EXECUTIVE SUMMARY REPORT
"METALLIC GLASSES FOR HIGH PERFORMANCE MECHANISM APPLICATIONS ON LONG TERM MISSIONS"

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Metallic Glasses for High Performance Mechanism Applications on Long Term Missions

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SUMMARY

The main goal of activity was to study processing and properties of a new class of materials – bulk metallic glasses. Project was divided in 5 work packages as follows:

WP1	• Literature review of metallic glasses • applications, materials, processes • Trade off and application selection
WP2	• Definition of key requirements • Development of test plan • Manufacturing document
WP3	• Material manufacturing • Material testing • Metallic glass characterization test plan - trade off/down selection
WP4	• Production of samples • Testing and characterization of samples • Testing results/implementation plan/lessons learned
WP5	• Management

Metallic glasses are amorphous alloys in which nucleation and crystallization has been supressed by rapid quenching of liquid metal. Compared to their crystalline counterparts, the absence of long-range order and dislocation-like defects result in combination of unique properties such as high strength, elasticity and hardness and superior corrosion resistance.

Firstly, literature review of bulk metallic glasses focused on identification of applications, materials reported in literature and their processing was done within WP1.

Based on literature and trade-off review, 3 applications (i.e. wear, spring and coatings for HDRM) and 6 promising material candidates (commercial as well as experimental) were identified (Figure 1 and Table 1).

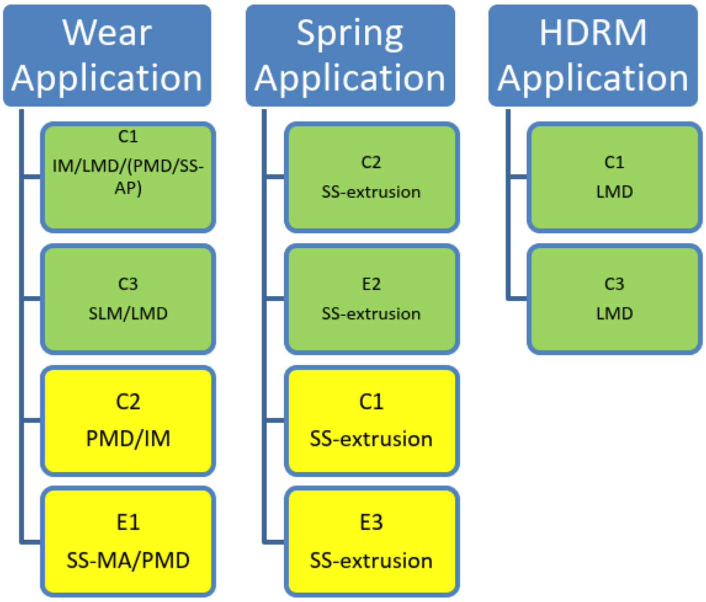


Figure 1 Summary of material selection for the 3 different applications.

Table 1 Summary of selected materials.

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

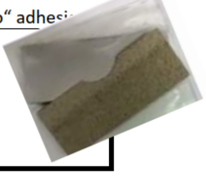
Selected manufacturing techniques were covered within the consortium and linked to the application. Following manufacturing routes have been investigated:

- **Solid state processing**
    - Rapid densification using rapid sinter pressing (RSP) and inductive hot pressing (IHP)
- **Liquid state processing**
    - Injection moulding/casting
- **Additive manufacturing**
    - Plasma metal deposition (PMD)
    - Selective laser melting (SLM)
    - Laser melting deposition (LMD)

WP2 was focused on elaboration of documentation linked to the definition of key requirements for identified application, manufacturing approach and test and characterization plan. Within WP3, a rather complex manufacturing of samples followed by characterization and testing was done. Based on the outcomes of manufacturing and testing, only the most promising material candidates and manufacturing routes were selected for further study and development. Samples were characterized with respect to visual inspection, density measurement and phase analysis. Selected samples were further characterized – mechanical properties, microstructure and corrosion resistance were investigated. WP4 was focused on manufacturing of selected metallic glass candidate materials and characterization linked to identified application – prepared samples were tested with respect to spring application, friction and cold-welding properties. Detailed overview can be seen in following table.

Table 2 Applications seen feasible with processes/candidates:

Application **→ *component***	**Currently made of**	**Typical dimensions (examples)**	**Typical cross section (contact surface)**	**Comment / example image**	**Candidate material (TBC)**	**Process**
Ball bearing **→ *races of inner rings***	AISI440C	• "Small": OD=12 ID=8 H=5 [mm] • "Med":OD=40 ID=30 H=11 [mm] • "Thin":OD=40 ID=38 H=8 [mm]	LxB ≈ 2 x 5 [mm] ≈ 5 x 12 [mm] ≈ 2 x 8 [mm] Inner ring		C1	RSP
HD-Gear-CS **→ *circular spline (ring)***	SS15-5PH	• "Med": OD=60 ID=50 H=10 [mm] • "Small": OD=30 ID=20 H=4 [mm]	LxB ~ 10*8mm, d~1mm LxB ~ 5*4mm, d~0,5mm Inner surface = toothing, D= Depth for toothing		C1	RSP (for small) IHP
HD-Gear-FS **→ *flex spline "cup"***	SS15-5PH	• "Med": OD=50 ID=48 H=30 [mm], • "Small": OD=20 ID=19 H=20 [mm]	cup with wall thickness ≈ 1 mm		C2	LS
Wave Spring	SS304, etc	On bearing shafts: e.g. "Med": OD=25, I=~20mm, H~1[mm]	"wavy ring": single		C1 C1,C2	LMD (>100µm) PMD (10-100µ) Injection (TBD) (depositon on model with „no" adhesi
HDRM **→ *separable contact surface***	Several: • SS 3xx • Ti6Al4V • Al-Alloys	• Ring/Cone:OD=50 ID=40 H=5 [mm] • Sphere: OD=30 [mm] • V-Nut / Cone:30 x 5 / DM=8 [mm]	OD x width ≈ OD x 3-5 [mm] ≈ few cm²		C1 C1,C2	LMD PMD



GREEN: Proposed Materials/Technologies selected from trade-off and proposed for WP 4
YELLOW: Backup Materials/Technologies selected from trade-off and proposed for WP 4

- **Solid state processing**

Solid state processing was focused mainly on commercially available AMZ4 and VITRELOY 105. In addition, experimental NiTiCuSn based material was investigated. For experimental grade, mechanical alloying was used to prepare appropriate amorphous starting powder.

Many optimization cycles were done for each investigated material to prepare dense and amorphous samples. Typically, the prepared samples were very porous or crystalline. Several processing parameters must be properly considered, such as Targeted temperature, heating and cooling rate, applied pressure, pressure ramp and even pre-compaction of green bodies. Finally, proper set of processing conditions was defined for investigated materials. C1 manufactured by rapid densification was also selected as a promising material candidate for preparation of samples for wear application such as ball bearings and gears. Fully dense AMZ4 test vehicles (see) with minimum porosity were prepared by both techniques and provided for further characterization. AMZ4 samples exhibited very good corrosion resistance and fair mechanical properties.

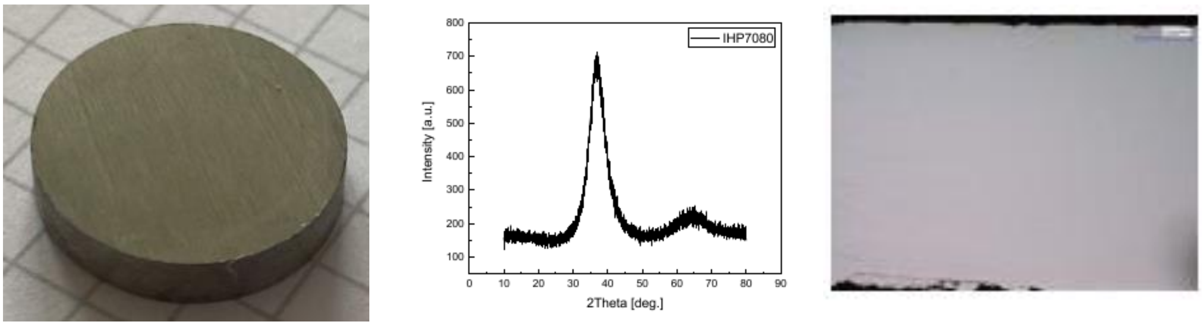

Sample XRD Microstructure

Figure 2 AMZ4 sample prepared by IHP.

- **Liquid state processing**

Liquid state processing was initially investigated for AMZ4 and VIT105 materials. Fully crystalline commercially available ingots were used for experiments. During processing It was observed that this is a very sensible process influenced by many parameters such as starting temperature of copper mould, quantity of casted material, sample geometry, temperature, dwell time at targeted temperature, heating and cooling rates, tightness of tooling.

Fully amorphous near net shape cups were successfully prepared by IM/casting from VIT105 – see Figure 3

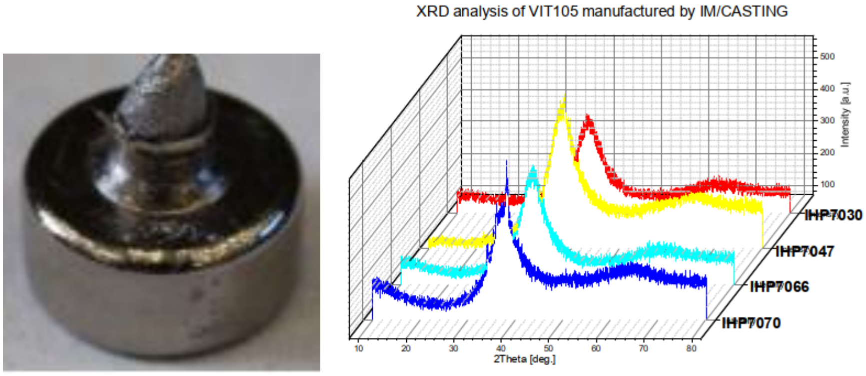


Figure 3 VIT105 (C2) prepared by IM/Casting. XRD analysis confirmed fully amorphous structue of tested samples.

Casted VIT105 showed excellent corrosion resistance and very low wear. In addition, few springs for testing were machined out of the cups.

- **Additive manufacturing**

Plasma metal deposition:

C1, C2 and E1 material (mechanically alloyed as well as elemental mixture) were considered for PMD processing as backup solution for wear (C2 and C3) and HDRM (E1) application. Three different variations of process were investigated:

- “standard” PMD process
- PMD process with optimized feeding system
- Low energy pmd process

The main outcomes can be summarized as follows:

- Poor flowability of commercial AMZ4 (C1) and VIT105 (C2) powders – not possible to process by PMD
- Deposition of C3 (Fe based) by PMD feasible but semi crystalline structure prepared and poor corrosion resistance observed

- PMD with optimized feeding system enabled to process C1 and C2 but poor quality test seams with (semi) crystalline structure prepared
- Energy input of PMD too high for processing of metallic glass powders
- Low energy pmd resulted in preparation of fully amorphous coatings but optimization required to improve the microstructure and strength; this approach allowed to prepare fully amorphous springs for testing (Figure 4)

Figure 4 springs prepared by pmd via deposition of AMZ4 (left) and VIT105 (right) powders on alumina substrate.

Selective laser melting

Processing of Fe-based BMG powder (base material: C3 - FeCrMoBWCMnSi) using SLM was tested.

The obtained sample properties were comparable to those yielded with similar Fe-based BMG alloys reported in literature. Based on the results, it is supposed that the processability of the powder might be improved slightly by further parameter optimization. However, the results also suggest that complex amorphous BMG items cannot be manufactured out of material C3 using SLM. Prospectively, varying the manufacturing parameters alone cannot compensate for the material being too brittle and prone to cracking. It is therefore supposed that in order to reduce brittleness and render the material fit for SLM, the alloy composition of C3 needs to be optimized.

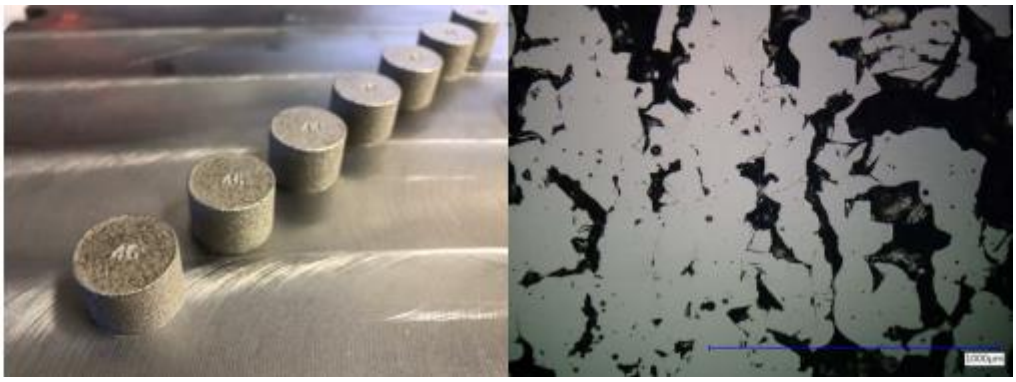


Figure 5 Intact amorphous cylindric samples manufactured in SLM test campaign (left) and microsection of one of the samples revealing internal porosity and micro-cracking (right).

Laser melting deposition

The LMD processing ofAMZ4 and VIT105 materials was performed in 4 optimization loops. Various deposition parameters, substrates and deposition strategies were investigated. It was found that the technique is not appropriate for preparation of bulk materials. LMD of AMZ4 was selected as a promising candidate for spring and HDRM application.

For spring application, AMZ4 material was deposited on Ti64 rods. XRD analysis confirmed fully amorphous structure. However, it was seen that the material is very brittle. This activity was stopped since the machined springs were typically broken. As an optimization, near net shape springs were deposited. XRD analysis performed on grinded surface of spring showed crystalline structure. Therefore, these springs were not further machined for testing.

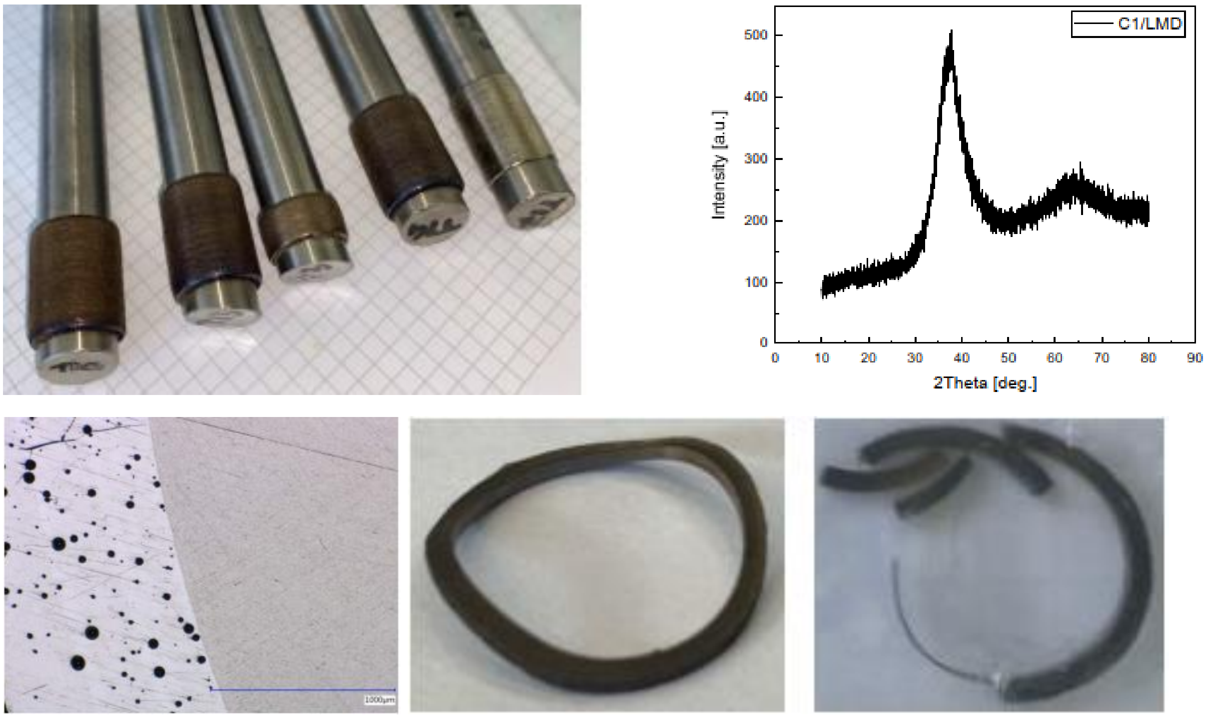


Figure 6 LMD of C1 for spring application.

Figure 7 shows the AMZ4 samples prepared by LMD process for HDRM application. It demonstrates as received samples and machined set of pin and disc XRD analysis showed for all samples semicrystalline structure typical for LMD processing of metallic glasses.

Figure 7 LMD deposited sample and machined set of pin and disc.

CONCLUSIONS

Springs

Two batches of wave springs were tested. The first being very thin offered very low stiffness, but even there repeated loading/unloading (10 times) did not lead to fracture. A second batch of thicker wave springs (1,5mm) showed proper behaviour, being in its behaviour comparable to standard steel wave springs. Stiffness in range from 120 to 180 N/mm related to thickness from 1,5 to 2,1mm were calculated. Cyclic loading was performed without fracture for 10 times, assuming that a mechanism needs to be revised a few times during ground testing.

Outlook on new perspectives of springs made of BMG (outperforming the drawback for manufacturing): right now an advantage might be seen in the low tendency to cold welding. Springs must not stick to their housings (via the contact surfaces) as this would equalise the preloads. In addition to the wave springs, this might be even more of interest in clock springs: they are often made from austenitic steels, which is again a material showing strong adhesion forces to itself. This increases the risk that the blades of the clock spring weld together (when they hit together during launch) thereby getting fixed and not anymore applying tension to the mechanism. Some reports were received, that the location of this welding between the blades is outside of applying coatings (e.g. out of sight for PVD like MoS_2). Hence, here the material itself needs to offer low tendency to cold welding.

Friction (Gears)

Concluding results in friction and wear, it can be said that BMG-to-BMG offers promising options compared to current combinations based on PH-steels. Especially, C2 (VIT105) which was manufactured by a casting process would therefore be a candidate for the flex spline in a Harmonic Drive® gear. As opposite part, the circular spline C1 (AMZ4, a ring with cross section of e.g. 5*4mm) could be manufactured by IHP. Discs used for testing herein, had thickness of 6mm and were proven to be fully amorphous.

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.

Cold welding (HDRM)

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***.

Secondly, some applications cannot easily be coated like e.g. clock springs, or also braids for electric shielding: both components are made often of austenitic stainless steels, which are linked to high tendency to cold welding. In ***a clock spring***, the loops may hit together under launch which may cause cold welding and thereby loss of is tension.

On the other hands, ***cables ("harness")*** undergo bending and need to stay flexible. They are often electrically shielded by ***braids,*** i.e. a fabric of strands of stainless steel. During launch vibration may cause the single strands to rub against each other, which may cause them to cold welding. This leads the harness to become rigid and either to hinder further motion (motor not strong enough) or to break during a subsequent bending motion (motor sufficiently strong). Both malfunctions endanger a mission. As the contact points in such braids cannot be coated (not accessible to a coating processes) the material itself should be not prone to cold welding. BMG would offer here less risk for failure than austenitic steel.