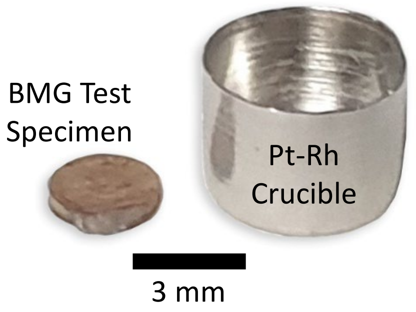
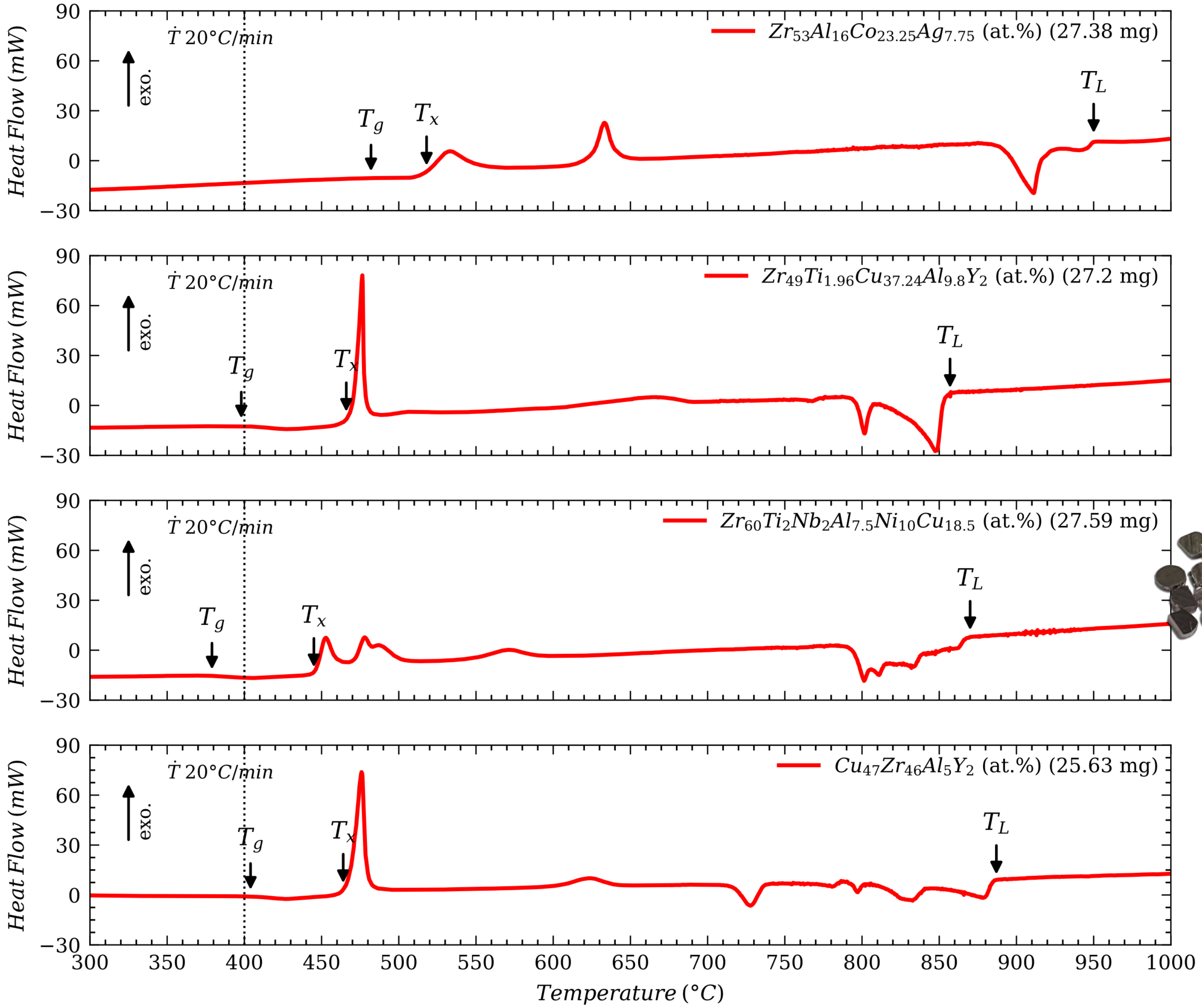
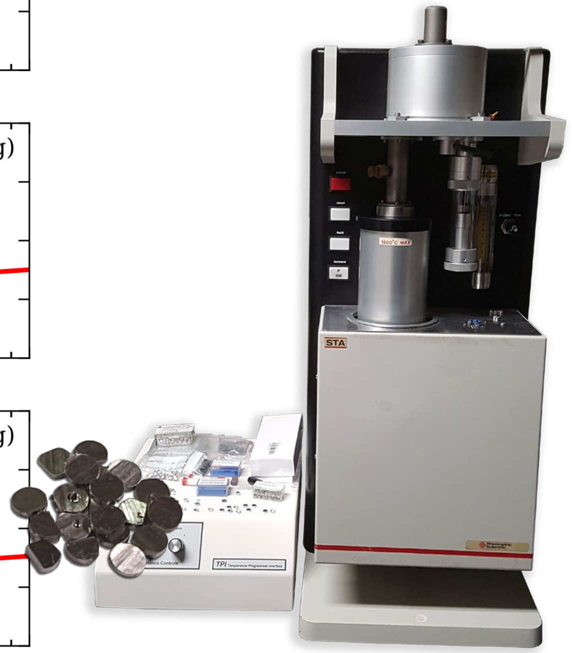
- Ball-on-Disc (BOD) Wear Testing

Differential Scanning Calorimetry (DSC): increasing T

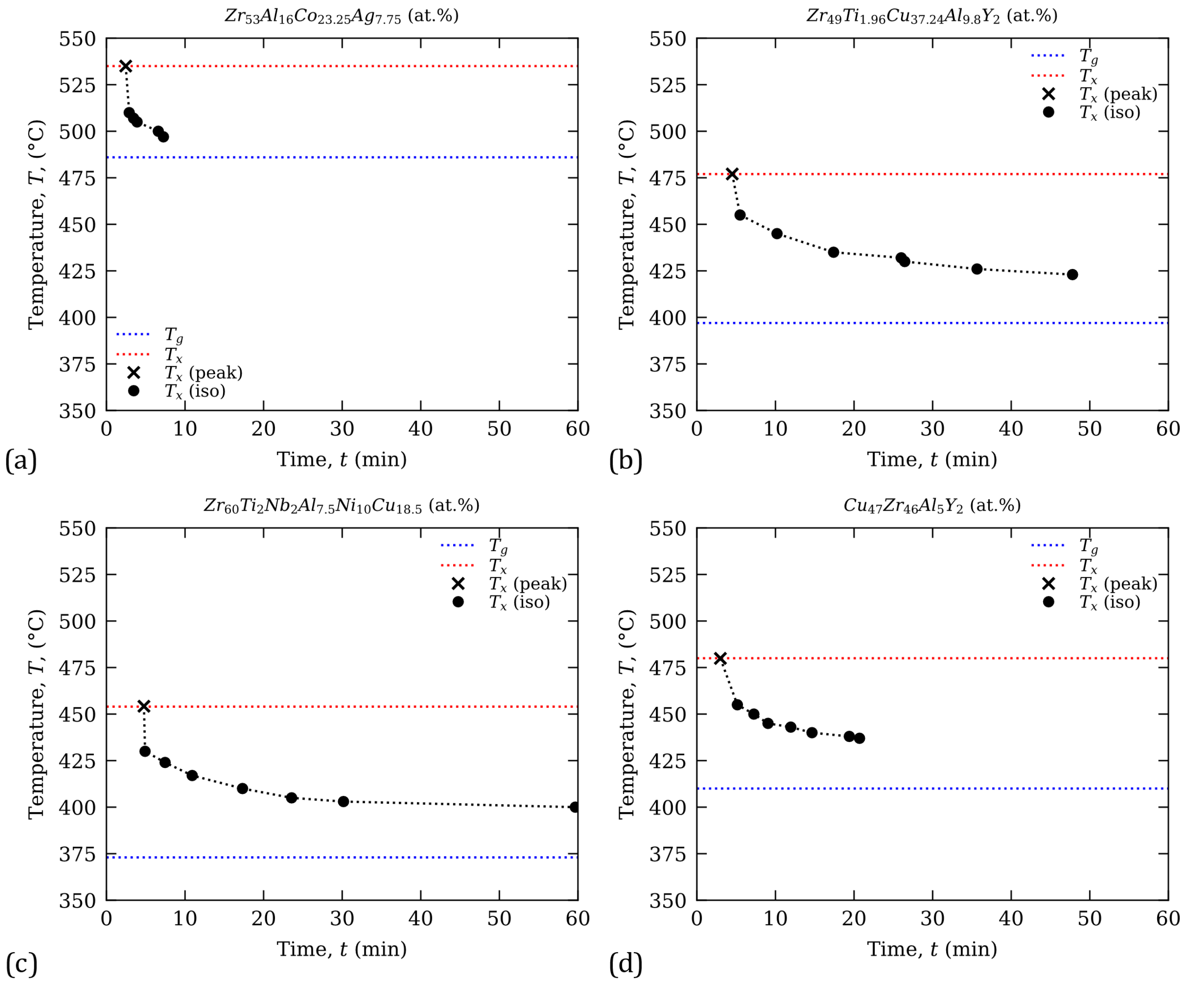
- Rheometric Scientific STA1500 Differential Scanning Calorimeter
- Pt-Rh Crucibles
- Test Specimens ~28 mg
- Heating Rate: 20 °C/min
- Temperature Range: 25 °C – 1,000 °C

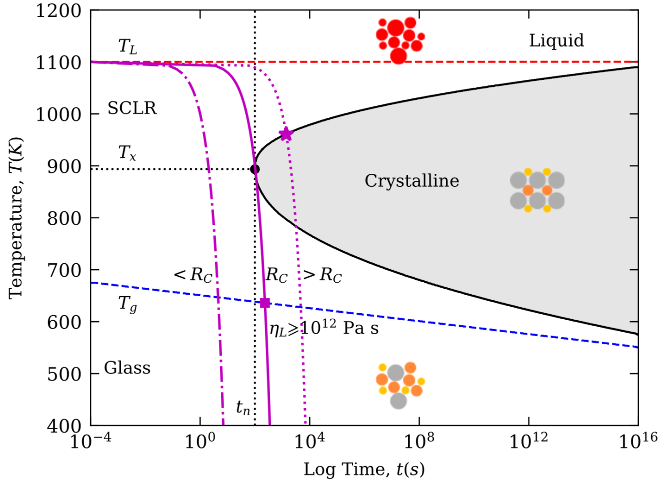






Differential Scanning Calorimetry (DSC): isothermal holds at T





Schematic TTT Diagram

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.

Results – Differential Scanning Calorimetry (DSC):

- Transition temperature values determined for all four project composition alloys
- Measured values in agreement with published values

C	*Composition (at.%)*	T_g (°C) *Onset*	T_g (°C) *End*	T_x (°C)	ΔT (°C) (T_x - T_g(End))	T_m (°C)	T_L (°C)
C12	$Zr_{53}Al_{16}Co_{23.25}Ag_{7.75}$	485	503	516	13	875	954
C16	$Zr_{49}Ti_{1.96}Cu_{37.24}Al_{9.8}Y_2$	399	429	472	43	787	858
C18	$Zr_{60}Ti_2Nb_2Al_{7.5}Ni_{10}Cu_{18.5}$	376	404	448	44	780	870
C35	$Cu_{47}Zr_{46}Al_5Y_2$	409	428	470	42	704	889

Experimentally determined temperature transitions for each of the project compositions. T_g: glass transition temperature; T_x: crystallisation temperature; T_m: melting temperature; T_L: liquidus temperature.

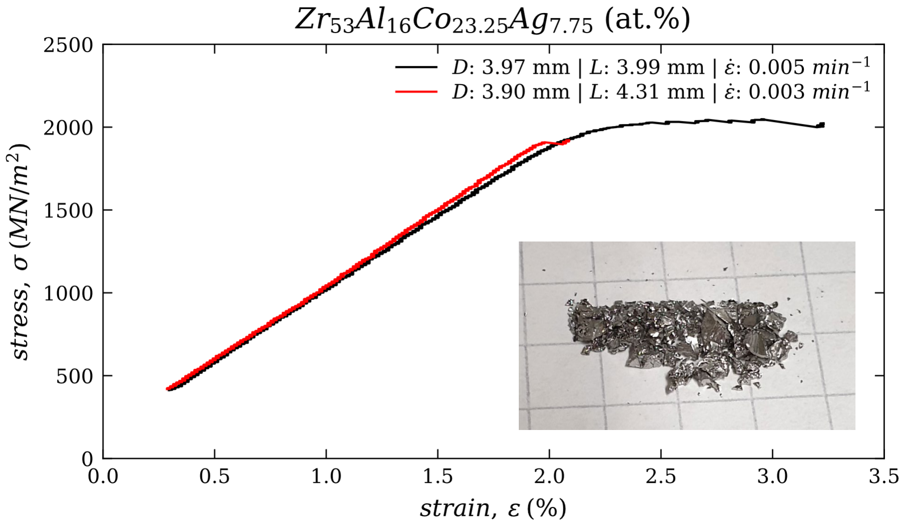
ΔT is the width of the supercooled liquid region (SCLR)

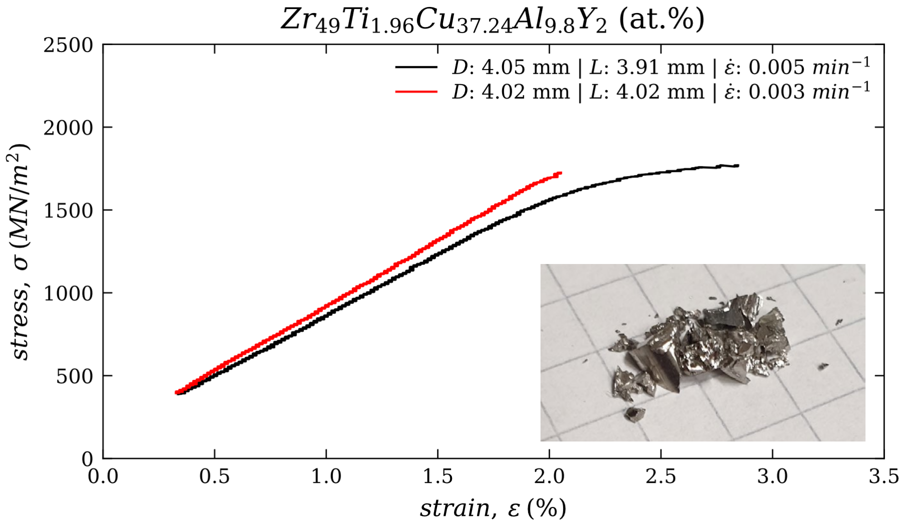
Testing:

- Density Measurements
- XRD Analysis (Amorphous Verification)
- EDX Analysis
- DSC Analysis
- Compression Testing
- Hardness Testing (HV)
- Fatigue Testing
- Ball-on-Disc (BOD) Wear Testing

Compression Testing:

- Hounsfield H50KS Universal Testing Machine





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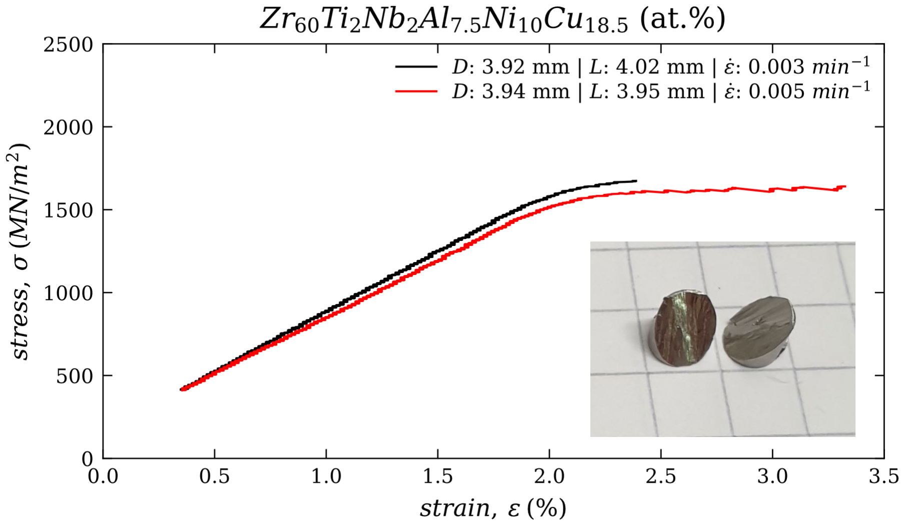
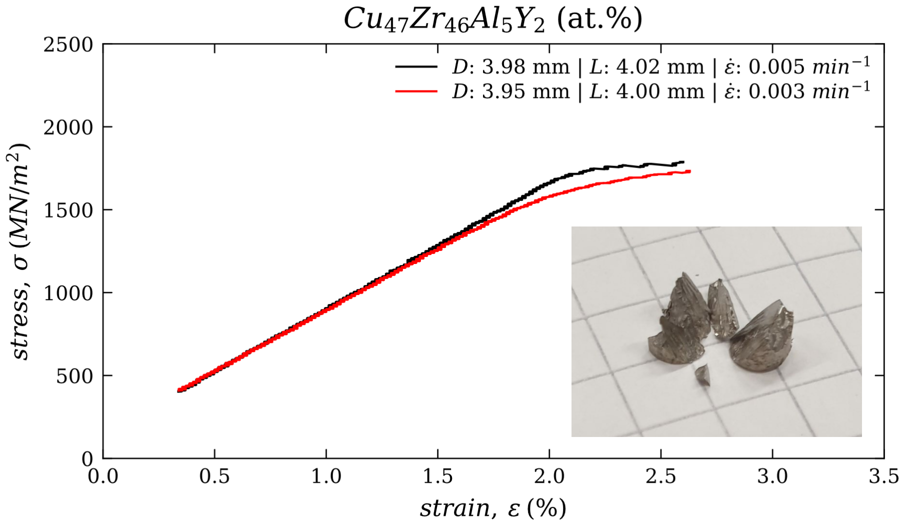
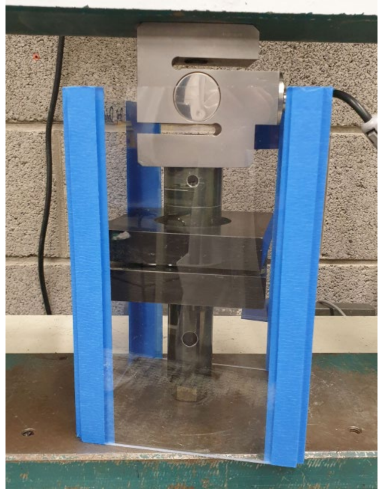






Results – Compression Testing:

- Elastic modulus (*E*), yield strength (σ_y), fracture strength (σ_f), elastic strain limit (ε_e), and plastic strain limit (ε_p) determined for all four project composition alloys
- Average values in agreement with published values (except C35).
- Significant performance variation from specimen to specimen indicates properties highly influenced by processing conditions
- “Best in class” performance misleading when compared to average

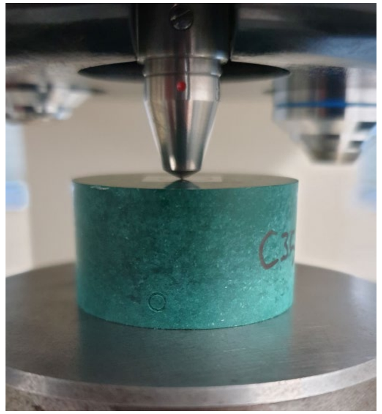
C	Composition (at.%)	E (GPa)	σ_y (GPa)	σ_f (GPa)	ε_e (%)	ε_p (%)
C12	$Zr_{53}Al_{16}Co_{23.25}Ag_{7.75}$	94 ± 3	1.9 ± 0.0	1.9 ± 0.1	2.0 ± 0.1	0.7 ± 0.9
C16	$Zr_{49}Ti_{1.96}Cu_{37.24}Al_{9.8}Y_2$	87 ± 3	1.6 ± 0.1	1.7 ± 0.1	1.9 ± 0.1	0.4 ± 0.5
C18	$Zr_{60}Ti_2Nb_2Al_{7.5}Ni_{10}Cu_{18.5}$	80 ± 3	1.5 ± 0.1	1.6 ± 0.1	1.8 ± 0.1	1.1 ± 0.6
C35	$Cu_{47}Zr_{46}Al_5Y_2$	87 ± 2	1.6 ± 0.1	1.8 ± 0.1	1.9 ± 0.1	0.8 ± 0.2

Testing:

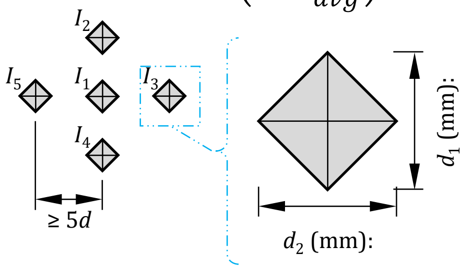
- Density Measurements
- XRD Analysis (Amorphous Verification)
- EDX Analysis
- DSC Analysis
- Compression Testing
- Hardness Testing (HV)
- Fatigue Testing
- Ball-on-Disc (BOD) Wear Testing

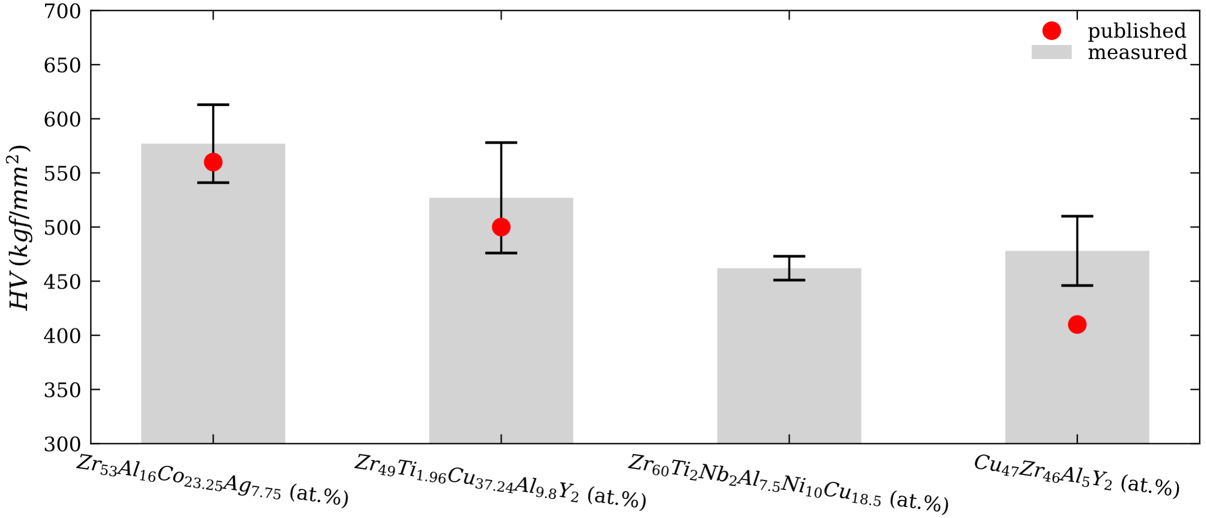
Vickers Hardness Testing:

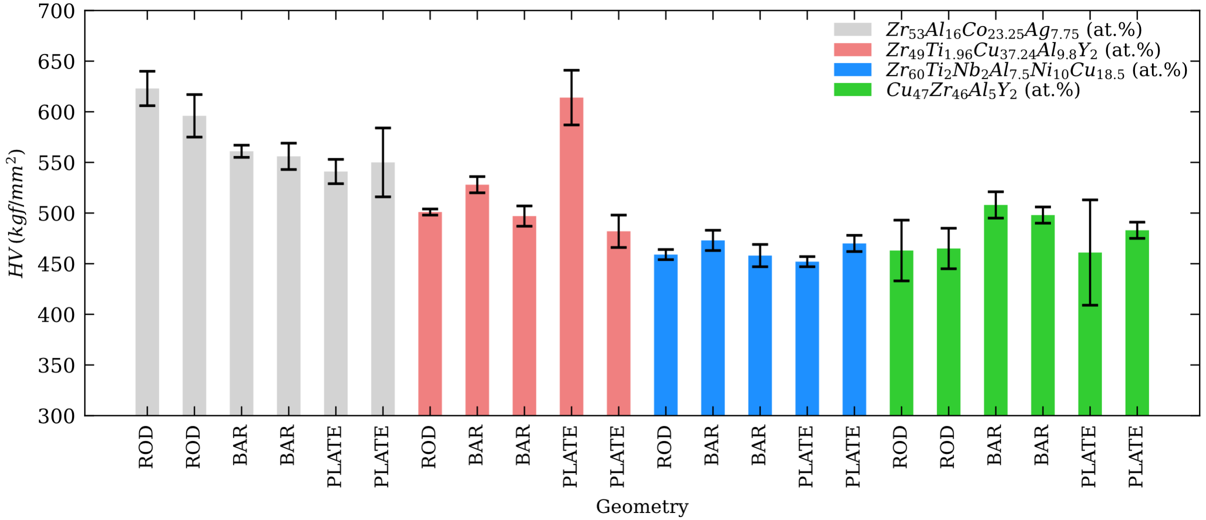
- Mitutoyo AVK-C2 Hardness Tester
- Indent Loadings: 1 kgf, 2 kgf, 10 kgf (5 at each loading)
- Dwell Time: 10 s
- Test Specimen Surface Finish: Ra < 1 um



$$HV \cong 1.8544\left({}^{F}/_{d_{avg}^{2}}\right)$$







Results – Vickers Hardness Testing:

- Vickers Hardness values determined for all four project composition alloys
- Average values in agreement with published values
- Significant performance variation from stock material to stock material indicating properties highly influenced by processing conditions

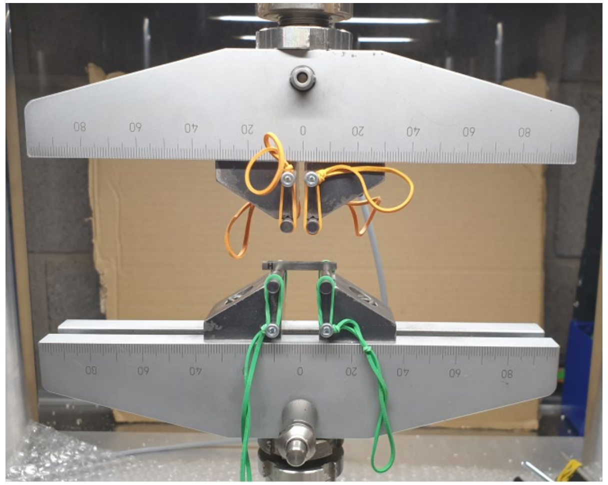
C	*Composition (at.%)*	*HV (kgf/mm²)*
C12	$Zr_{53}Al_{16}Co_{23.25}Ag_{7.75}$	577 ± 36
C16	$Zr_{49}Ti_{1.96}Cu_{37.24}Al_{9.8}Y_2$	527 ± 51
C18	$Zr_{60}Ti_2Nb_2Al_{7.5}Ni_{10}Cu_{18.5}$	462 ± 11
C35	$Cu_{47}Zr_{46}Al_5Y_2$	478 ± 32

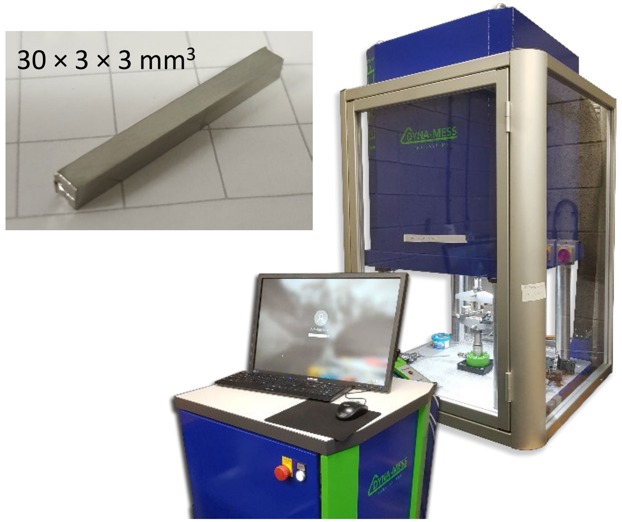
Testing:

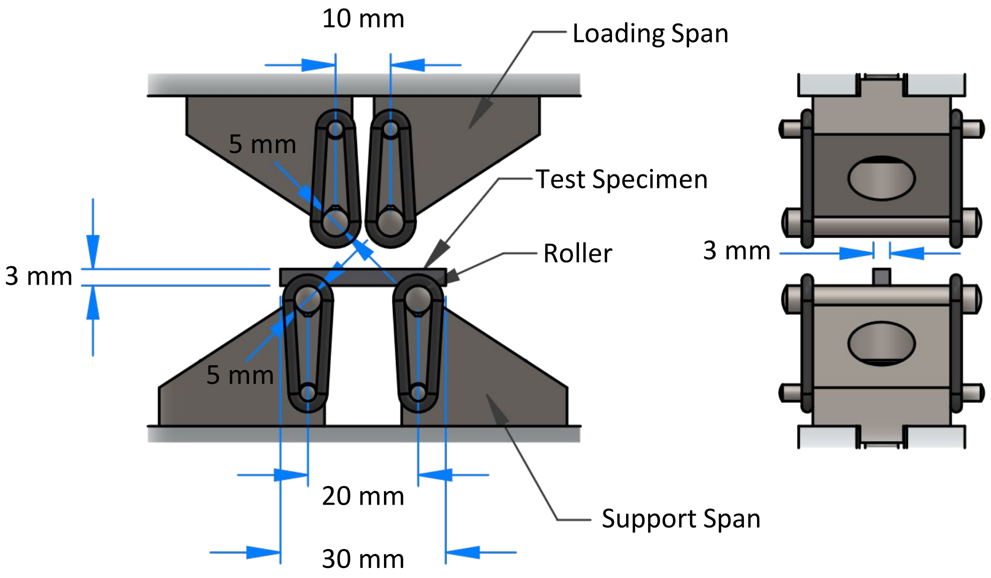
- Density Measurements
- XRD Analysis (Amorphous Verification)
- EDX Analysis
- DSC Analysis
- Compression Testing
- Hardness Testing (HV)
- **Fatigue Testing**
- Ball-on-Disc (BOD) Wear Testing

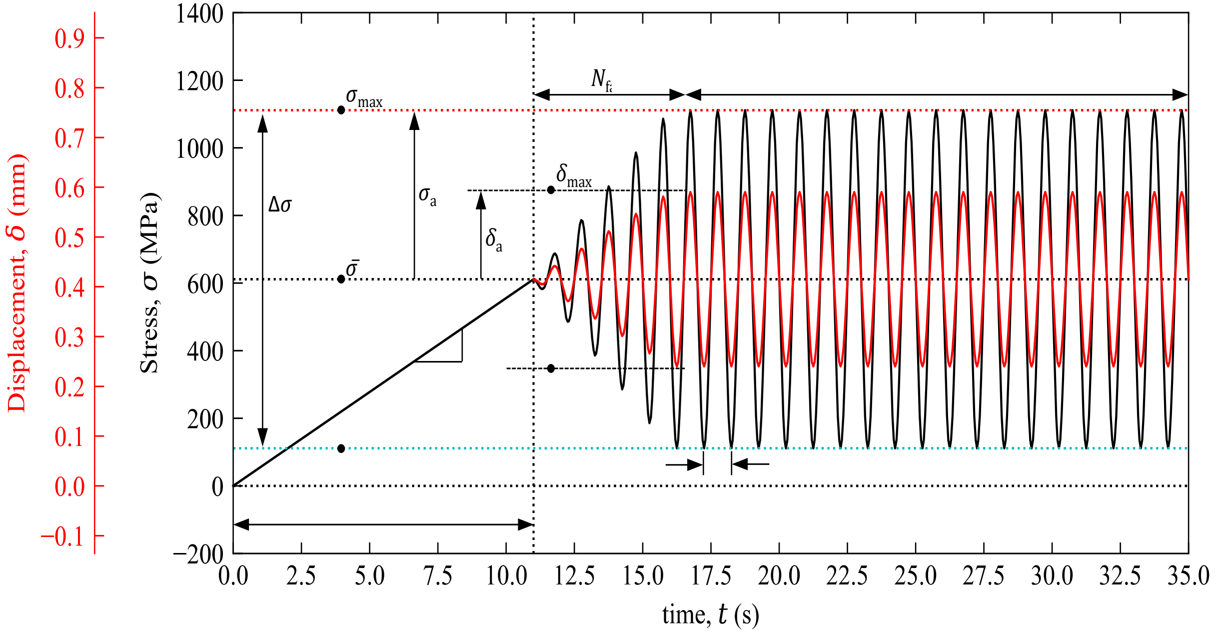
Fatigue Testing:

- Dyna-Mess TE 7 HCF 4-Column Testing Machine
- 4-Point Bend Test Setup (20 mm outer span, 10 mm inner span)
- Test Specimen dimensions: 30 mm x 3 mm x 3 mm
- Frequency: 25 Hz
- Stress Ratio: 0.1
- Stress Ranges: 1000 MPa, 600 MPa, 400 MPa, and 200 MPa



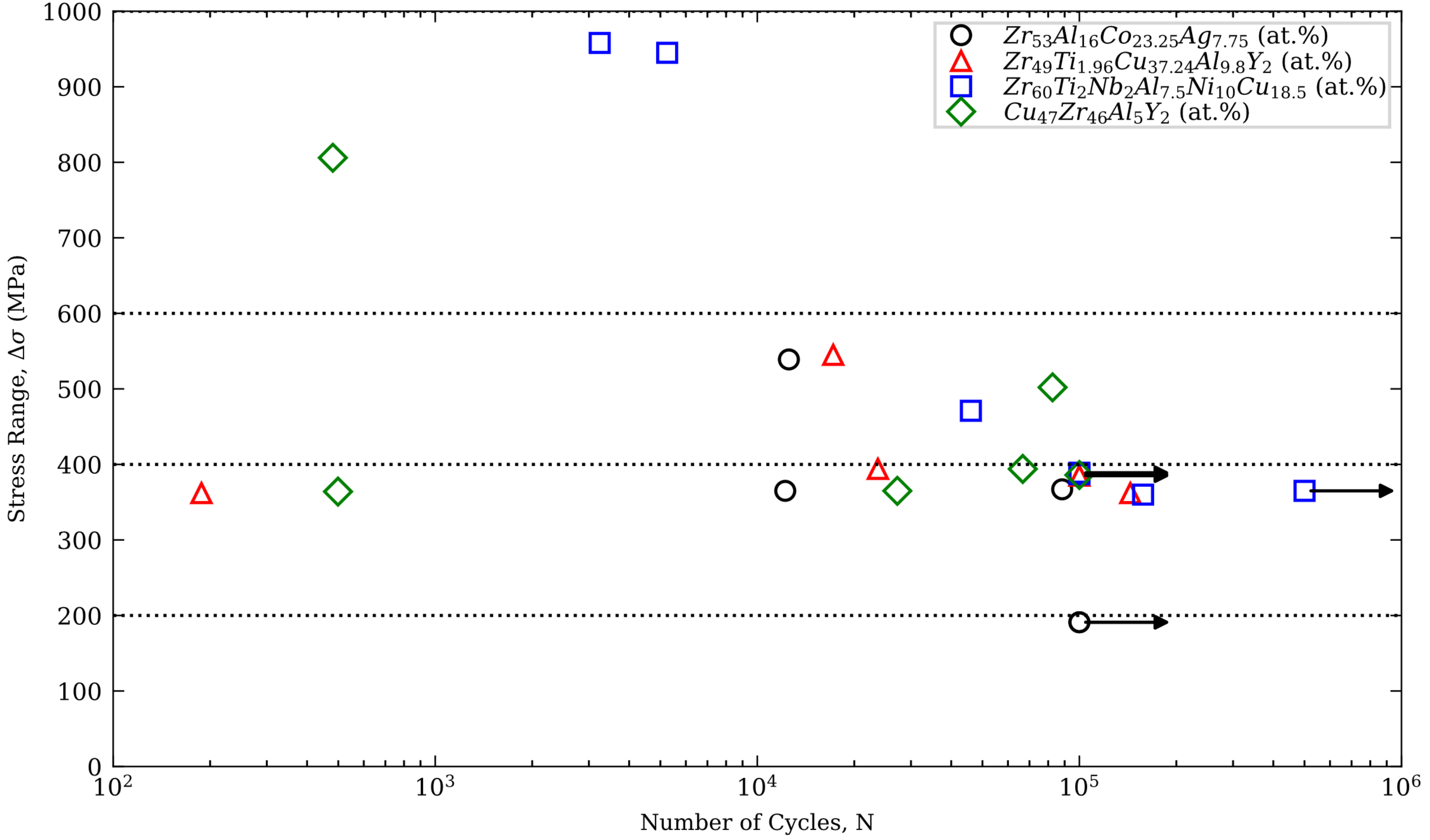


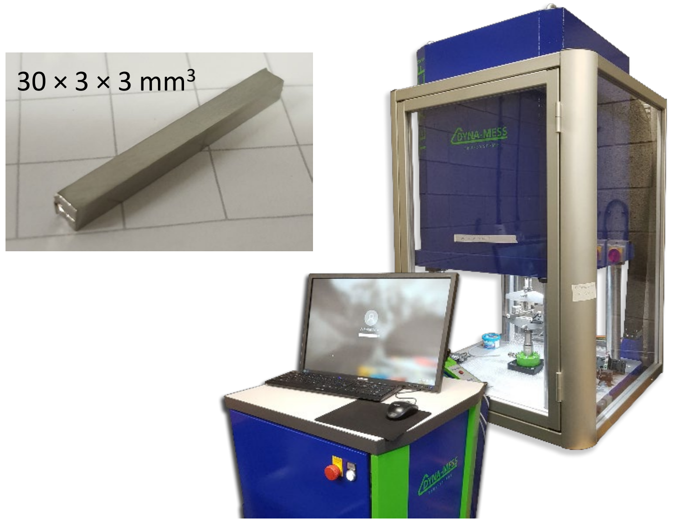


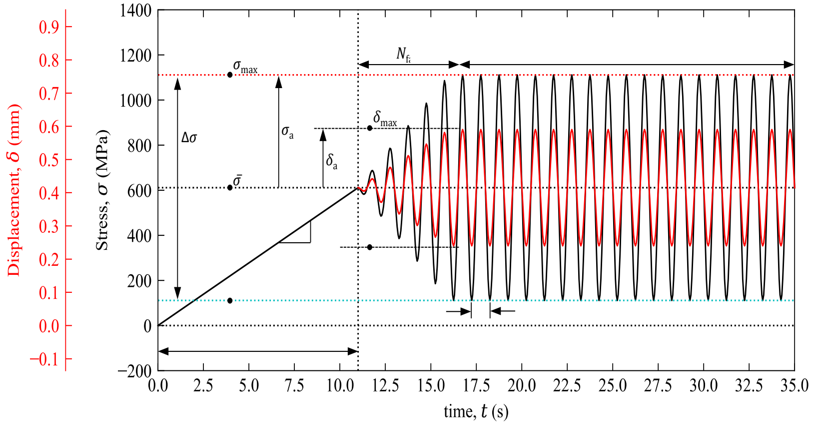


Bulk Metallic Glasses for Space Mechanism Applications

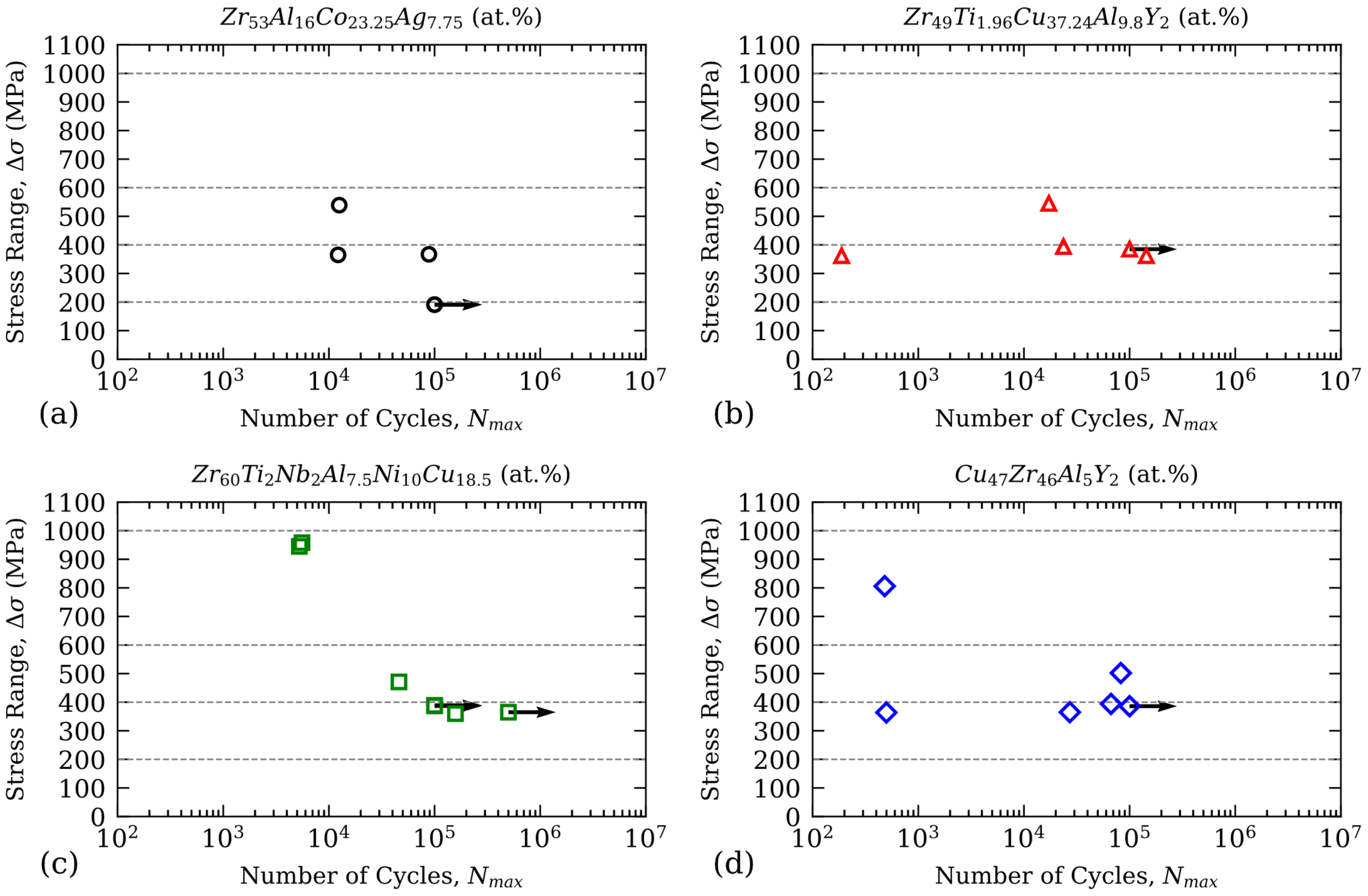
Fatigue Testing: Results







Results – Fatigue Testing:



S-N plots of fatigue test results listed in . (a) Composition C12. (b) Composition C16. (c) Composition C18. (d) Composition C35. Arrows indicated test specimens that did not fail before reaching N_{max}. Horizontal dashed lines at σ_{target}. All other markers represent run-to-fail test specimens.

Testing:

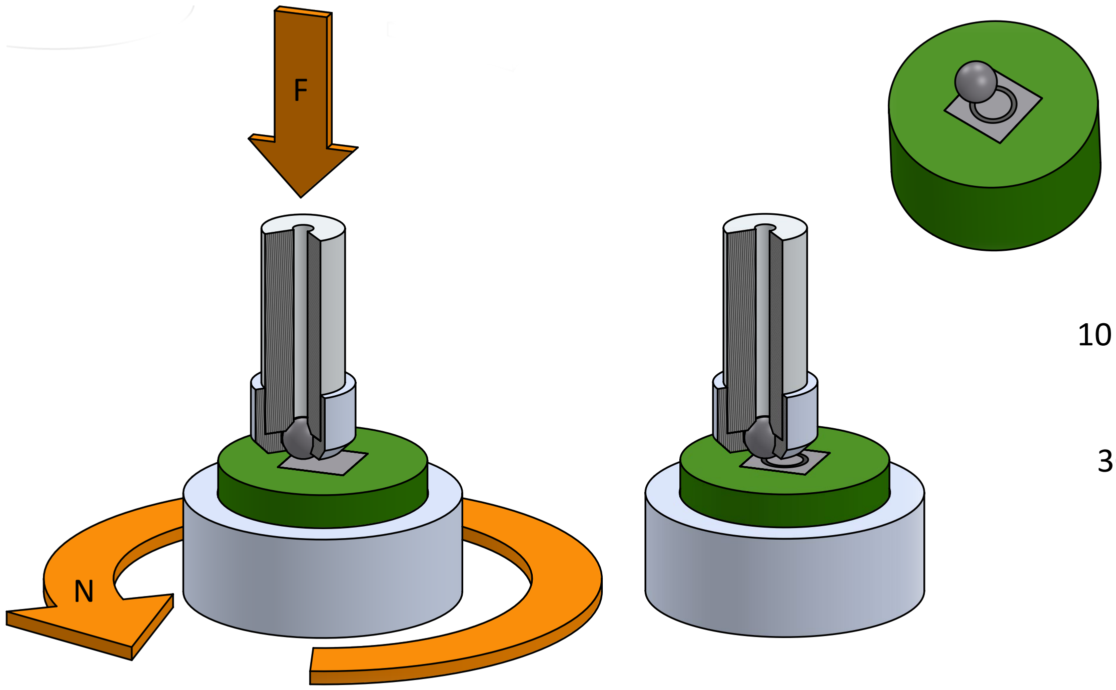
- Density Measurements
- XRD Analysis (Amorphous Verification)
- EDX Analysis
- DSC Analysis
- Compression Testing
- Hardness Testing (HV)
- Fatigue Testing
- Ball-on-Disc (BOD) Wear Testing

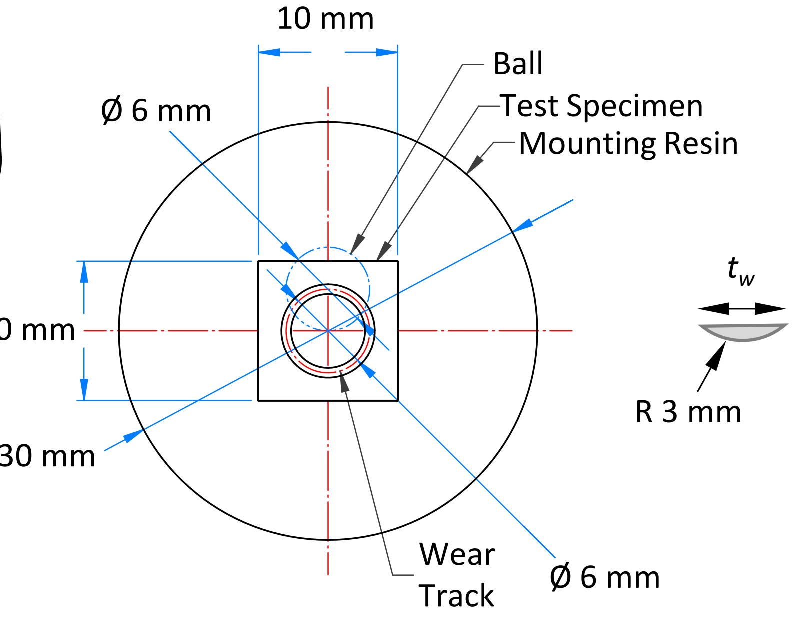
Bulk Metallic Glasses for Space Mechanism Applications

Wear Testing (BOD):

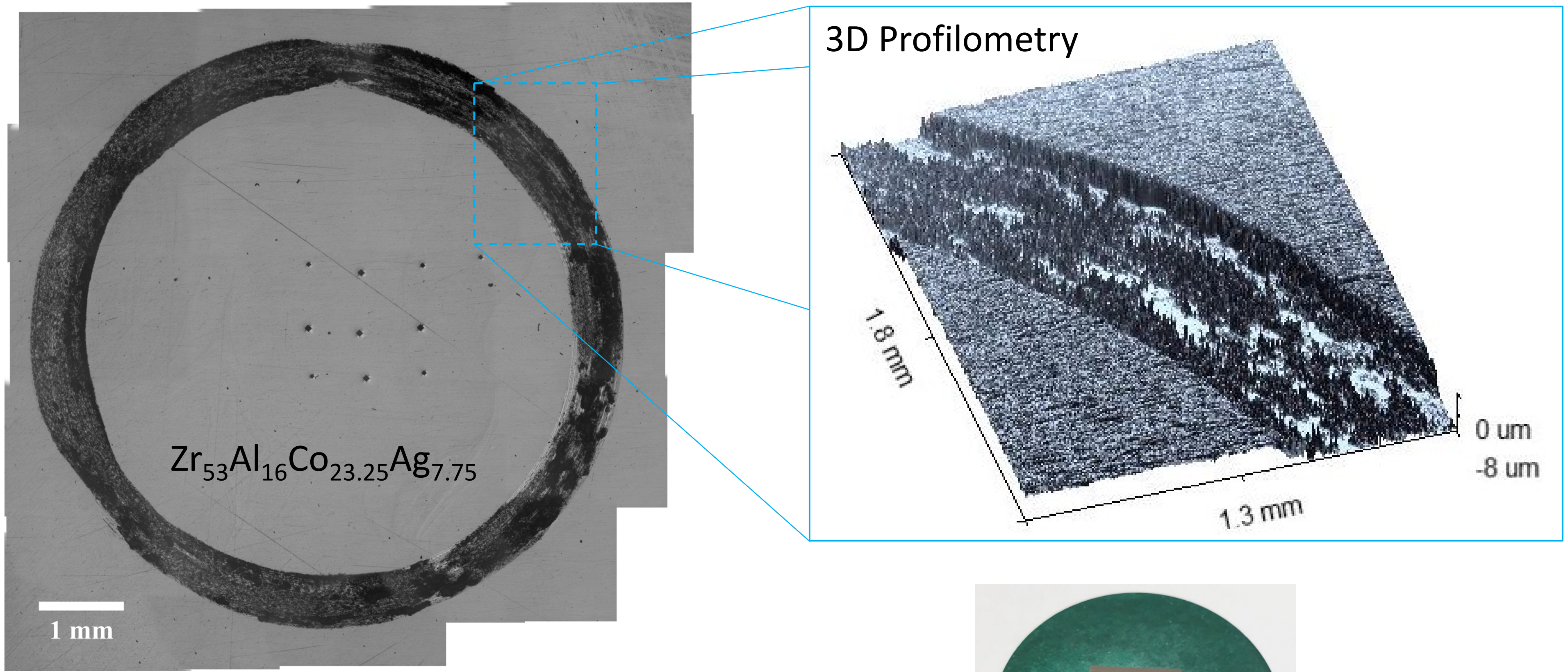
- Neo-Tribo MFW120 POD Wear Test System
- Load/Speed Ranges: 2 N/60 mm/s, 5 N/20 mm/s
- Ball Material: WC-Co (1585 HV), ZrO_2 (1200 HV)
- Wear Track Diameter: ~6 mm
- Total Distance: ~180 m, ~60 m

$$K_A = \frac{V \times H}{F \times S}$$

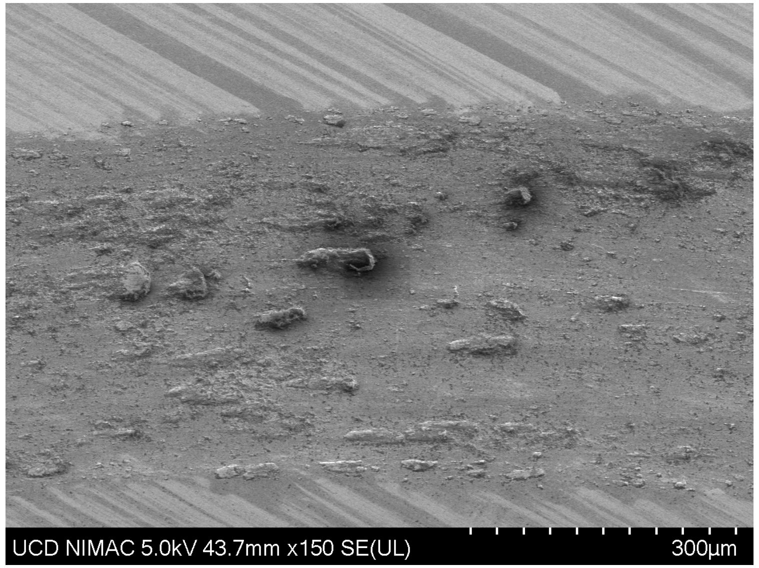




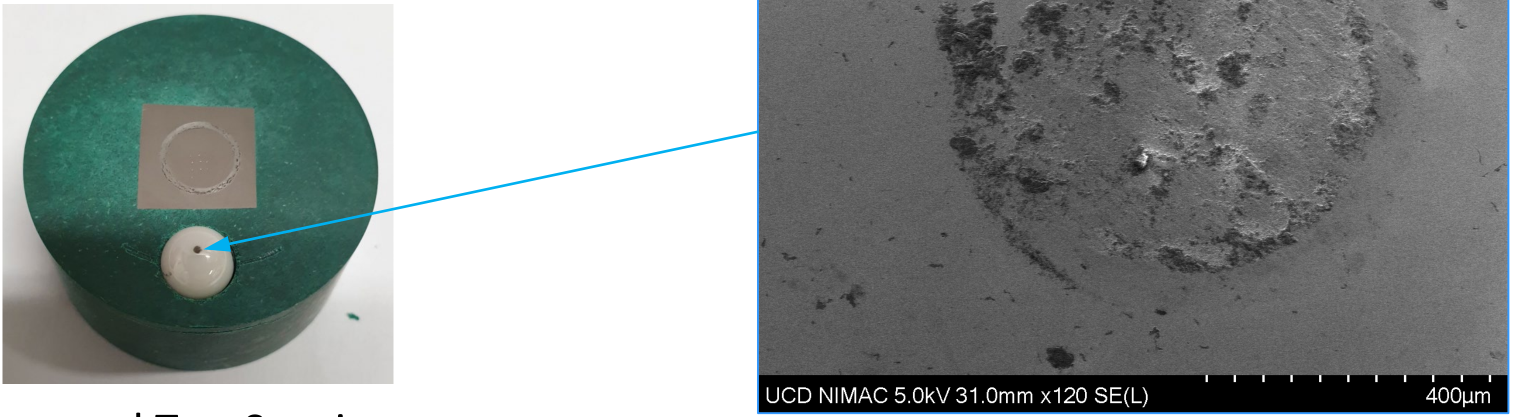
Wear Testing (BOD): Results



Wear Track
Ø 6 mm ZrO_2 Ball, 5 N load, 20 mm/s, 62.8 m



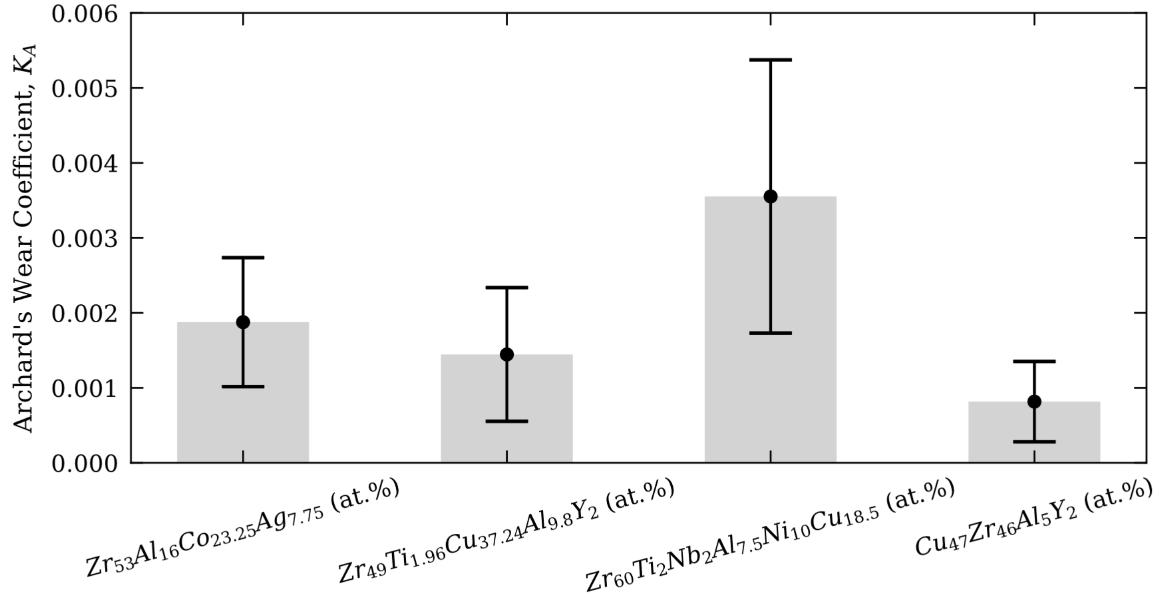
$Zr_{53}Al_{16}Co_{23.25}Ag_{7.75}$



Mounted Test Specimen

ZrO_2 Ball Debris

Results – BOD Wear Testing:



$$K_A = \frac{V \times H}{F \times S}$$

K_A :Archard wear coefficient

V: volume wear loss
H: hardness
F: normal force
S: sliding distance

→ Low K_A indicates good wear resistance

C	*Composition (at.%)*	*K_A (μ)*	*K_A (σ)*
C12	$Zr_{53}Al_{16}Co_{23.25}Ag_{7.75}$	0.0019	0.0009
C16	$Zr_{49}Ti_{1.96}Cu_{37.24}Al_{9.8}Y_2$	0.0015	0.0009
C18	$Zr_{60}Ti_2Nb_2Al_{7.5}Ni_{10}Cu_{18.5}$	0.0036	0.0018
C35	$Cu_{47}Zr_{46}Al_5Y_2$	0.0008	0.0005

Calculated average Archard's wear coefficient, K_A grouped by project compositions. Error bars represent one standard deviation from the calculated mean.

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, 091706

BMG Property Results – Overall Summary:

- All required thermophysical properties determined for all four project compositions
- Average values in agreement with published values
- Significant performance variation from stock material to stock material indicating properties highly influenced by processing conditions

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	$^*\sigma_e$ *(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

Experimental determined thermophysical properties of each of the four project compositions investigated in this work, 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.

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

Comparison with competing “legacy” space materials

These are conventional crystalline alloys:

- Ti-6%Al-4%V
- Cold-worked stainless steels: grades 303 and 304

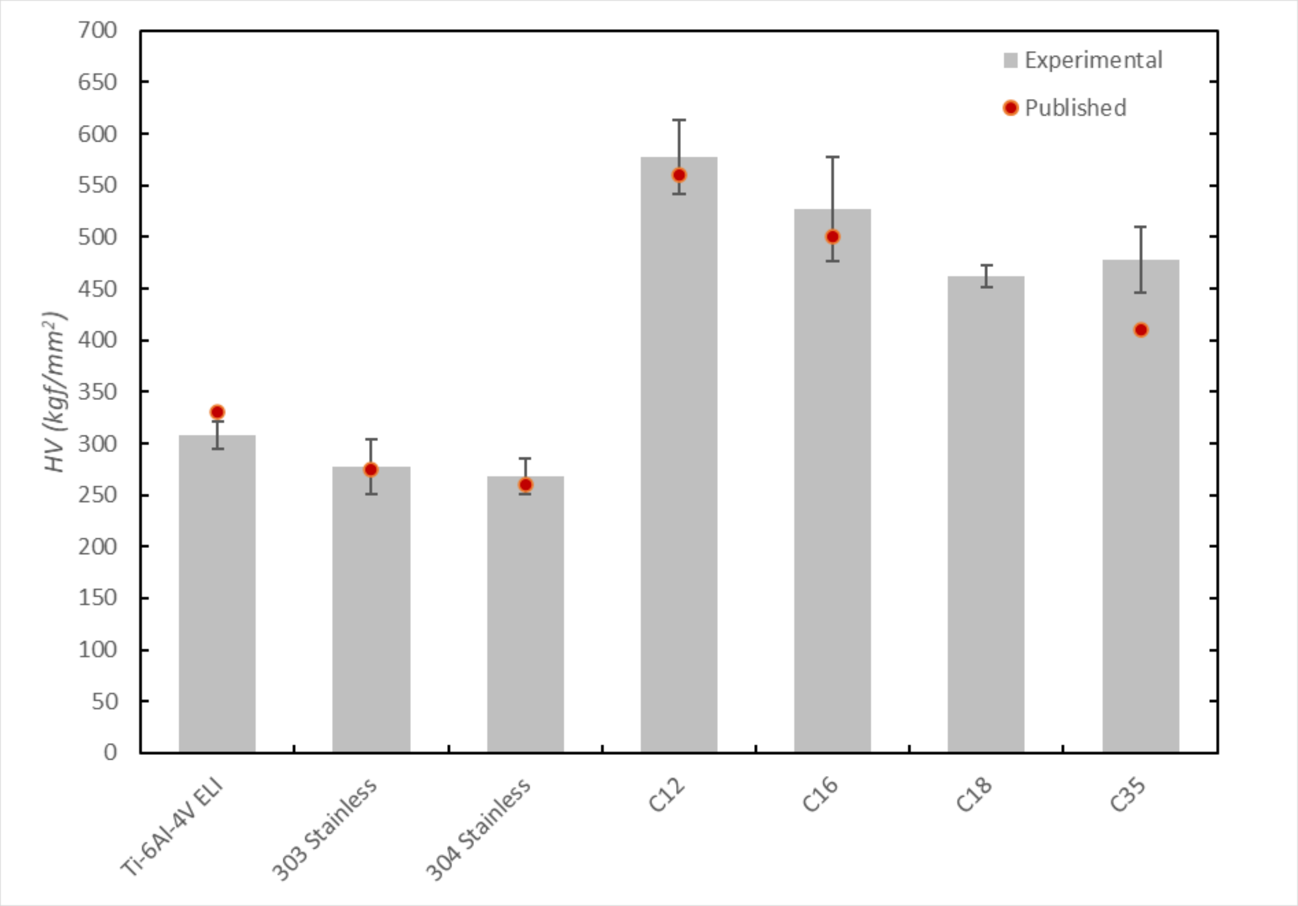
Hardness and Wear

Fatigue

Murphy, A.G., Meagher, P., Norman, A., Browne, D.J., “Mechanical and thermal stability of Bulk Metallic Glass alloys selected for space mechanism applications”, *Materials and Design*, under review.

Comparison with competing “legacy” space materials

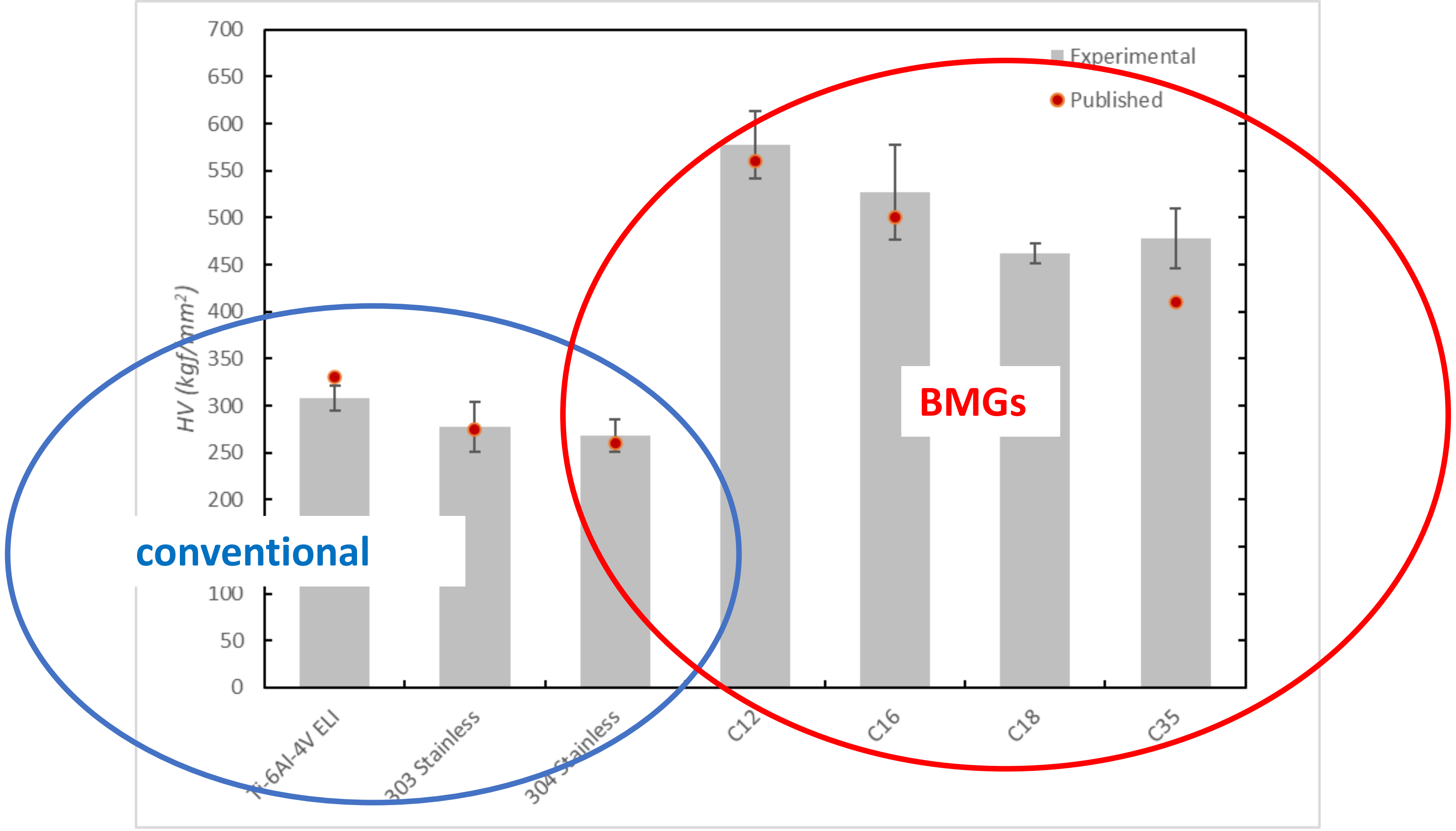
Hardness comparisons



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, 091706

Comparison with competing "legacy" space materials

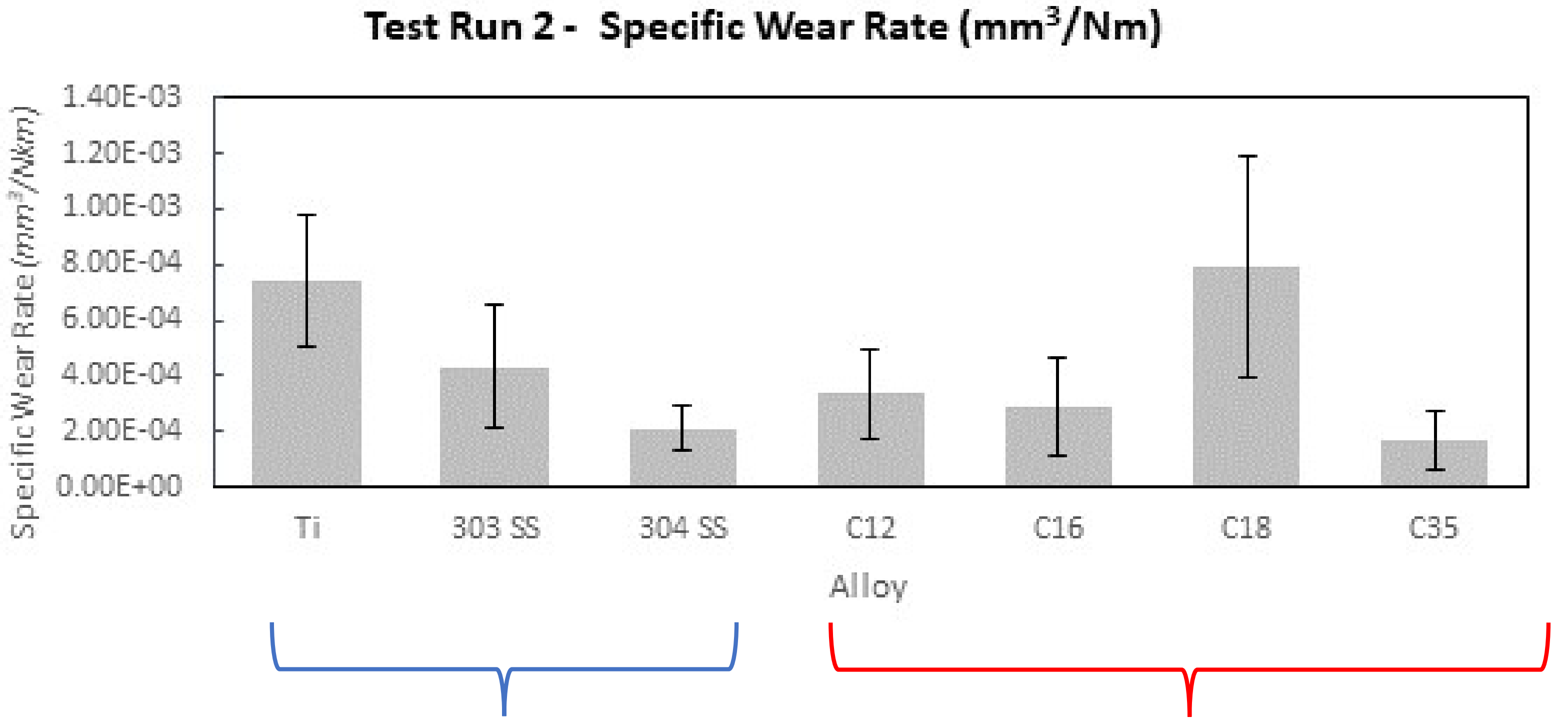
Hardness comparisons



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, 091706

Comparison with competing “legacy” space materials

Wear comparisons



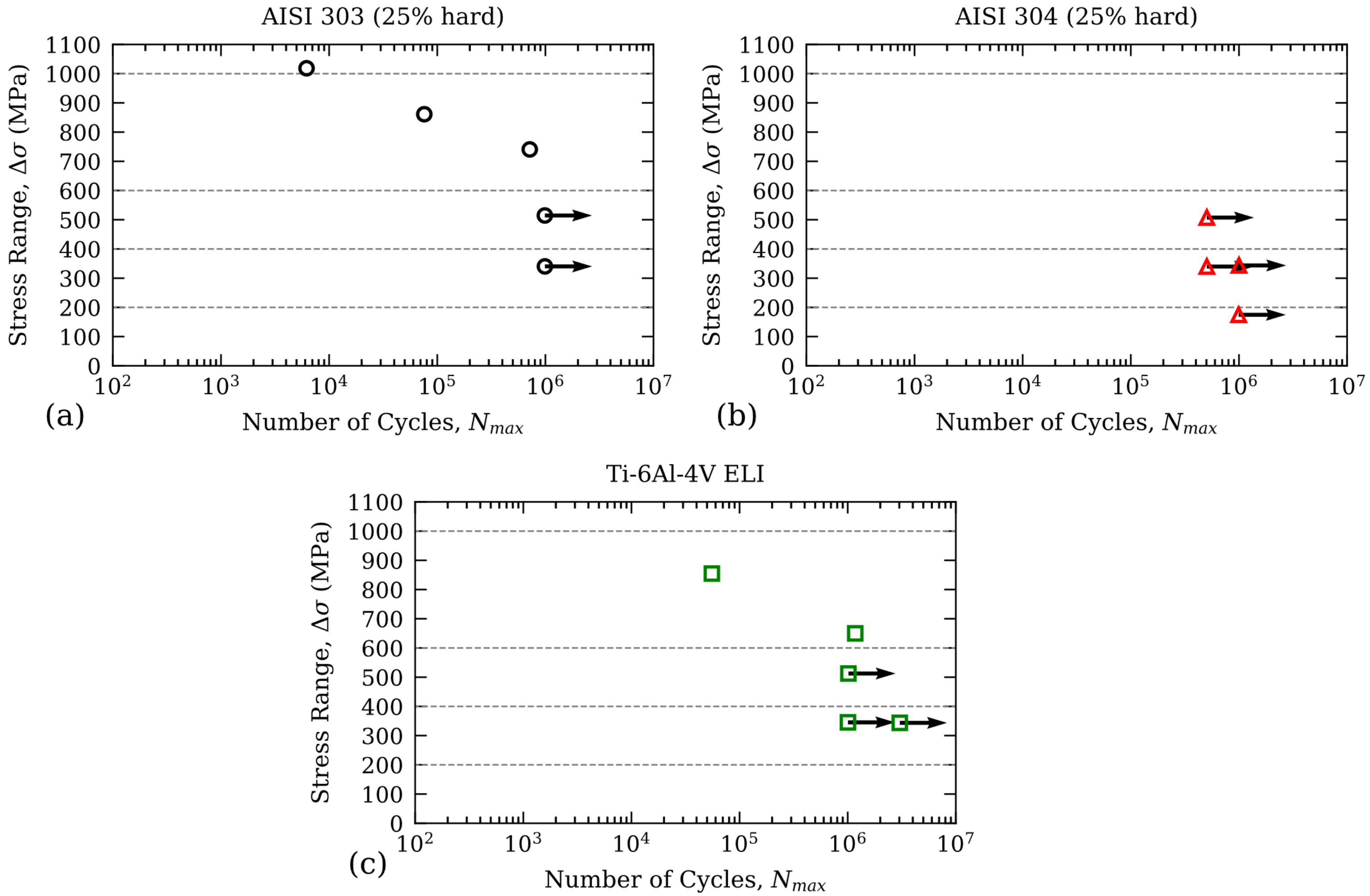
conventional
= crystalline

BMGs
= non-crystalline

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, 091706

Comparison with competing “legacy” space materials

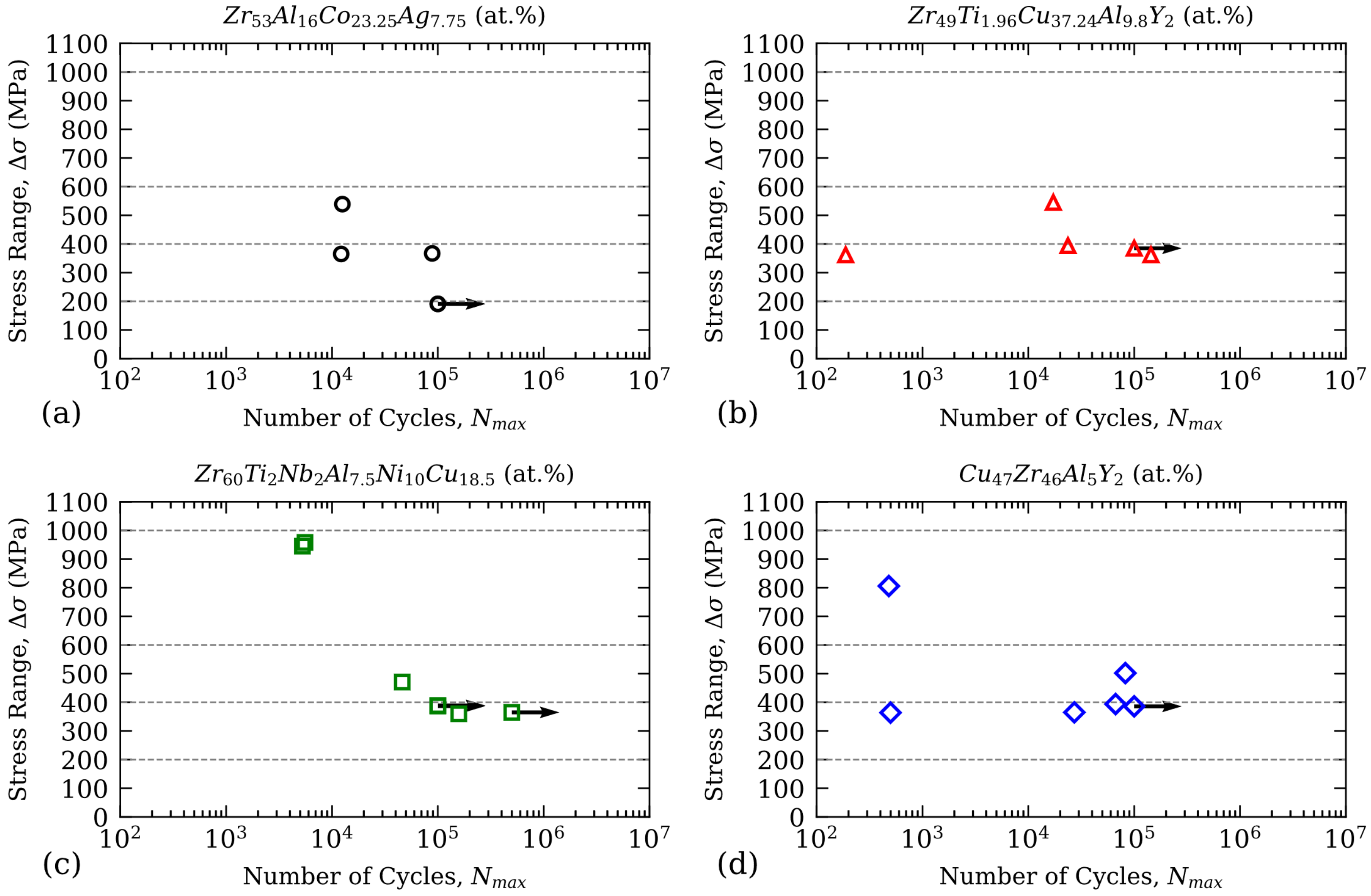
Connventional alloy fatigue behaviour



S-*N* plots of fatigue test results. Arrows indicated test specimens that did not fail before reaching $N_{\max}$. All other markers represent run-to-fail test specimens.

Comparison with competing "legacy" space materials

BMG Fatigue Behaviour



Conventional alloys have superior low cycle fatigue behaviour, and higher fatigue strength.

BMGs may have adequate fatigue life

More testing is required.

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

BMGs selected for applications (Give summary reasons)

- Gears: alloy C16: $\mathbf{Zr_{49}Ti_{1.96}Cu_{37.24}Al_{9.8}Y_2}$

Reasons: high hardness, wear resistance, high strength, easily processed, T_g ~ 400 °C, reasonable fatigue strength, machinable (see below).

- Flexures: alloy C18: $\mathbf{Zr_{60}Ti_2Nb_2Al_{7.5}Ni_{10}Cu_{18.5}}$

Reasons: high elasticity, high strength, highest plastic strain to failure, best fatigue properties.

Drawback: low T_g (376 °C) **but** good thermal stability in supercooled liquid region, just above T_g (hint – thermoplastic formability).

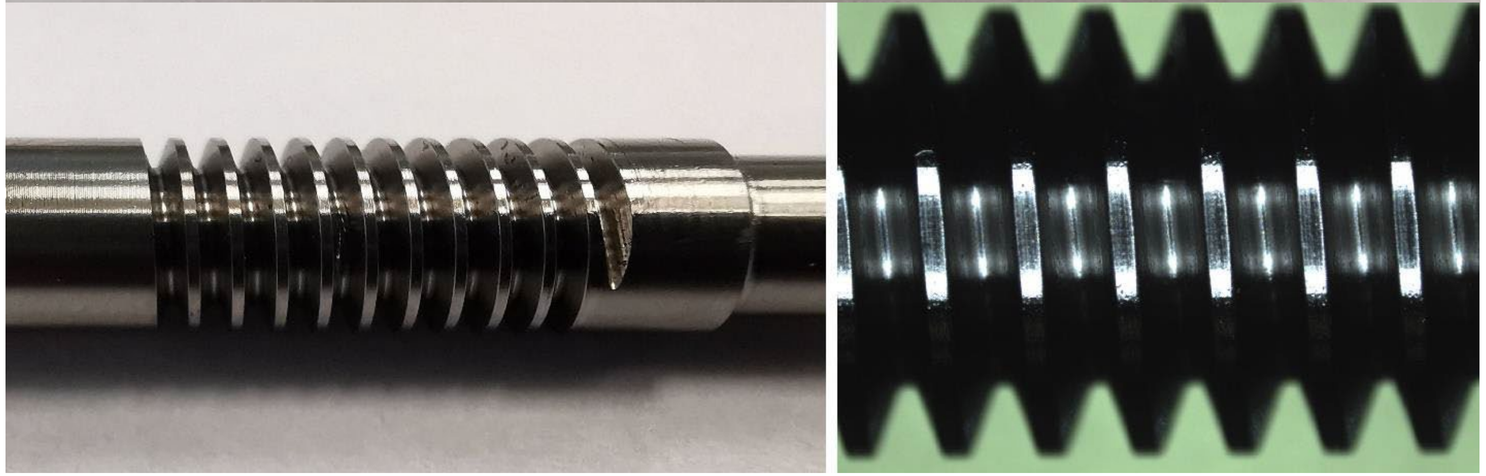
Machining Trials on BMG selected for gear applications

C16 alloy: machined from BMG rods ϕ 6.35 mm

- Rack

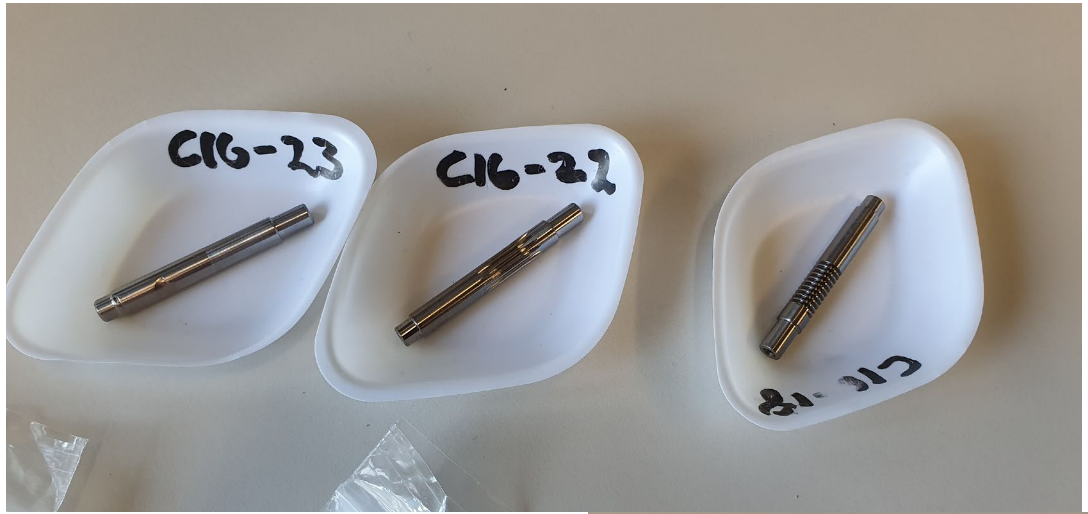
- Pinion

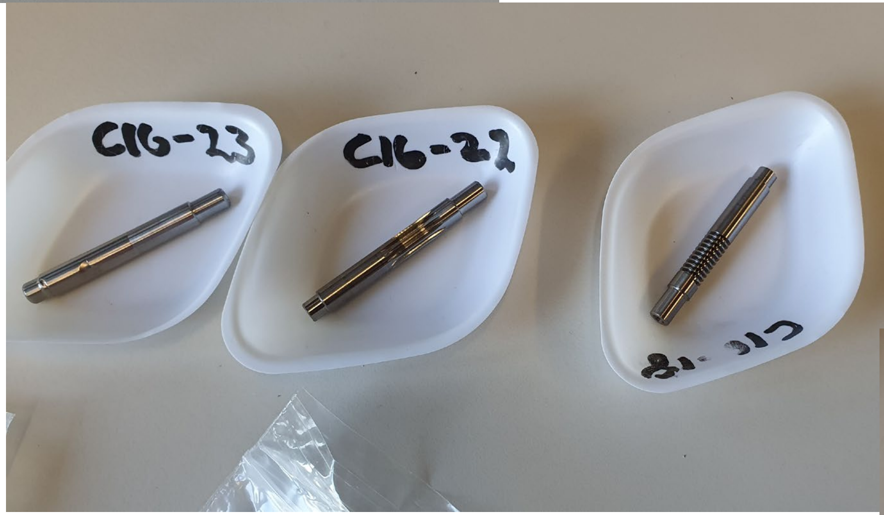
- Worm gear



$Zr_{49}Ti_{1.96}Cu_{37.24}Al_{9.8}Y_2$

Bulk Metallic Glasses for Space Mechanism Applications





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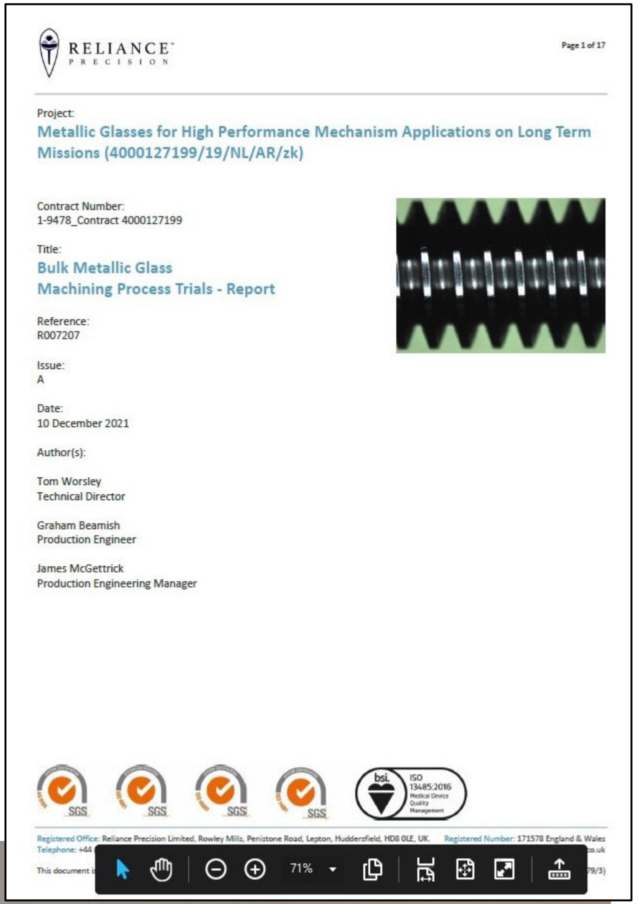
PRECISION



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Project:
Metallic Glasses for High Performance Mechanism Applications on Long Term Missions (4000127199/19/NL/AR/zk)

Contract Number:
1-9478_Contract 4000127199

Title:
Bulk Metallic Glass
Machining Process Trials - Report

Reference:
R007207

Issue:
A

Date:
10 December 2021

Author(s):

Tom Worsley
Technical Director

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Production Engineer

James McGettrick
Production Engineering Manager

Registered Office: Reliance Precision Limited, Rowley Mills, Penistone Road, Lepton, Huddersfield, HD8 0LE, UK. Registered Number: 171578 England & Wales
Telephone: +44 … co.uk

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$Zr_{49}Ti_{1.96}Cu_{37.24}Al_{9.8}Y_2$

Conclusions

- This work presents the initial finding from materials testing performed on four BMG alloy compositions selected for potential replacement for traditional space-mechanism metals.
- Based on preliminary results, BMG alloys selected exhibit favourable properties for the mechanisms of interest.
- Processing conditions play 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 can be machined into gear shapes with existing tools, following parameter optimisation.
- The BMG alloy C18 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.
- Further testing and analysis, under simulated space conditions, is required.

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
- Novel mechanisms can be designed for manufacture in bulk metallic glass.

Talk Outline:

- Project Introduction and Scope
- Mechanism, BMG, Processing Selection
- BMG Material Testing
- Conclusions & Future Work
- Acknowledgements/Questions & Comments

Acknowledgements:

Ms. Dhritica Bora, Ms. Laura Clarke, Mr. Gang Shen, Dr. Ian Reid, School of Mechanical and Materials Engineering, University College Dublin, for contributions to materials testing and data analysis.

Tadg Collins, Graham Beamish, James McGettrick at Reliance Precision Manufacturing Limited, Bandon, Ireland for machining trials on BMGs.

Martin Humphries of SpaceMech, UK, for advice on selection of space mechanisms for this study.

Funding for this work is provided by the European Space Agency under the Technology Development Element program, contract no. 4000127199/19/NL/AR/zk.

Thank you for your kind attention