BULK METALLIC GLASS

A force of our time.

Overview

RSALLOYS
HOLDING GROUP

Which materials can offer…

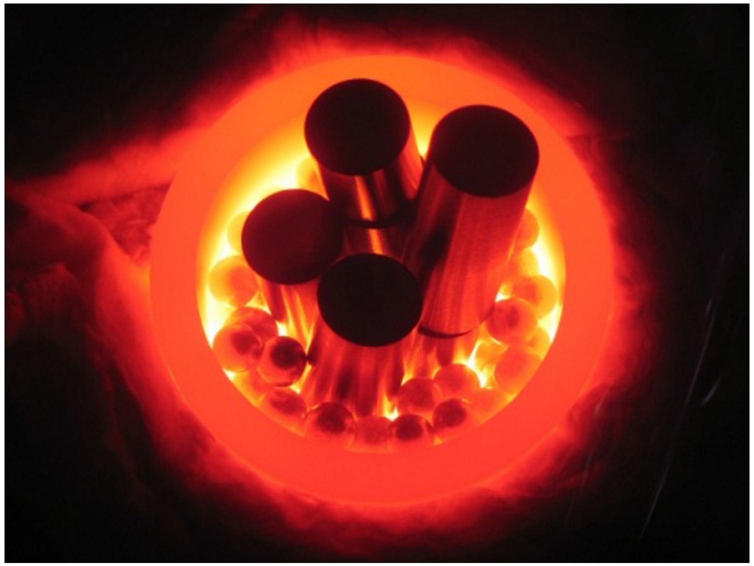
- The yield strength of high end steels
- The elasticity of plastics
- Corrosion resistance like precious metals
- The possibility to cast finished polished surfaces in one step

?

- **Bulk Metallic Glasses**

Overview

- Bulk Metallic Glass (Amorphous Metals)
- Alloy Properties
- Mechanical Properties
- Chemical behavior
- Applications
- Production
- Summary

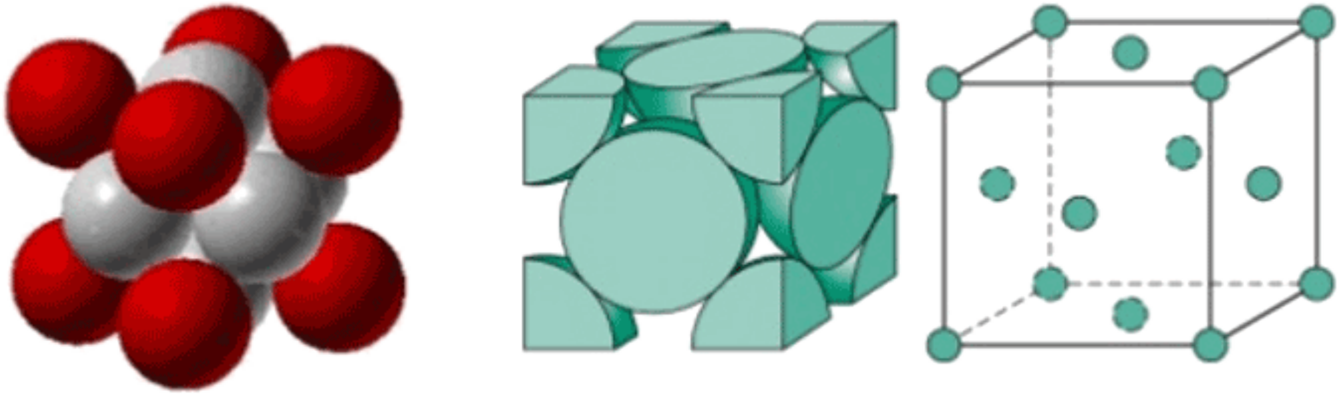


FACE CENTERED CUBIC STRUCTURE (FCC)

Atoms touch each other along face diagonals.
--Note: All atoms are identical; the face-centered atoms are shaded differently only for ease of viewing.

ex: Al, Cu, Au, Pb, Ni, Pt, Ag

- Coordination #= 12



4 atoms/unit cell: (6 face x 1/2) + (8 corners x 1/8)

Atomic Radii and Crystal Structures for 16 Metals

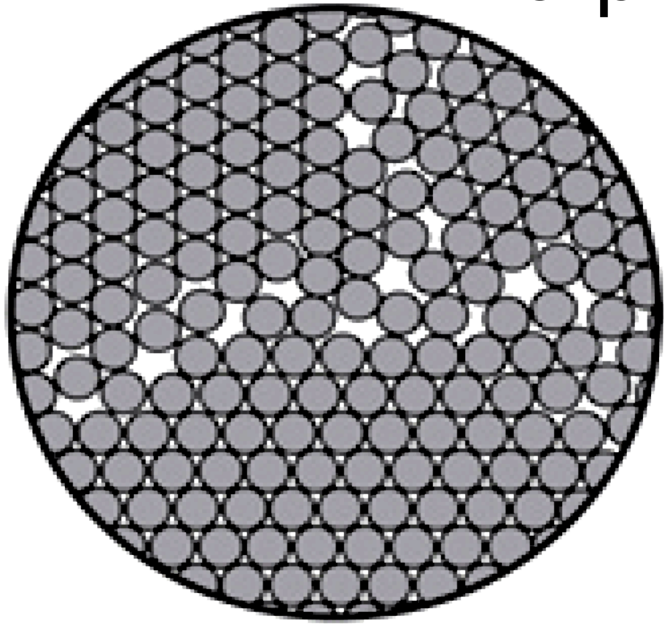
Metal	Crystal Structure [a]	Atomic Radius [b] (nm)	Metal	Crystal Structure [a]	Atomic Radius [b] (nm)
Aluminum	FCC	0.1431	**Molybdenum**	BCC	0.1363
Cadmium	HCP	0.1490	**Nickel**	FCC	0.1246
Chromium	BCC	0.1249	**Platinum**	FCC	0.1387
Cobalt	HCP	0.1253	**Silver**	FCC	0.1445
Copper	FCC	0.1278	**Tantalum**	BCC	0.1430
Gold	FCC	0.1442	**Titanium (α)**	HCP	0.1445
Iron (α)	BCC	0.1241	**Tungsten**	BCC	0.1371
Lead	FCC	0.1750	**Zinc**	HCP	0.1332

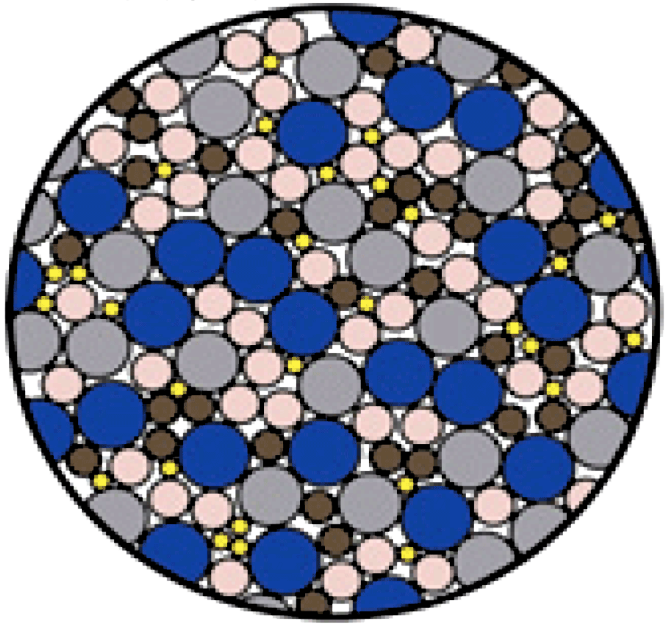
[a] *FCC = face-centered cubic; HCP = hexagonal close-paked; BCC = body-centered cubic*

[b] *A nanometer (nm) equals 10^{-9} m; to convert from nanometers to angstrom units (Å), multiply the nanometer value by 10*

Structure Matters

Amorphous Metals





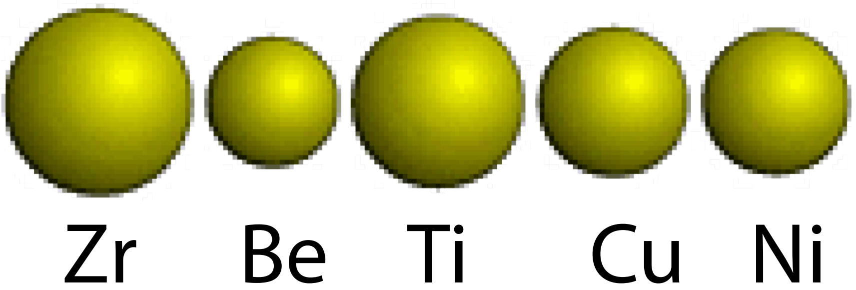
Most Metals

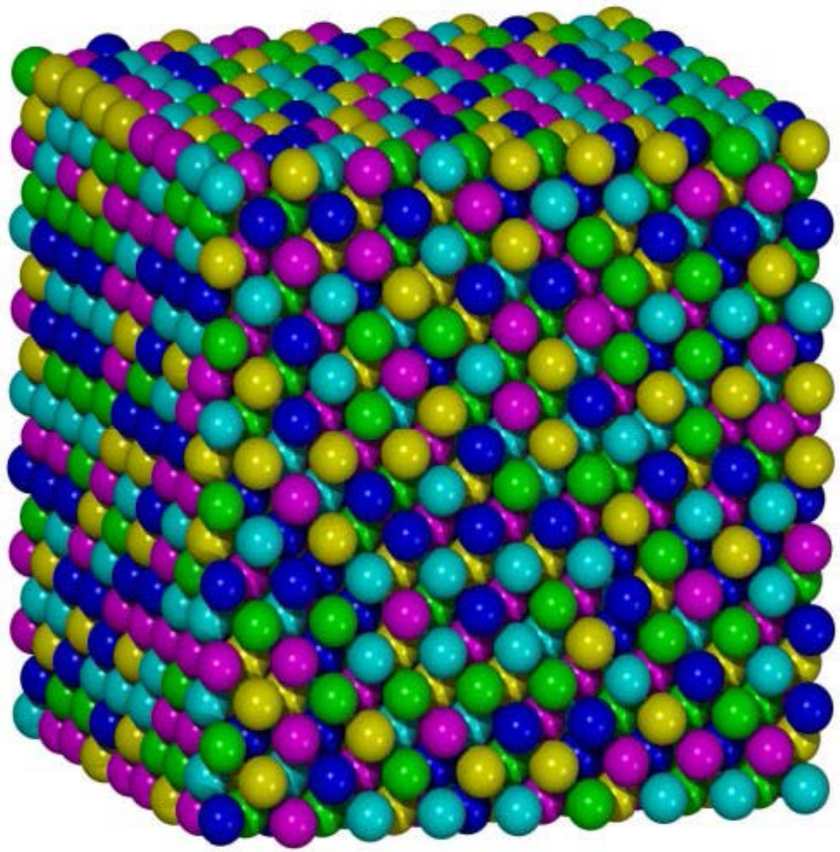
- Polycrystalline grains of varying shapes and sizes.
- Misaligned planes of atoms slip past each other easily, absorbing energy and allowing dislocations to move, making deformation permanent.
- Grain boundaries represent weak spots

Metallic Glass

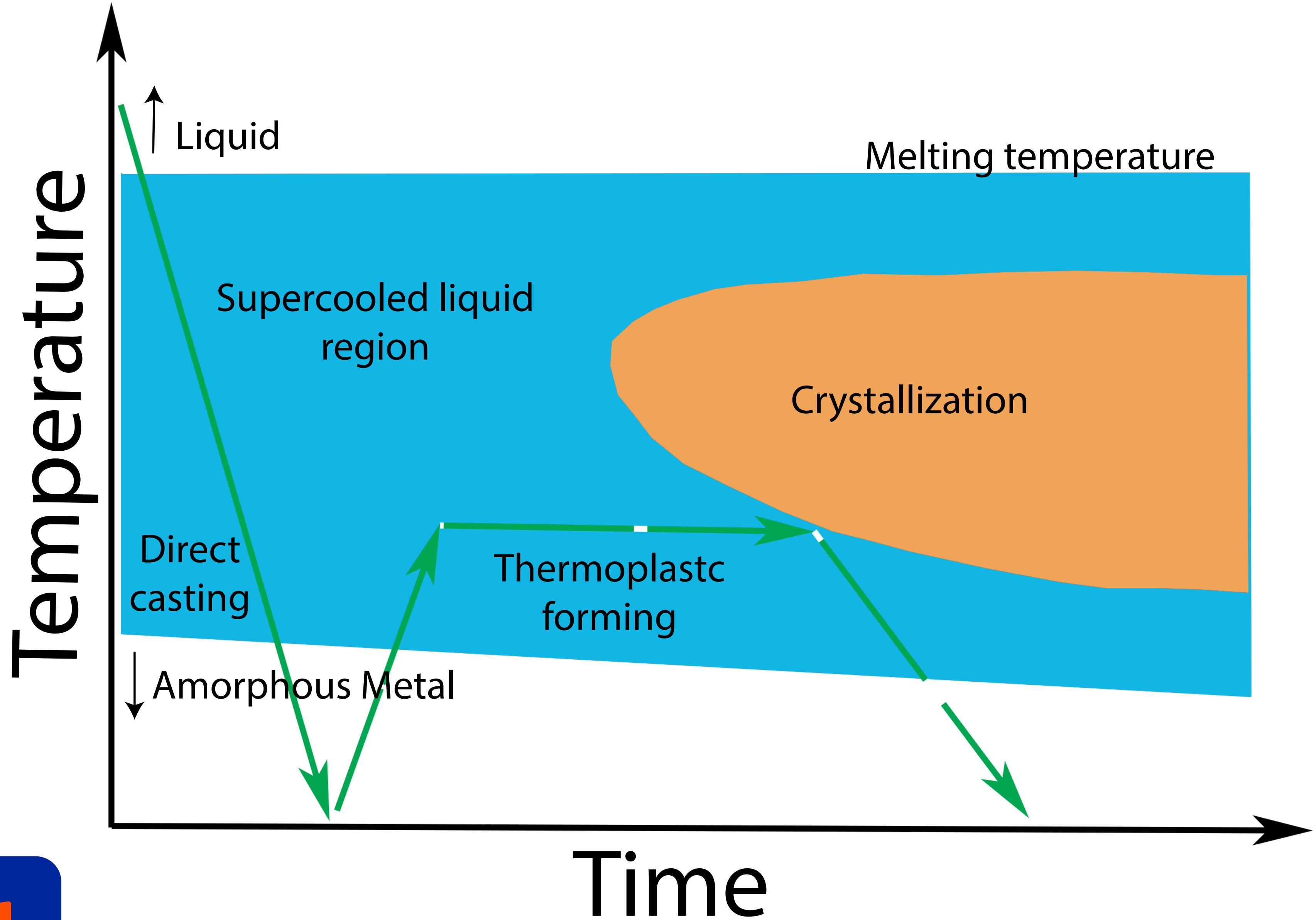
- Cooled faster than atoms can rearrange into a crystal
- Dislocation movement obstructed so absorbs less energy and rebounds elastically to its initial shape
- Resistant to corrosion and wear
- Slow heat conduction limits casting

Vit1B Structure





BMG Time Vs. Temperature



Bulk Metallic Glass

Vit1b:

- $Zr_{67}Cu_{10.6}Ni_{9.8}Ti_{8.8}Be_{3.8}$
- large temp. window

Vit601:

- $Zr_{62.5}Cu_{31}Ni_{3.2}Al_{3.3}Be_{0.1}$

Vit105:

- $Zr^*_{65.7}Cu_{15.6}Ni_{11.8}Al_{3.7}Ti_{3.3}$
-

Vit106a:

- $Zr^*_{70.1}Cu_{13}Ni_{9.9}Al_{3.6}Nb_{3.4}$

Additional alloys:

GMT: $Ni_{76}Cr_{8.5}Nb_{5.2}P_{9.4}B_{0.6}Si_{0.3}$
Pt850: $Pt_{85.24}Cu_{7.1}Ni_{2.36}P_{5.3}$
JPL: $Ti_{43}Zr_{41}Cu_{7}Al_{3}Be_{6}$

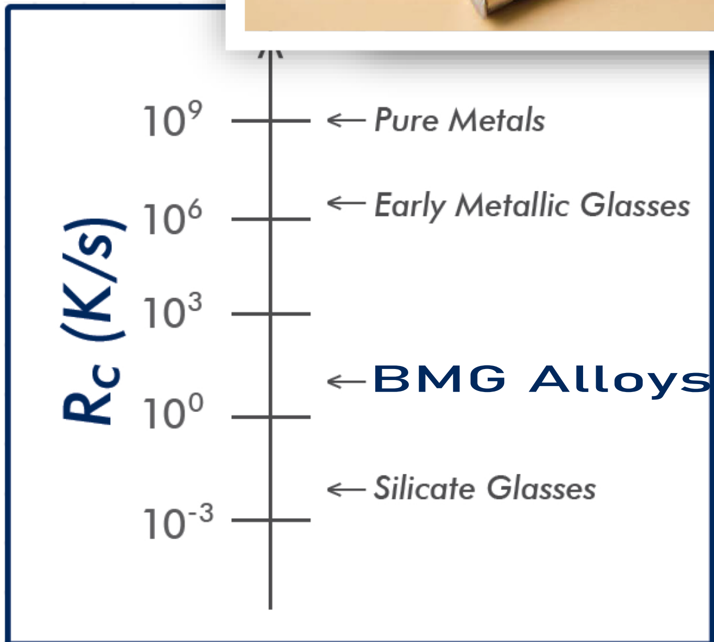
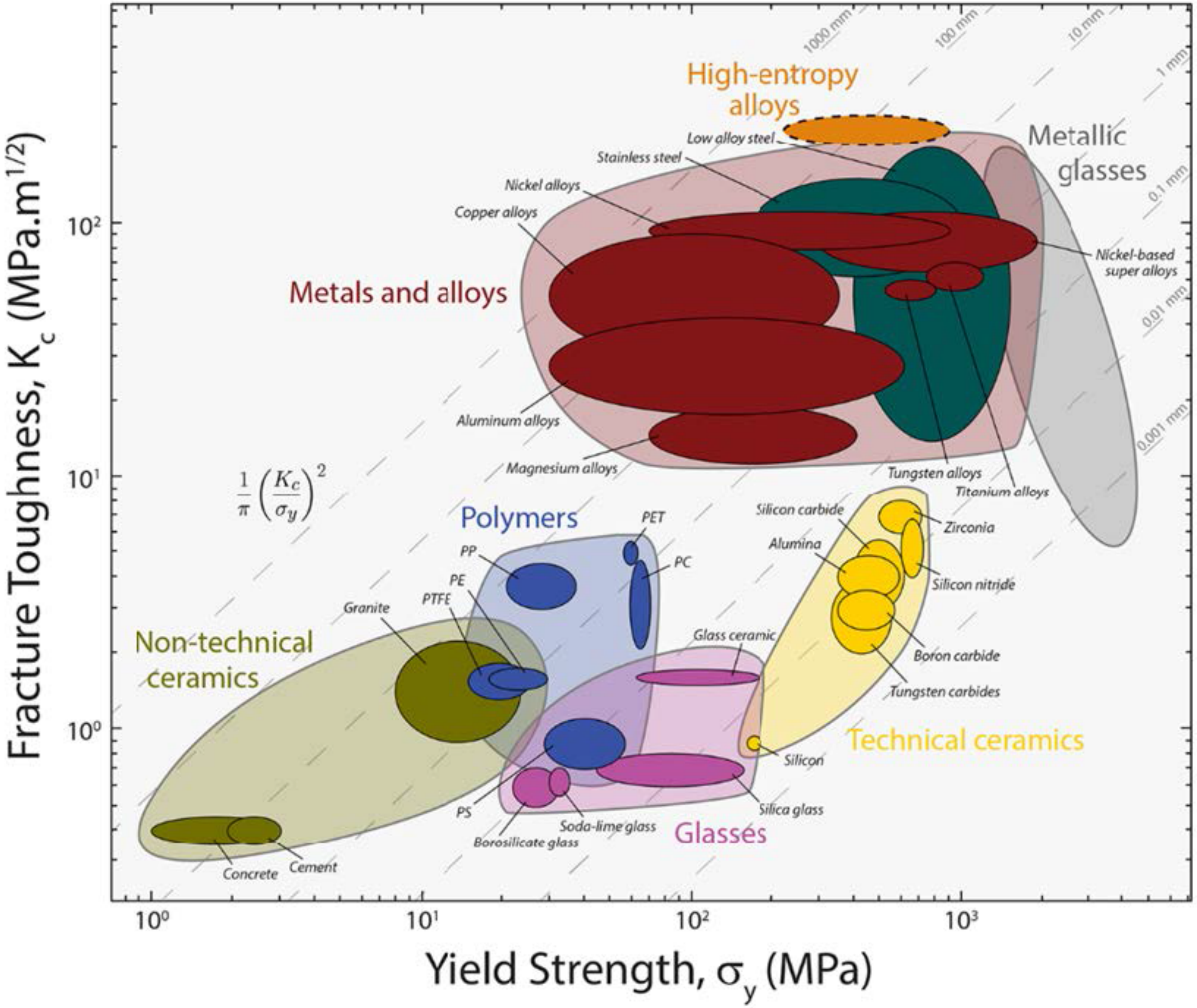


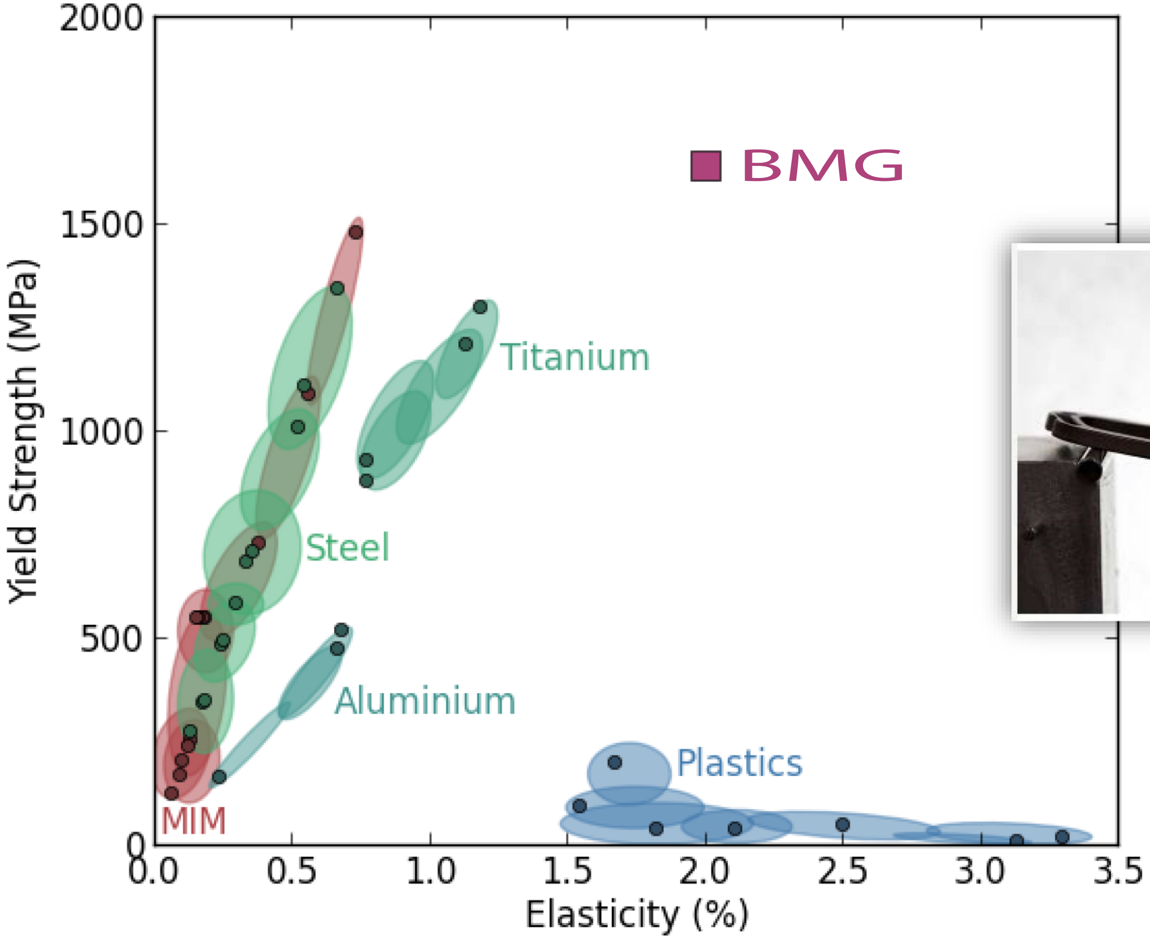
Figure 1. Cooling rates required to achieve an amorphous microstructure in various materials.

BMG Product Placement



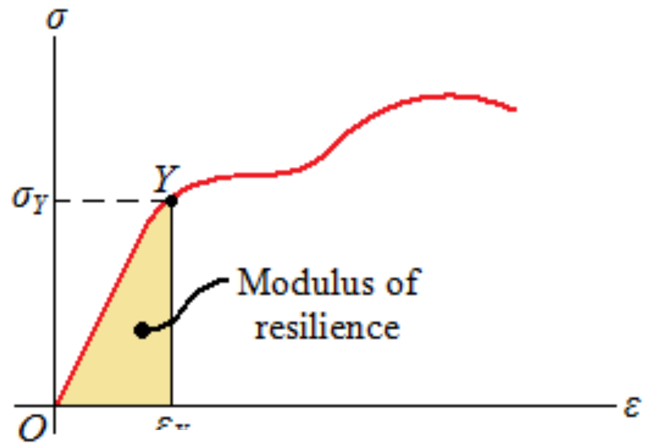
Extraordinary elasticity for metals

$$\text{Elasticity} = \frac{Re}{EMod}$$



Resilience

Energy that can be absorbed per volume before plastic deformation.

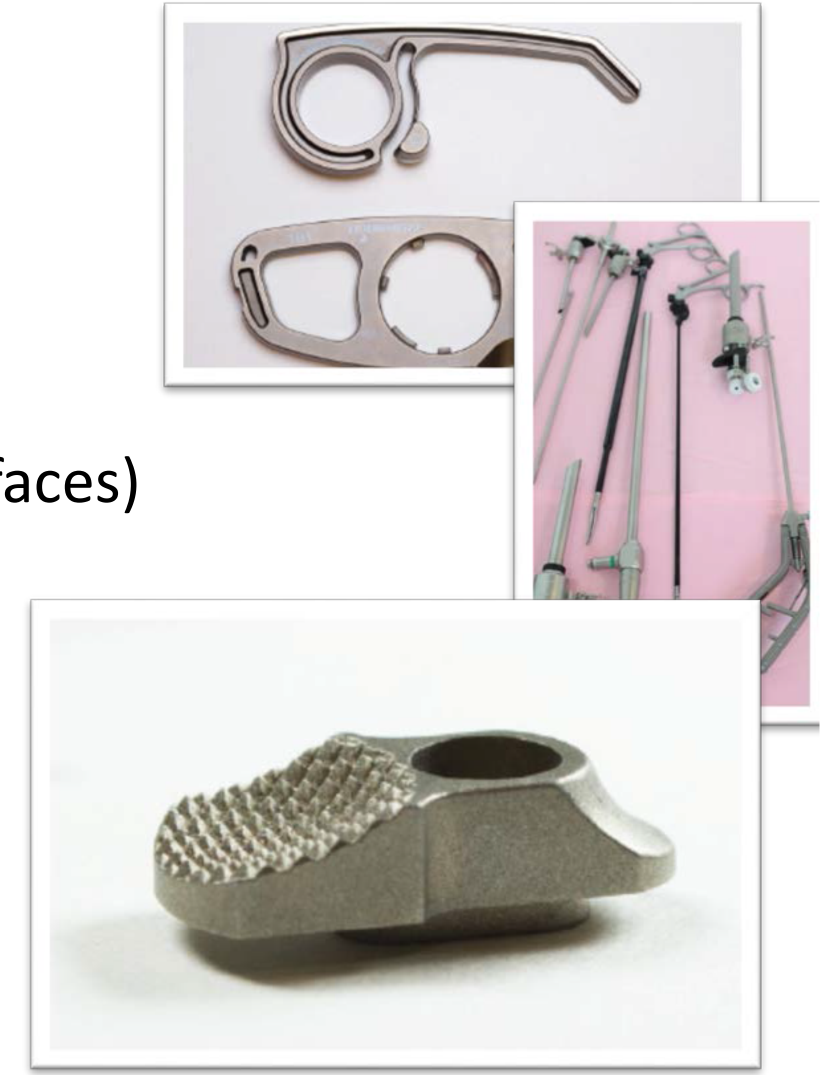


$$U_r = \tfrac{1}{2}\sigma_y\varepsilon_y = \frac{\sigma_y^2}{2E}$$

Alloy	YA MPa	E-Modul GPa	U_{RV}=1/2(Y_S^2/E) MPa
Vit105	1524	93	12.5
Federstahl 1.7176	1250	210	3.7
Ti-6Al-4V	880	128	3.0
7075 Aluminium	503	73	1.7

Characteristic properties of Bulk Metallic Glasses

- Complex shaping “in one step”
- Elasticity/spring properties
- High Strength(~ 1500 MPa)
- Tight tolerances (like CNC)
- High reflectivity (polishes surfaces)
- High Hardness (53 HRC)
- Corrosion resistance
- Bio compatibility
- CNC machining possible



Mechanical properties of Vit105

Yield Strength Re ~ Rm	1524 MPa
Young´s Modulus	93 GPa
Elasticity	~ 1,80 %
Hardness	53 HRC
Fatigue limit at 10^7 cycles	304 MPa
Fracture Toughness K1C	~ 40 Mpa m^1/2
Poisson´s	0,38

Physical properties of Vit105

Density	**6.57 g/cm³**
Heat capacity	329 J/kg K
Heat Volume	2161 kJ/m³K
Thermal Expansion	12 µm/mK
Electric Resistance	160 µOhm cm
Glas Transition Temperature	399°C
Crystalisation Temperature	468°C
Operating Temperature	≤250°C
non magnetic	µd = 0,999991

Zr BMG Properties

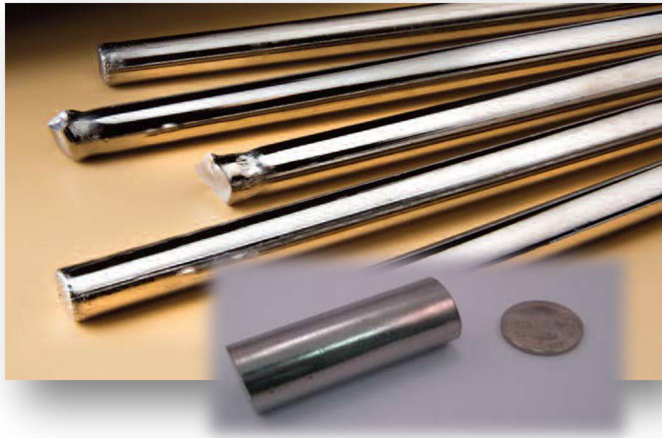
Alloys	Vit 1b	Vit 601	Vit 105	Vit 106a
Yield Strength MPa (ksi)	1800 (261)	1795 (260)	1850 (268)	1800 (261)
Elastic Modulus GPa (10^6 psi)	95 (13.8)	91 (13.3)		95 (13.8)
Fracture Toughness MPa√m (ksi√in)	55 (50.0)	70 (63.7)	75 (68.3)	30 (27.3)
Density g/cc (lbs./in^3)	6.0 (0.217)	6.9 (0.249)	6.6 (0.238)	6.7 (.242)
Glass Transition (Tg) C (F)	352 (665)	420 (788)	403 (757)	395 (743)
Crystallization (Tx) C (F)	466 (871)	495 (923)	469 (876)	499 (930)
Melt Temp (Tm) C (F)	644 (1191)	753 (1387)	805 (1481)	837 (1539)

Storyline of BMG

- Since the 90´s Materion is supplier for Liquidmetal®
- 2010: Liquidmetal® contacts Materion to supply the finished alloys
- 2015: Engel introduces metal injections molding machine "-e-motion 100"
- 2018: Eutectix replace Materion in producing and promoting BMG
- 2019: Engel introduces new metal injections molding machine "Victory 120"
- 2019: RS Acciai become official reseller in european market about BMG
- 2020: Eutectix agreement with Liquidmetal®

Bulk Metallic Glass Supply Chain

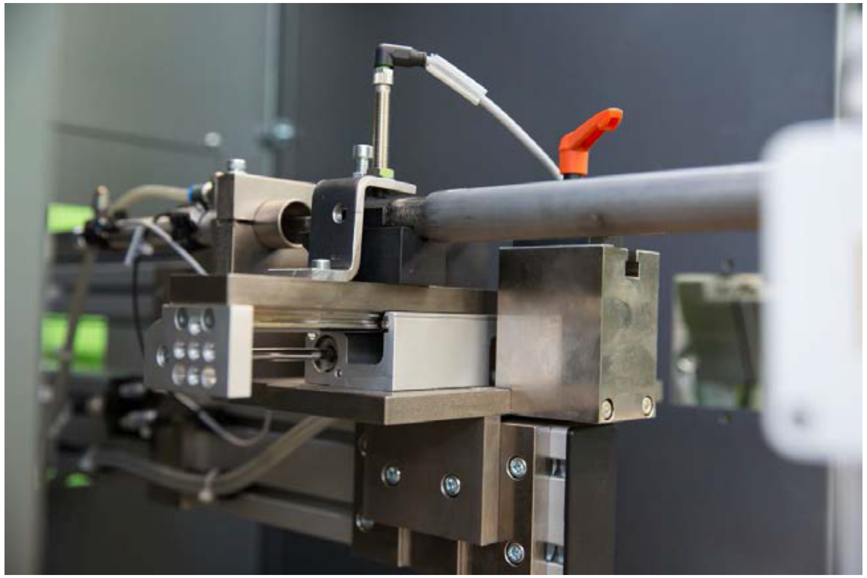
Materion VIM unit (Elmore, OH) - Materion

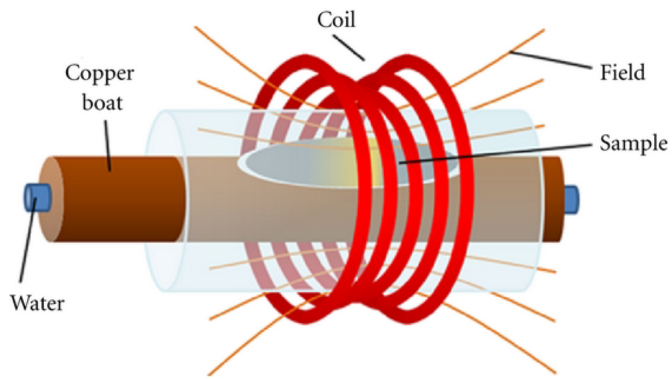


BMG Alloy Feedstock – Materion/Engel

Vacuum Injection Molding - Producer

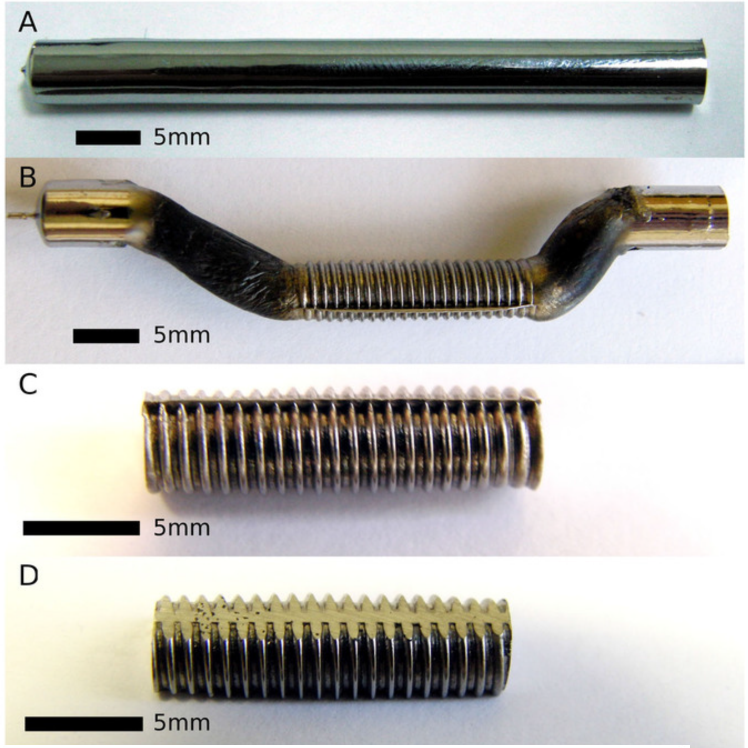
BMG Injection Molding Machine

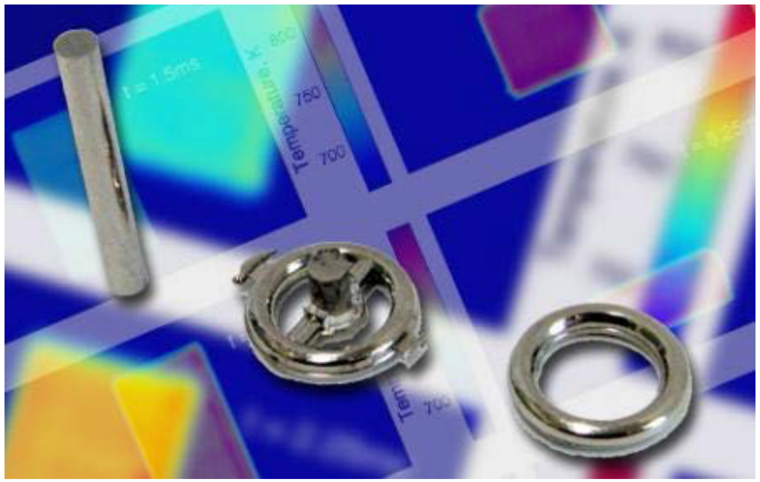


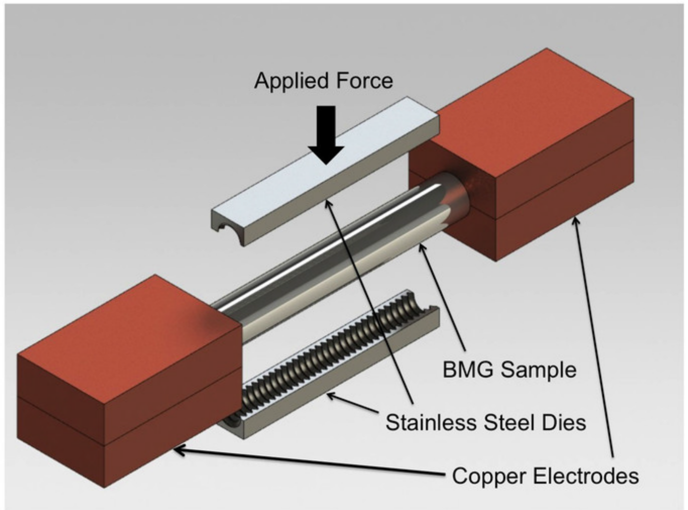


Rapid Discharge Forming Process

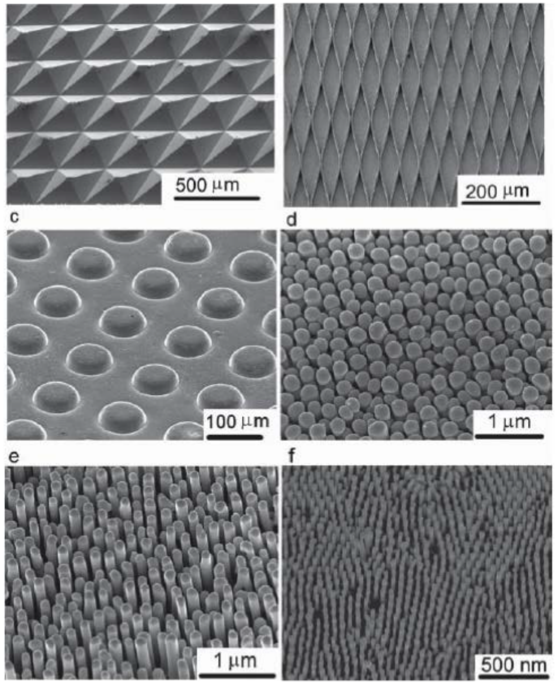
- Input Material
  - 5mm Dia. Rods
  - 8mm Dia. Rods
  - Length determined by part to mfg
- High Product Yield
- Recycle of alloy?
  Yes, material can be cleaned and recycled?





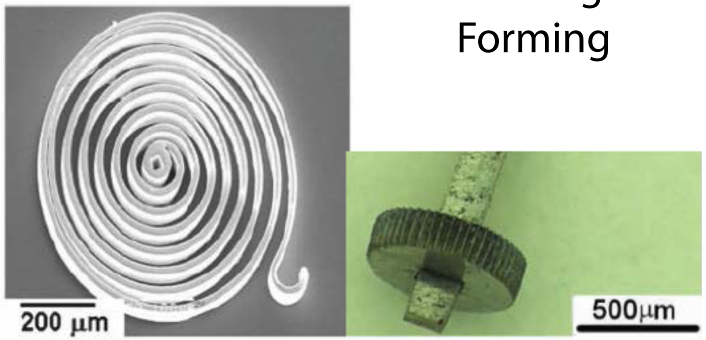


Bulk Metallic Glass – What else is special?



Small scale extrusions

Rapid Discharge Forming



Springs and Gears

Ease of processing

- Thermoplastic forming
- Rapid discharge forming
- Injection molding
- Die casting

Blow Molding

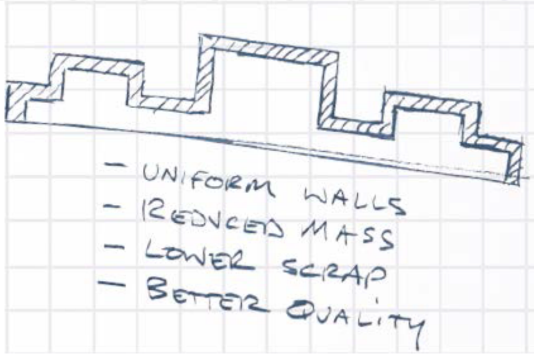
Golden et al., Adv Mater, 23, 461 (2011)

Injection Molding Guidelines

DESIGN CHARACTERISTICS

Here are a few basic guidelines for identifying candidate Liquidmetal parts:

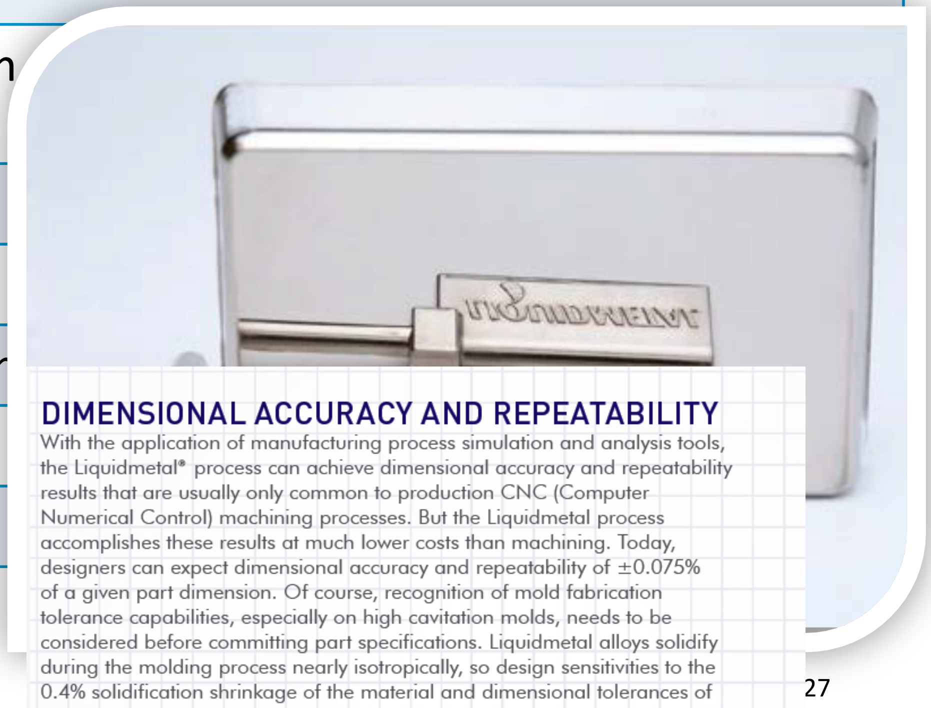
- Part weight up to 80 grams (100 grams maximum total shot size of which 80 grams is usable)
- Maximum dimension of 100mm
- Outer draft angles of 0.5° to 3°
- Inner draft angles of 1° to 5°
- Wall thickness 0.6mm to 4.0mm
- Dimensional tolerances of ±.025 mm for critical dimensions
- Production volumes from tens of thousands to millions of parts



Injection Molding Production Tolerance

	BMG	CNC	MIM
Tolerance	± 8 µm	±8 µm	± 75 – 125 µm

Form		Toleranzen
Function given part, linear shape		±0.02 per 25.4 mm
Standard tolerance, linear shape		±0.05 mm
Flatness	⏥	0.05 mm
Straightness	—	0.05 mm
Angle	∠	0.001 mm
Concentricity	◎	0.05 mm
Roundness	○	0.05 mm


DIMENSIONAL ACCURACY AND REPEATABILITY

With the application of manufacturing process simulation and analysis tools, the Liquidmetal® process can achieve dimensional accuracy and repeatability results that are usually only common to production CNC (Computer Numerical Control) machining processes. But the Liquidmetal process accomplishes these results at much lower costs than machining. Today, designers can expect dimensional accuracy and repeatability of ±0.075% of a given part dimension. Of course, recognition of mold fabrication tolerance capabilities, especially on high cavitation molds, needs to be considered before committing part specifications. Liquidmetal alloys solidify during the molding process nearly isotropically, so design sensitivities to the 0.4% solidification shrinkage of the material and dimensional tolerances of

Chemical Properties of Vit 105

- Salt Spray Test according to ASTM B117 – no signs of corrosion
- Resistant to acids and bases
- High corrosion and wear resistance
- Passed various biocompatibility tests:
  Toxicity, Irritation, Sensitization, Systemic Toxicity,
  Hemocompatibility, Mutagenicity, Pyrogenictiy

BMG – Production History Overview

VIIC Furnace (VC9)

Scaled production:

- Scaled from batches of 10 and 30 kg
- Currently batches of ~85 kg
- Alloyed and cast under vacuum

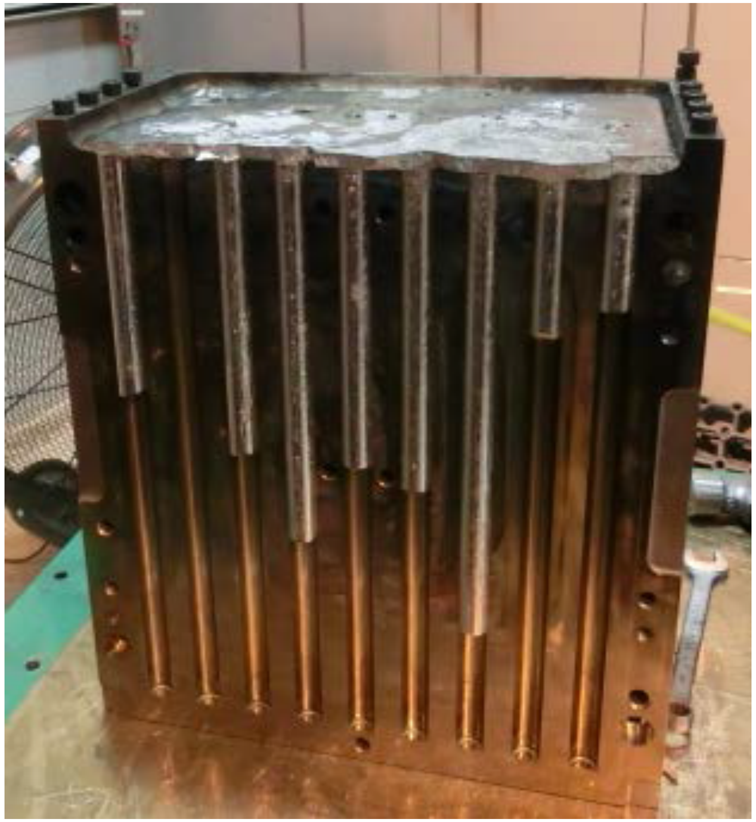
Casting mold (weight = 600kg)

Crucible charged for alloying

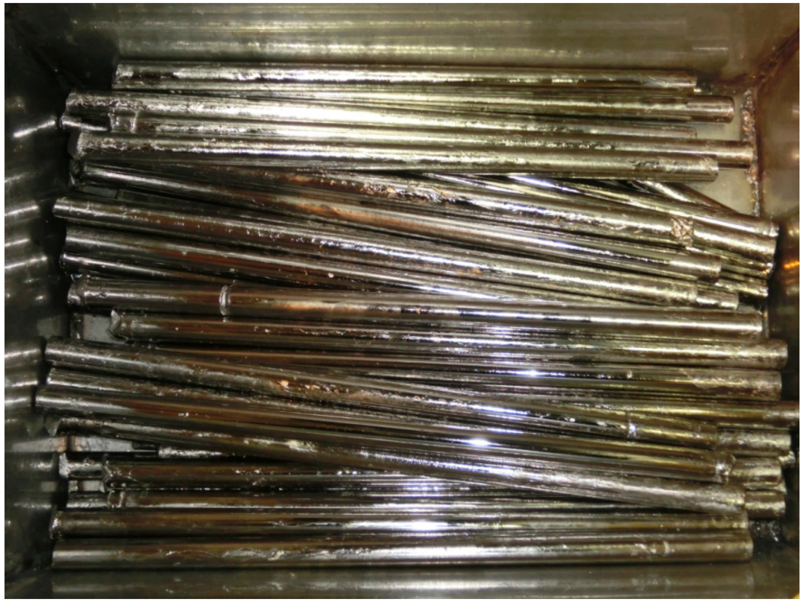
BMG – Production History Overview

Scaled production

- Each batch is cast into rods
- Rods are separated from the reusable casting material
- Finished rods are sold as complete rods or cut to length



Mold, alloyed rods partially removed



Complete rods removed from the mold

Bulk Metallic Glass Markets

Consumer Electronics (CE)

Industrial Components

Aerospace/Defense

Biomedical

Oil and Gas

Performance Automotive

Watches and Luxury Goods

Sporting Equipment

BMG Gears - NASA

BMG Gears

Bulk Metallic Glass (BMG) Gears

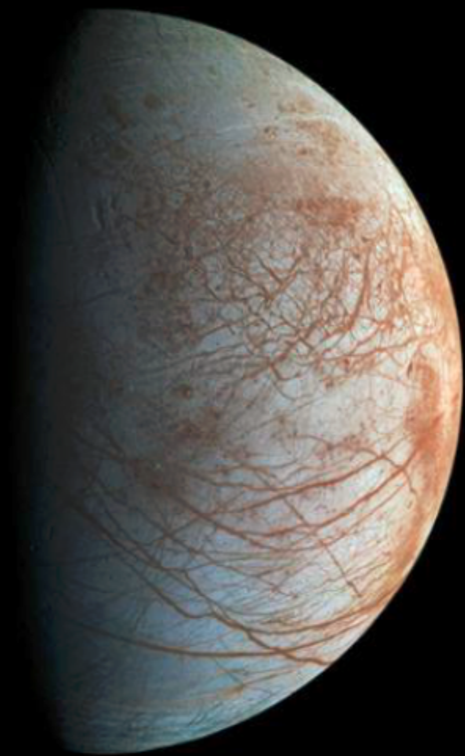
- BMG Gears is developing dry lubricated and non-lubricated planetary and strain wave gearboxes fabricated from new bulk metallic glass alloys for power constrained cryogenic environments.

- The technology enables mechanisms to function in cryogenic environments, such as on the surface of Europa, without having to use heaters thus allowing more science return for the available power.

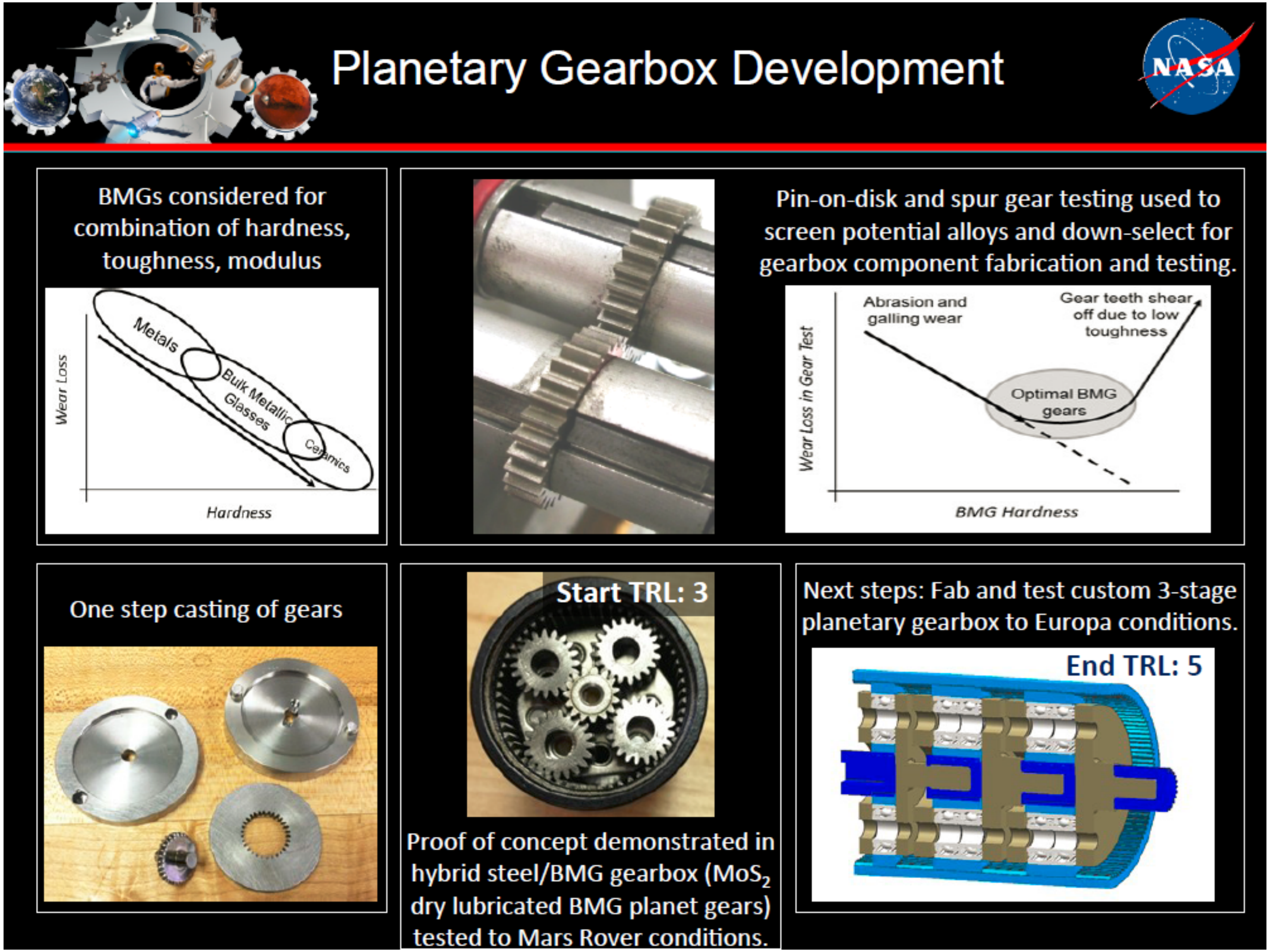
BMG Gears

BMG Gears - Motivation

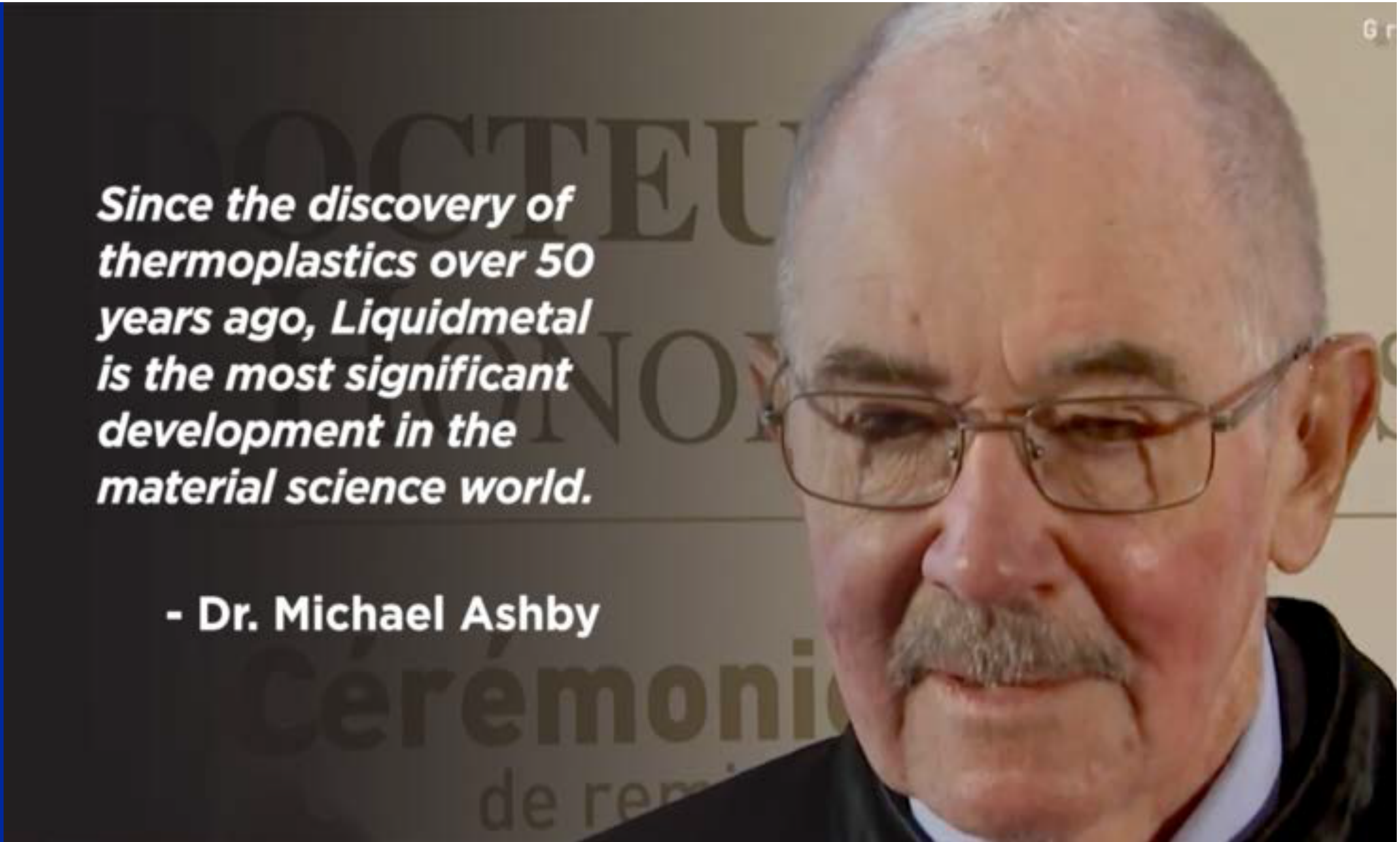
- Future NASA missions, such as landing on and investigating the surface of Europa where the temperature is below -170 °C, will be very power constrained.
- The use of power hungry heaters to allow mechanism like robotic sampling arms to function will reduce the mission lifetime and decrease the science return.
- Newly developed BMG alloys for planetary and strain wave gearboxes enable them to function with dry lubricants or even unlubricated, thereby requiring no electrical power for heaters to operate, reduced system complexity, and increased mission lifetime/science return.



BMG Gears



Planetary Gearbox Development
NASA
BMGs considered for combination of hardness, toughness, modulus
Wear Loss
Hardness
Metals
Bulk Metallic Glasses
Ceramics
Pin-on-disk and spur gear testing used to screen potential alloys and down-select for gearbox component fabrication and testing.
Abrasion and galling wear
Gear teeth shear off due to low toughness
Optimal BMG gears
Wear Loss in Gear Test
BMG Hardness
One step casting of gears
Start TRL: 3
Proof of concept demonstrated in hybrid steel/BMG gearbox (MoS_2 dry lubricated BMG planet gears) tested to Mars Rover conditions.
Next steps: Fab and test custom 3-stage planetary gearbox to Europa conditions.
End TRL: 5



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MADE TO PERFORM