**2018 Spring**

# "Advanced Physical Metallurgy"

# - Bulk Metallic Glasses -

**06.20.2018**

**Eun Soo Park**

**Office: 33-313**
**Telephone: 880-7221**
**Email: espark@snu.ac.kr**
**Office hours: by appointment**

# Are amorphous metals useful?

## 10

*Applications*

## 10.2 Special Characteristics of BMGs

# 1) Bulk formation: cast into large section thickness

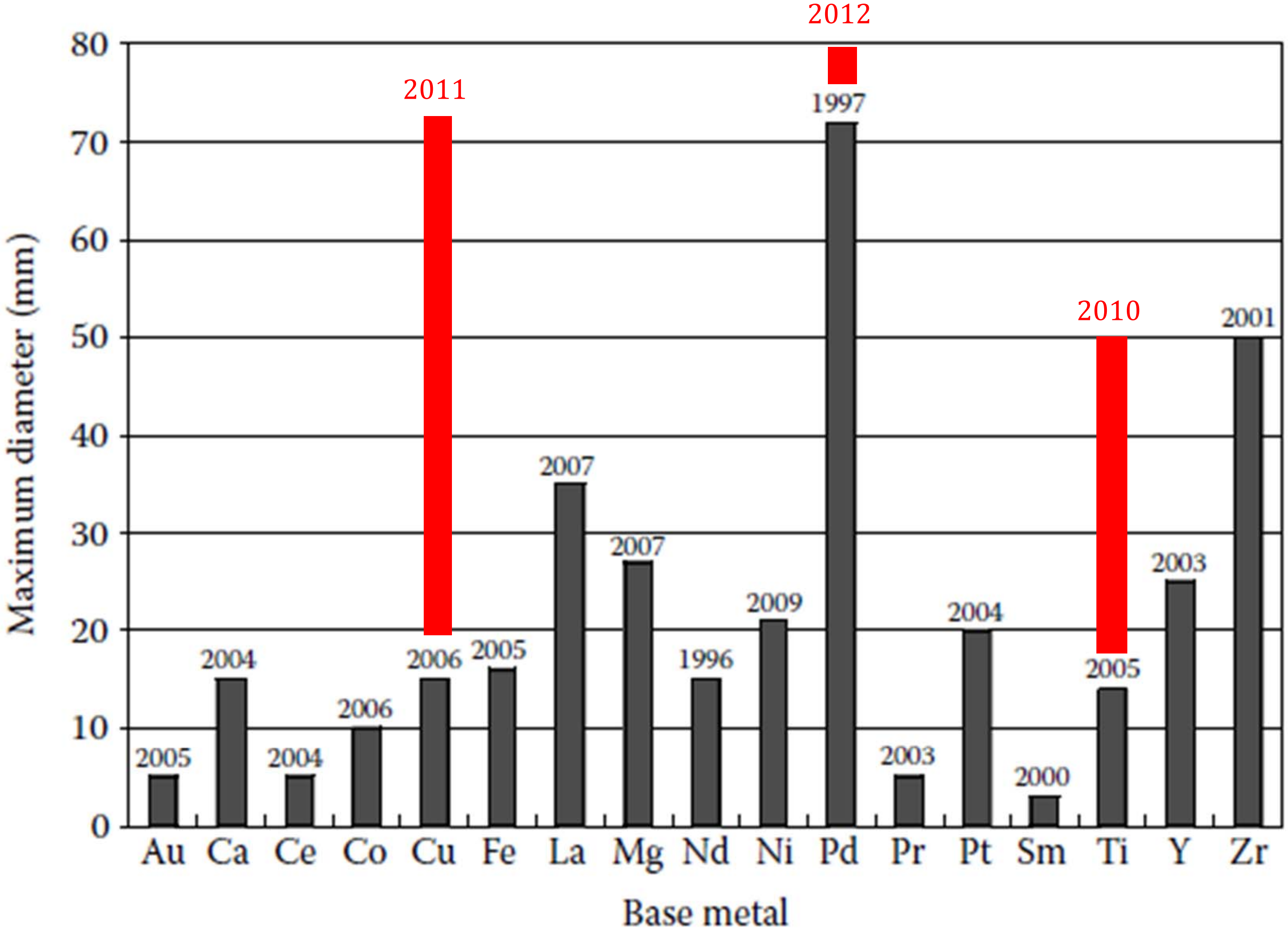
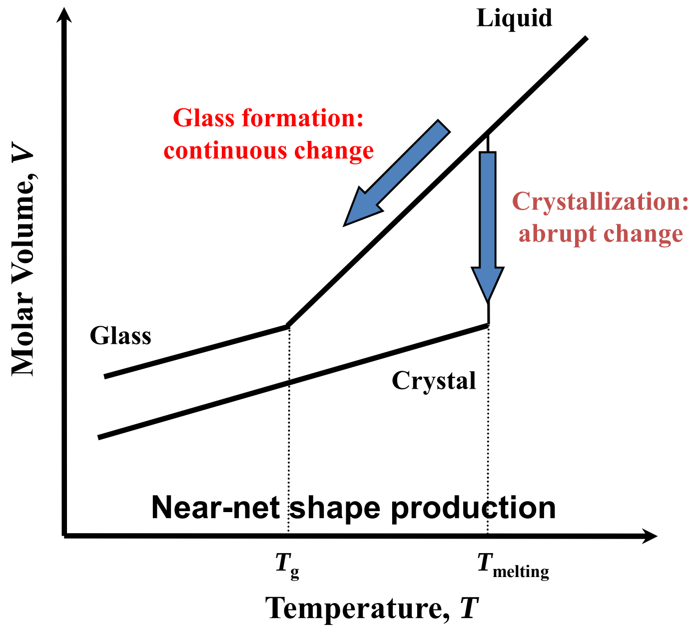


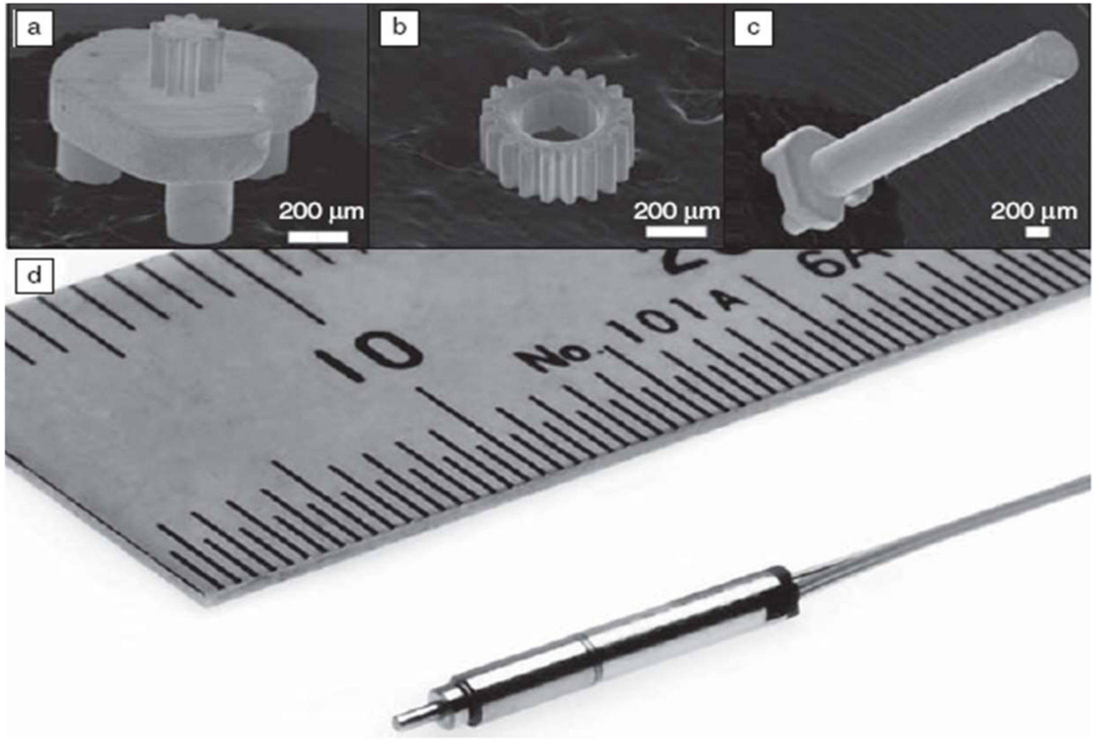

**FIGURE 2.7**
Maximum diameters of the BMG rods achieved in different alloy systems and the years in which they were discovered.

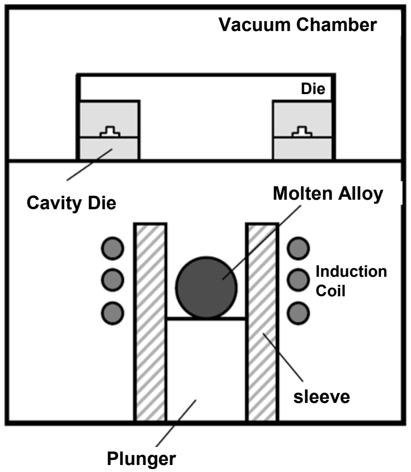
# 10.2 Special Characteristics of BMGs

## 2) Processing metals as efficiently as plastics

### a) Micro-casting : ΔV ~ 0

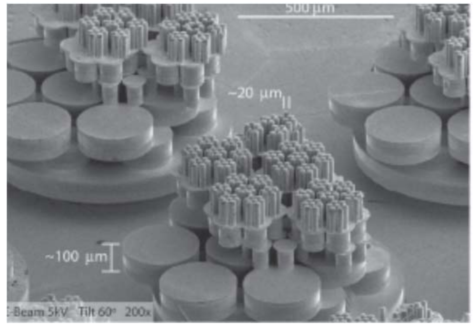



**Precision die casting**

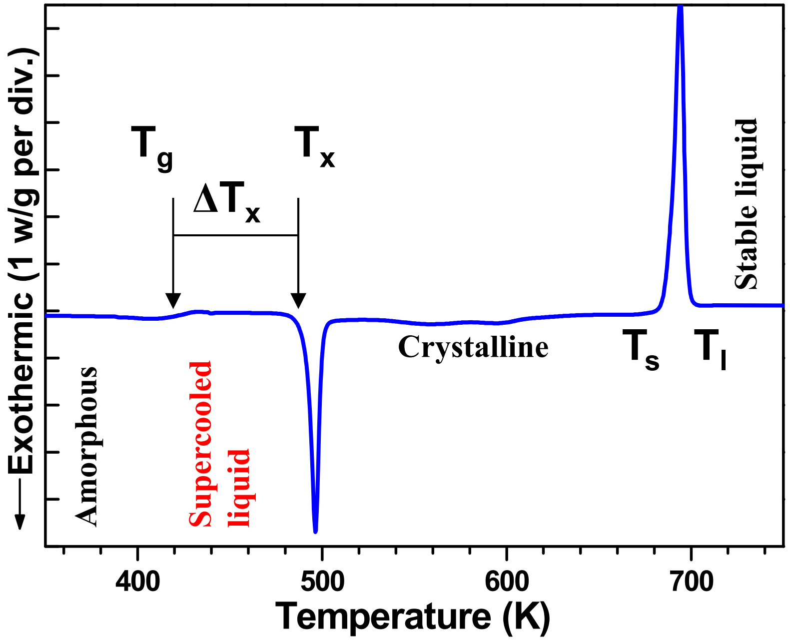
**Precision Gears for Micro-motors**



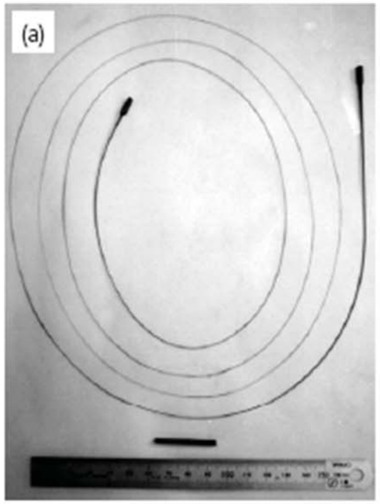

*MRS BULLETIN* ***32*** *(2007)654.*

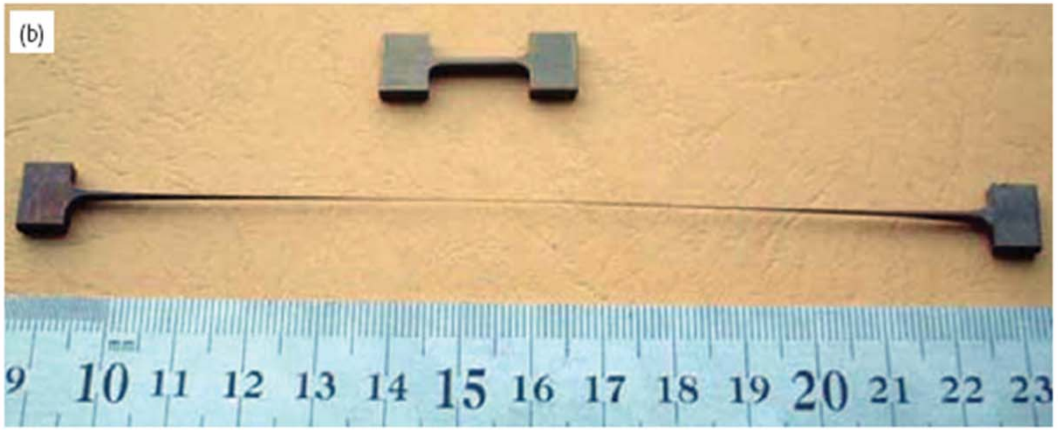
## 2) Processing metals as efficiently as plastics

### b) Thermoplastic forming
### : Large supercooled liquid region



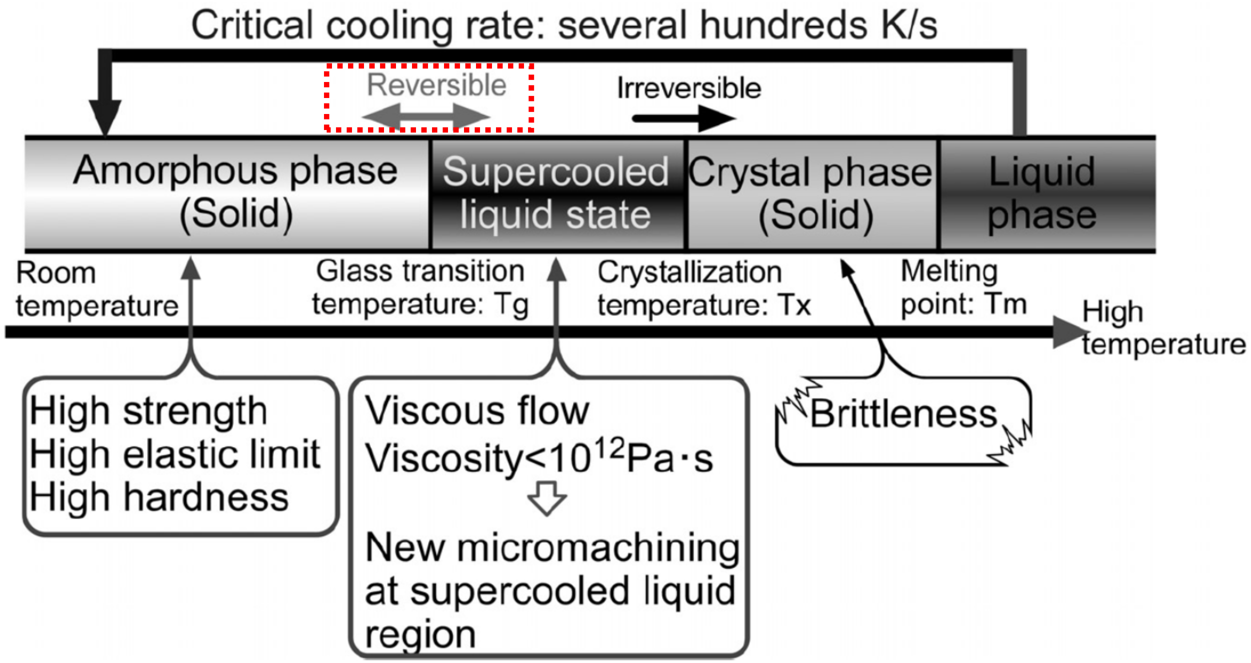

**Tensile specimens following superplastic forming in supercooled liquid region**



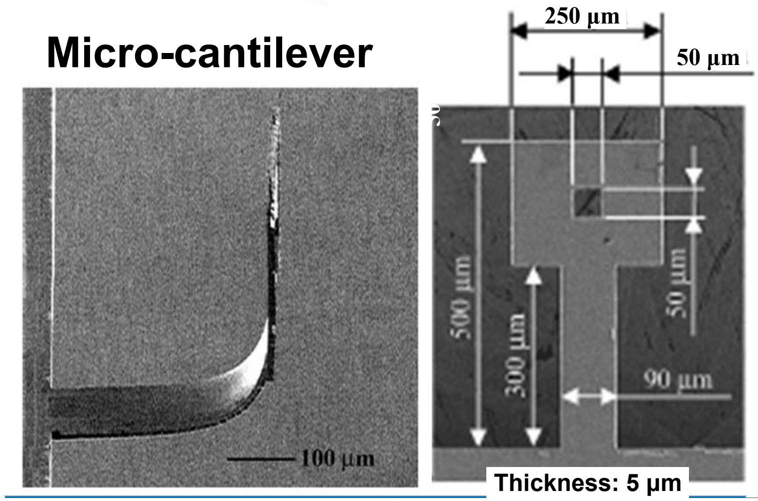
# 2) Processing metals as efficiently as plastics

## c) Micro-forming

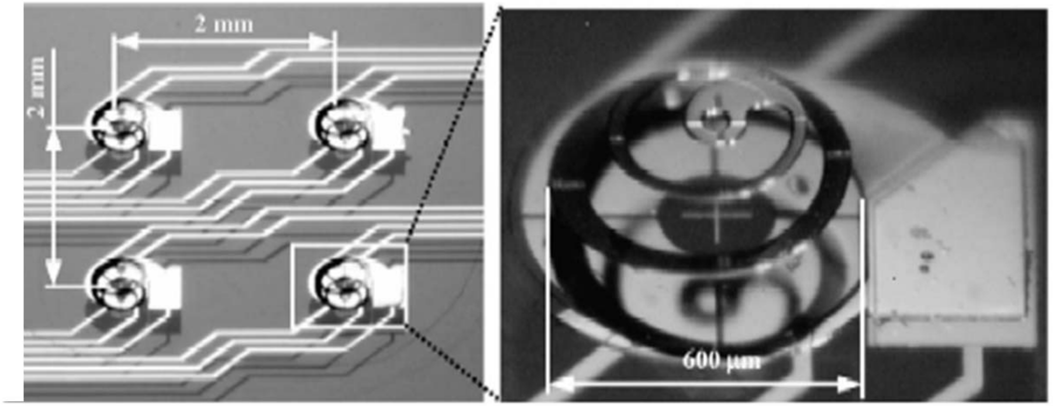



**Micro-forming of three-dimensional microstructures from thin-film metallic glass**

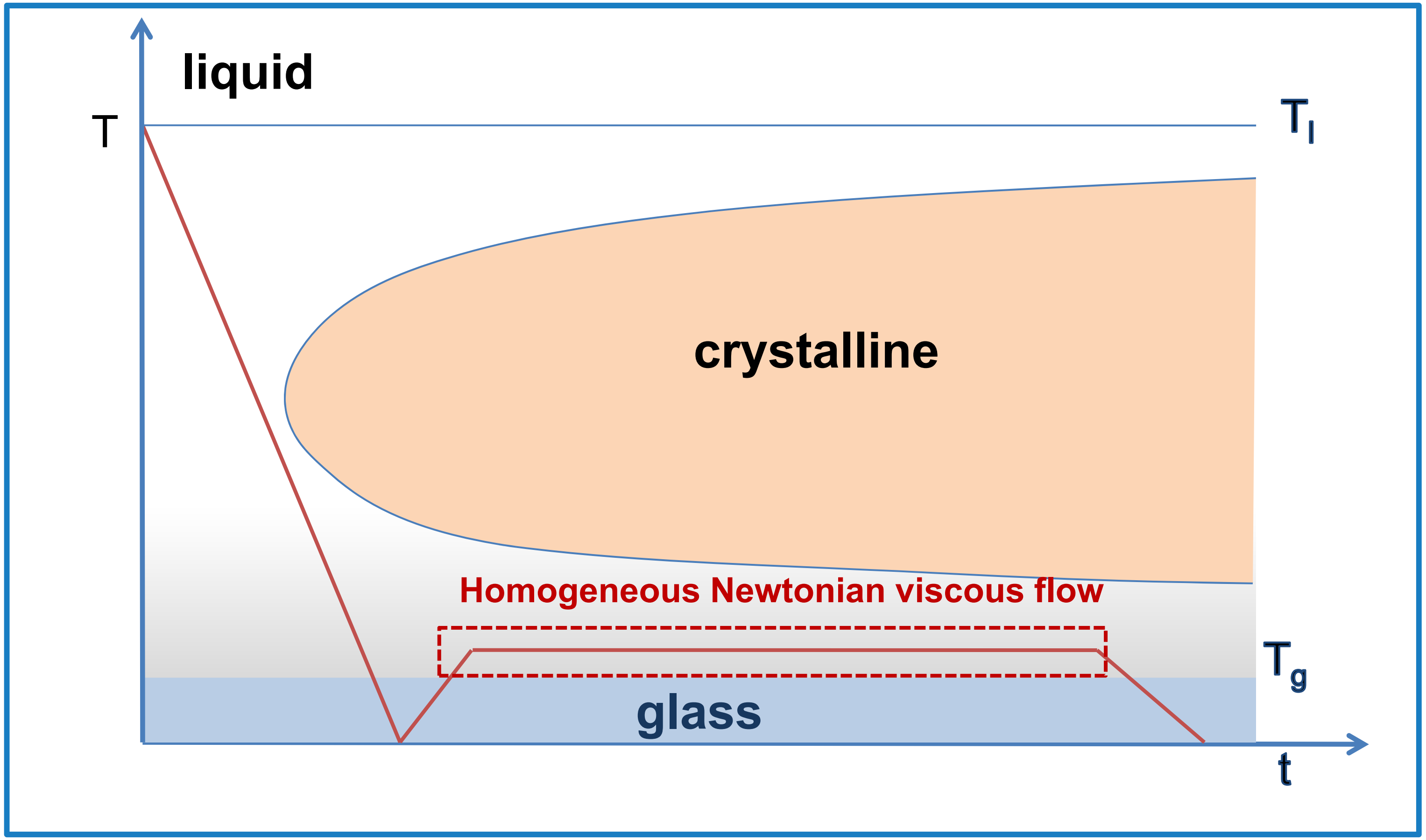
**Micro-cantilever**




**Integrated conical spring linear actuator**



# Thermoplastic forming in SCLR

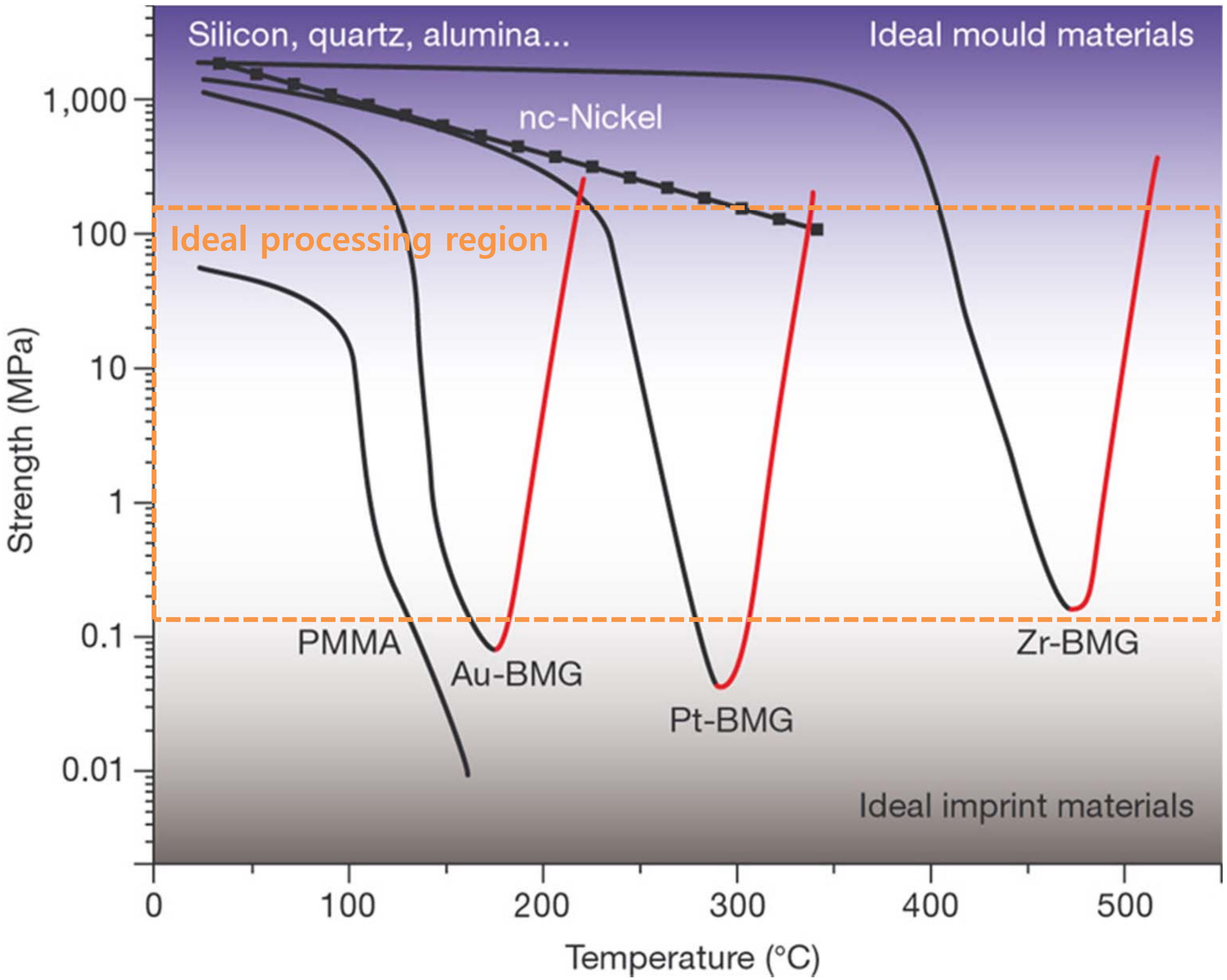



**Metallic glass can be processed like plastics by homogeneous Newtonian viscous flow in supercooled liquid region (SCLR).**

➡ **Possible to deform thin and uniform MG**

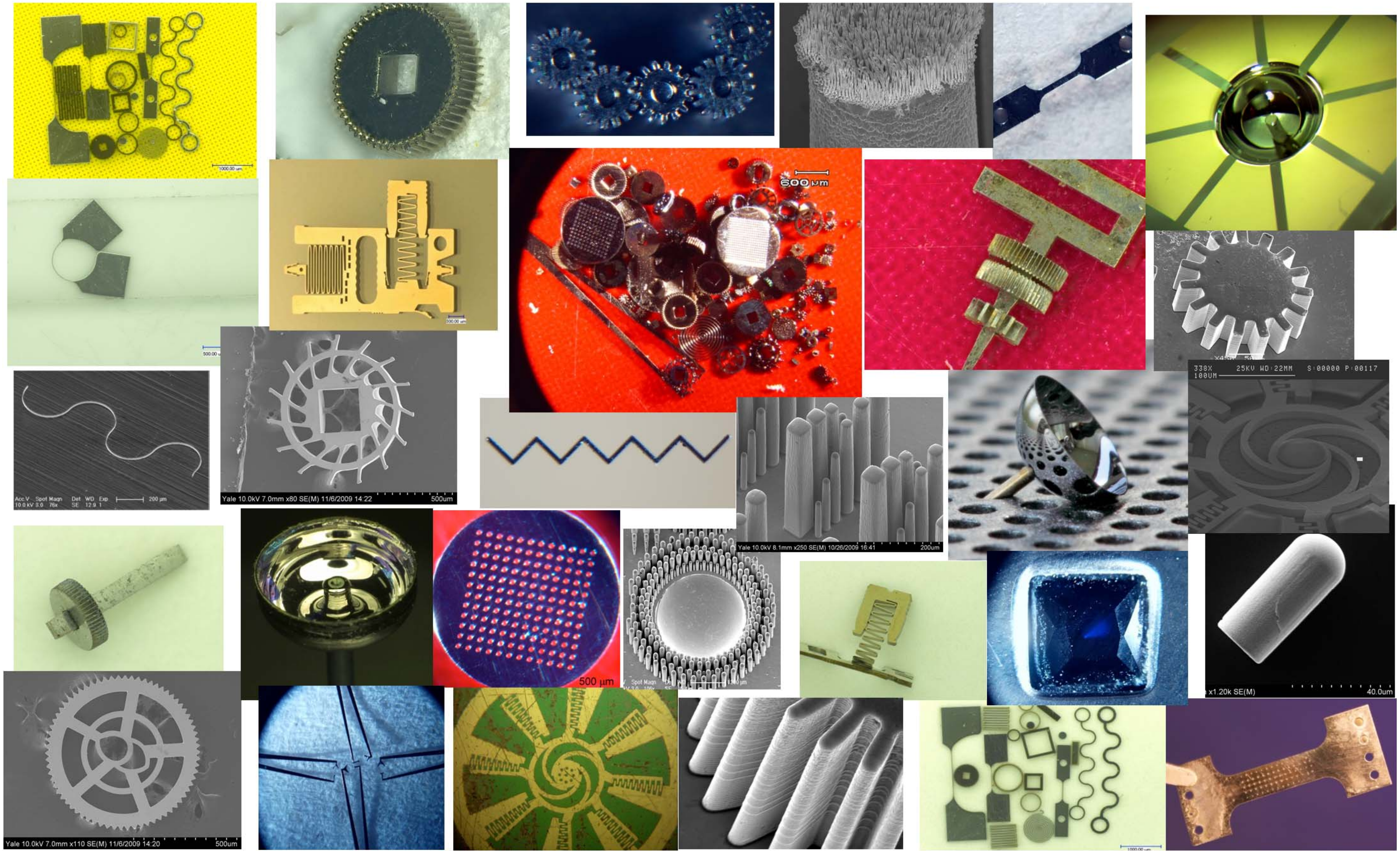
# High processibility of metallic glass according to temperature

*Nature* ***457***, *868-872* (12 February 2009)

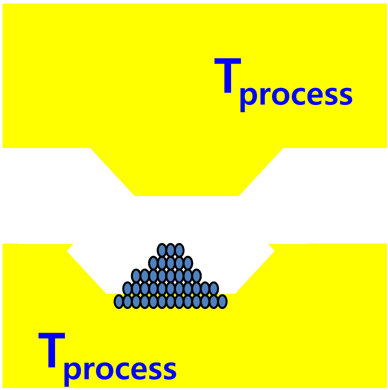


# Processing of Bulk Metallic Glass

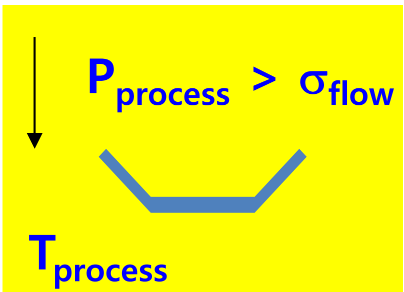
*Adv. Mater.* **2009**, *21*, 1–32



# TPF-based Compression Molding : No size limitation!



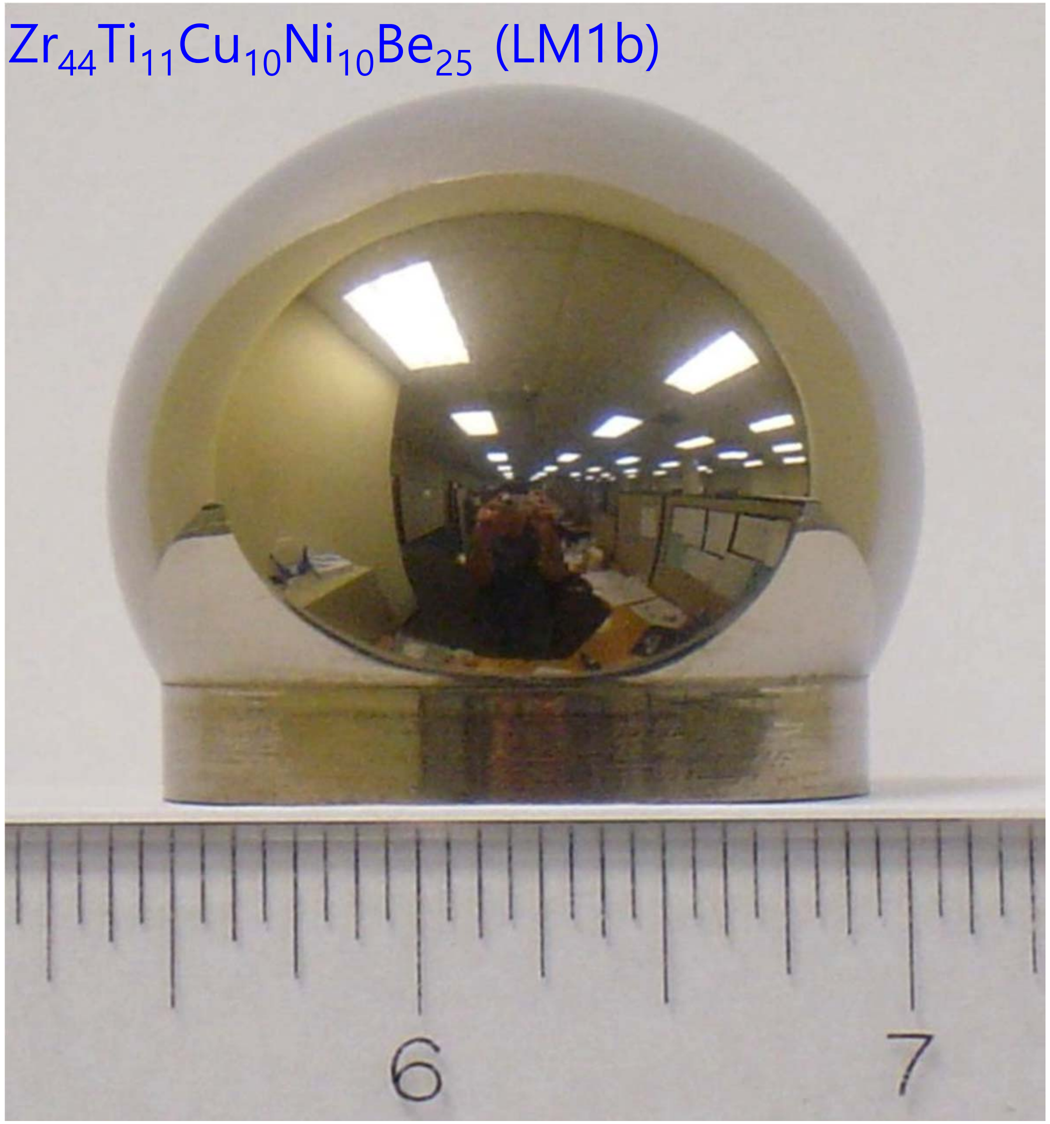

$T_g < T_{process} < T_x$

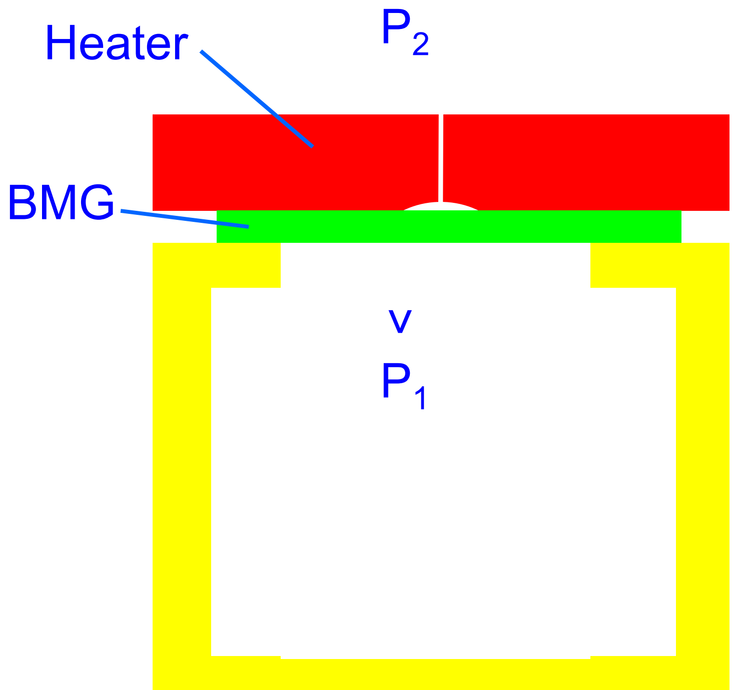



$T_{process} < t_{cryst}$


J. Schroers, JOM, 57, 34 (2005)

# Blow Molding – No Contact Area




$10^5$ Pa, 400% strain

T=460° C, t =40 sec

J. Schroers, T. Nguyen, A. Peker, N. Paton, R. V. Curtis, Scripta Materialia, 57, 341 (2007)


SCHROERS LAB
YALE SCHOOL OF
ENGINEERING &
APPLIED SCIENCE
N°5
CHANEL
PARIS
EAU DE PARFUM


SuperCool
shaping technologies

# “Yale professor makes the case for Supercool Metals”

According to Yale researcher Jan Schroers, This material is 50 times harder than plastic, nearly 10 times harder than aluminum and almost three times the hardness of steel."


**Jan Schroers, Adv. Mater., 2010, hologram pattern**

TICAL
OPTICAL
OPTICAL
ITY OPT
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RITY

# Processing metals as efficiently as plastics: net-shape forming!

Seamaster Planet Ocean Liquidmetal® Limited Edition

- Superior thermo-plastic formability

  : possible to fabricate complex structure without joints

  ↳ Multistep processing can be solved by simple casting

  ↳ Ideal for small expensive IT equipment manufacturing

# Apple buys exclusive right for Liquidmetal


**Apple is using Liquidmetal for…**

USIM ejector (iphone 4)

Enclosure / Antenna

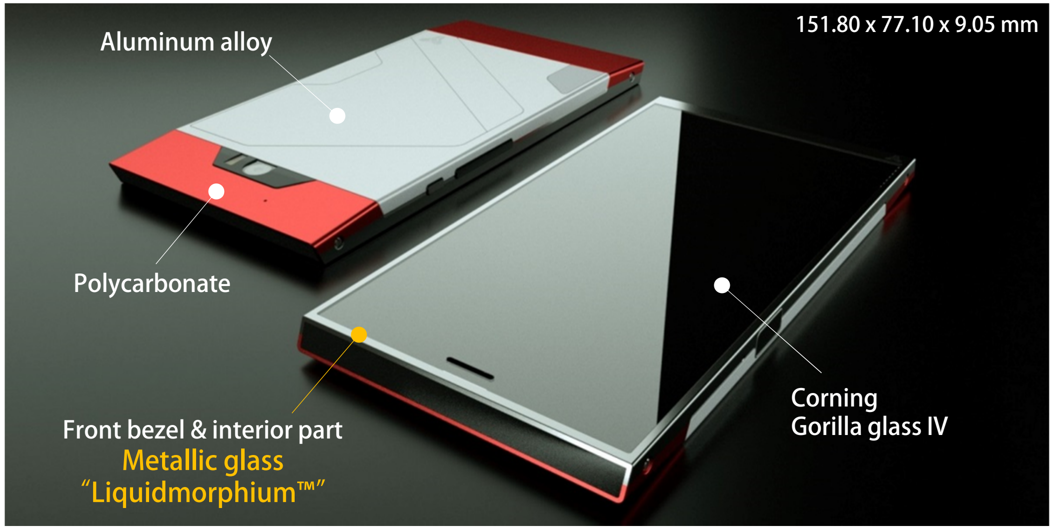
# World-first Smart Phone with BMG exterior (2015)

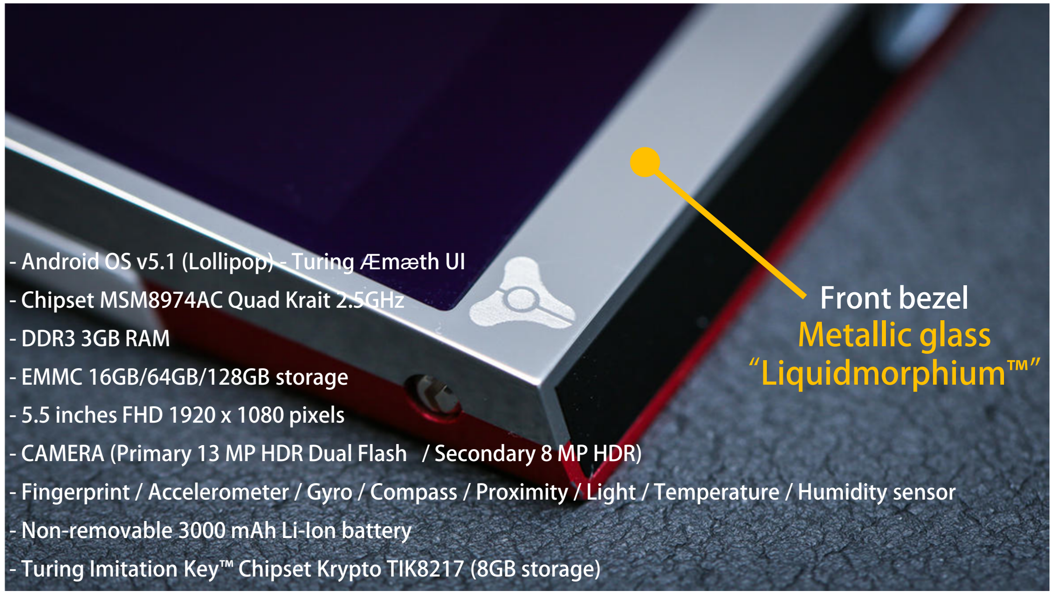
## Turing phone

by Turing Robotics Industries (UK)

with

Metallic glass
"Liquidmorphium™"




"Unhackable"
"Waterproof"

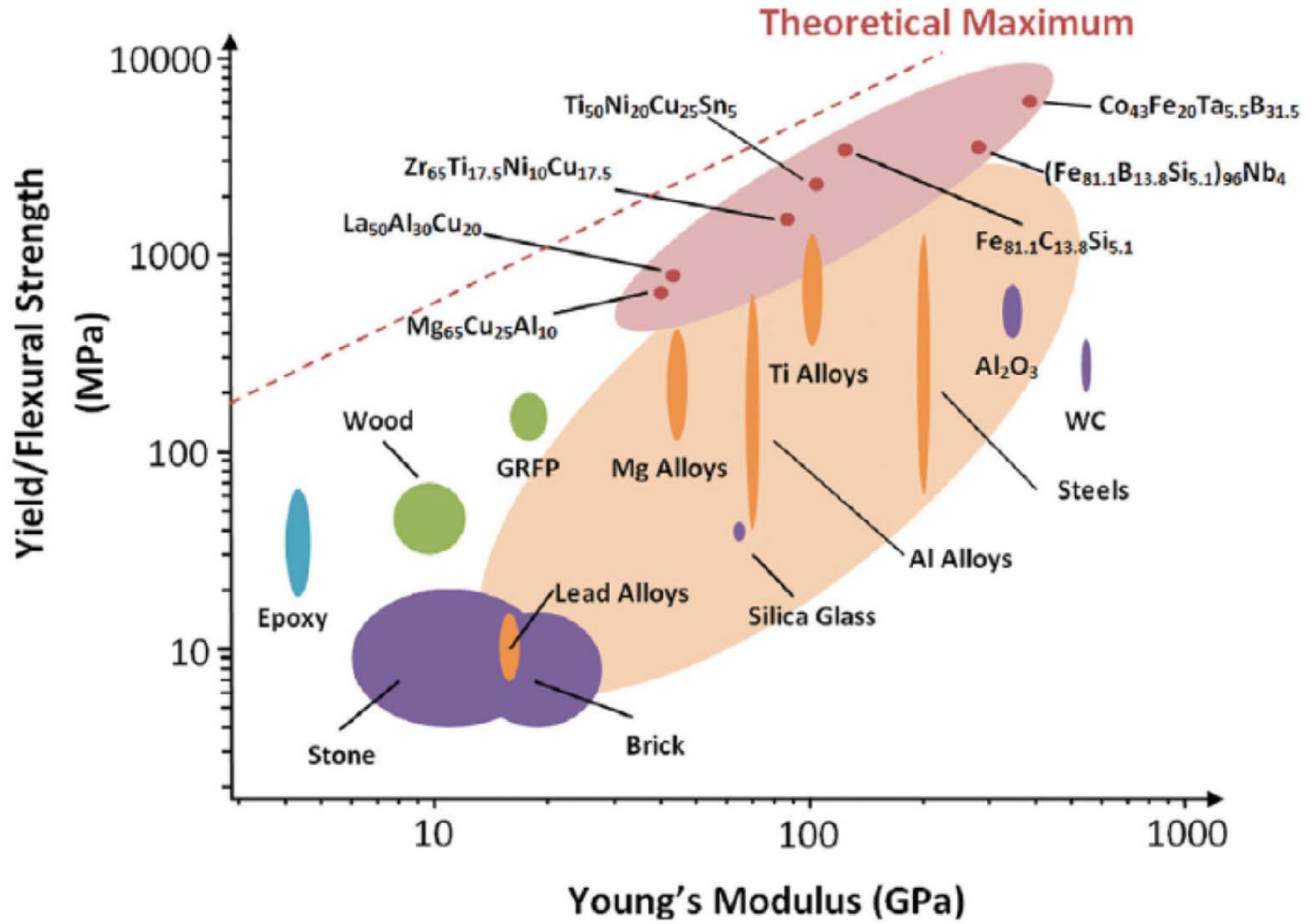
+

"Unbreakable"

The Turing Phone is built with a pioneering material called **Liquidmorphium™**, an amorphous "liquid metal" alloy tougher than either titanium or steel - so what's in your hand is as strong as your privacy protection.

from https://www.turingphone.com/

# 3) High yield (or fracture) strength and hardness




**High fracture strength over 5 GPa in Fe-based BMGs**

*A.L. Greer, E. Ma, MRS Bulletin, 2007; 32: 612.*

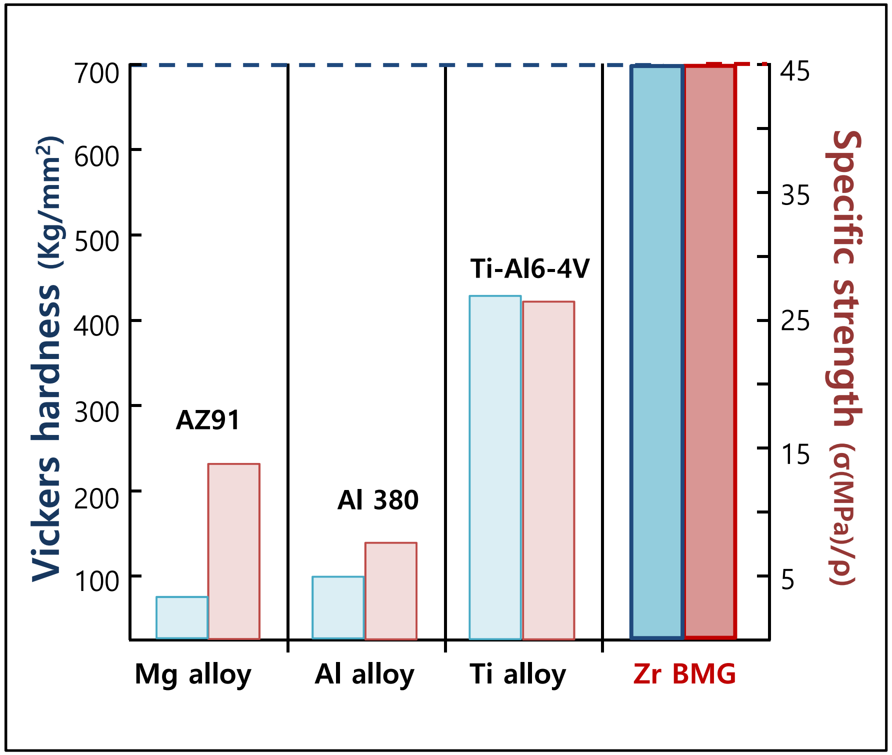
## 3) High yield (or fracture) strength and hardness

# Bulk metallic glasses with high strength

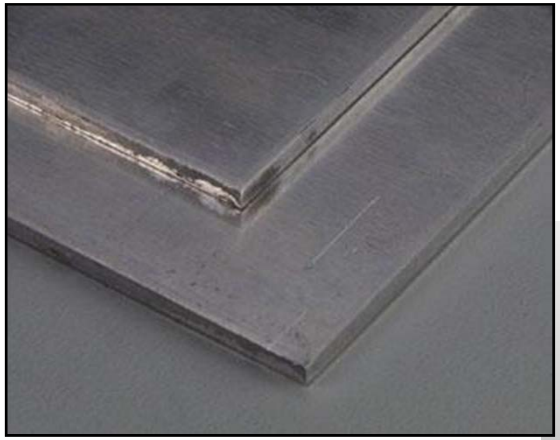
- **"High specific strength"** → Ultra-thin product with reasonable strength

  : Possible to reduce more thickness with same standard strength than conventional light alloys due to superior specific strength

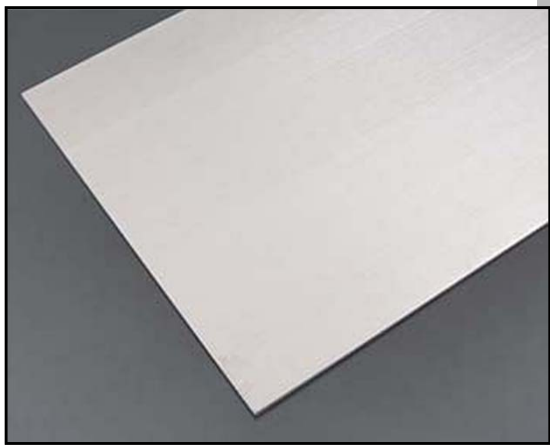
  → **Flexible / Wearable electronics**




Comparison of specific strength among Zr based BMG and conventional light alloys

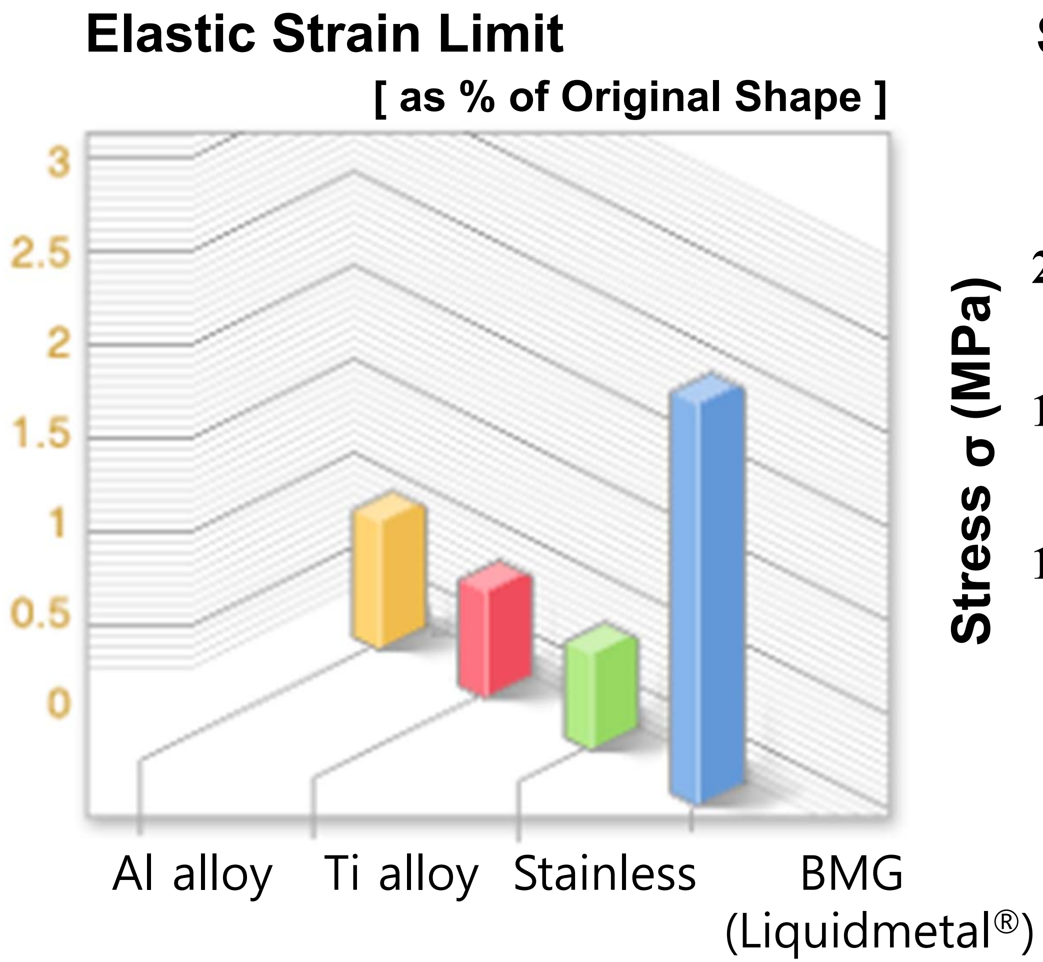


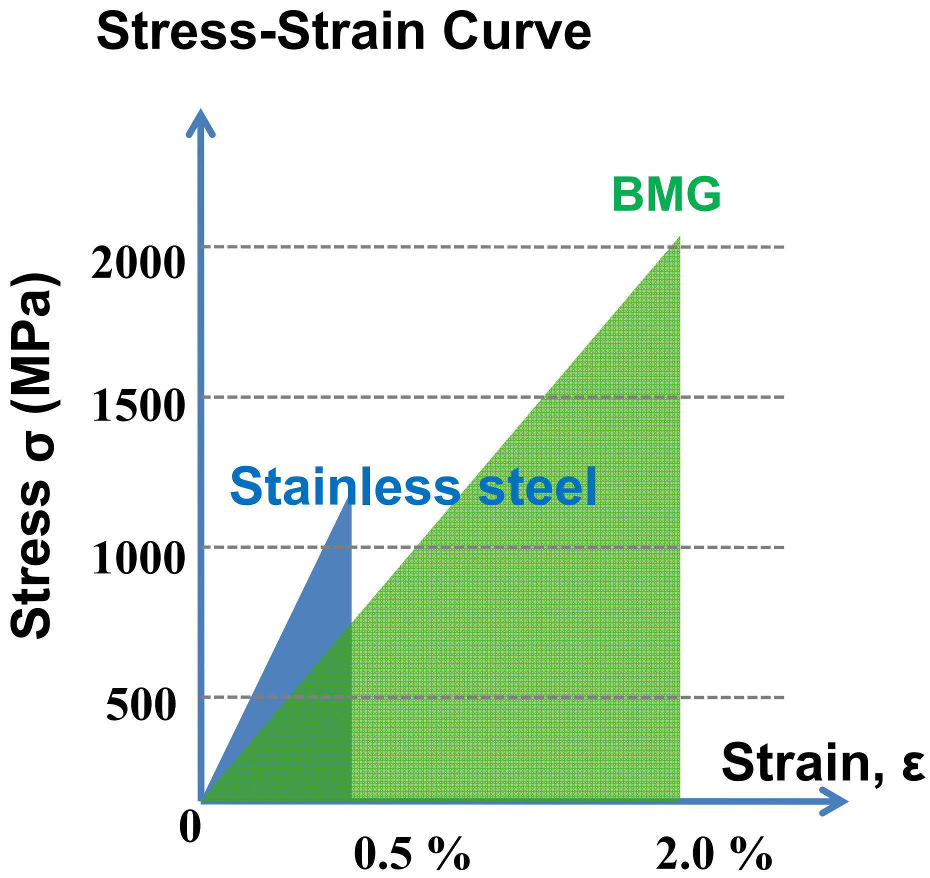
Mg – AZ91



Thinner plate: BMG

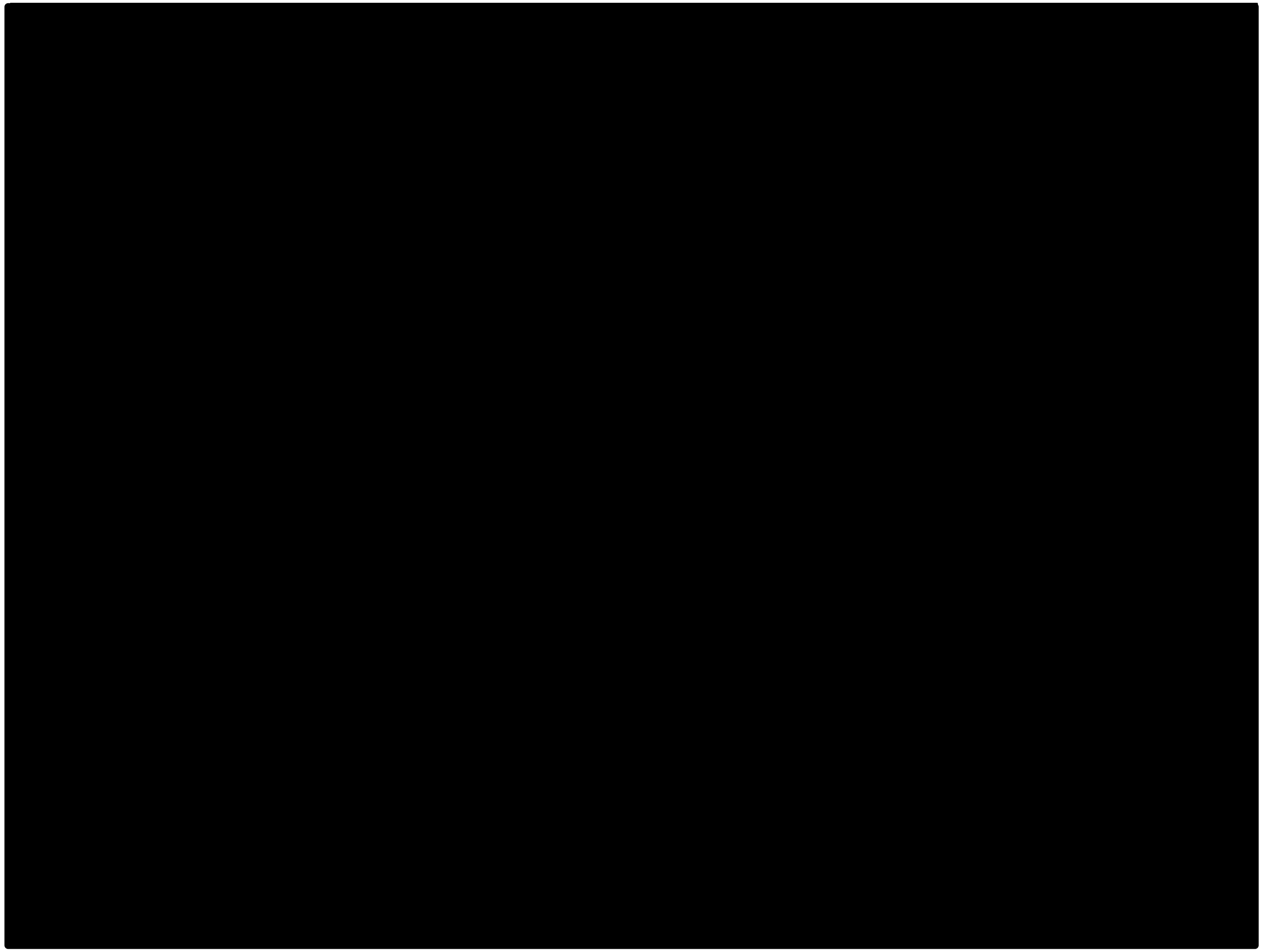
## 4) Large elastic strain limit of about 2 % at room temperature



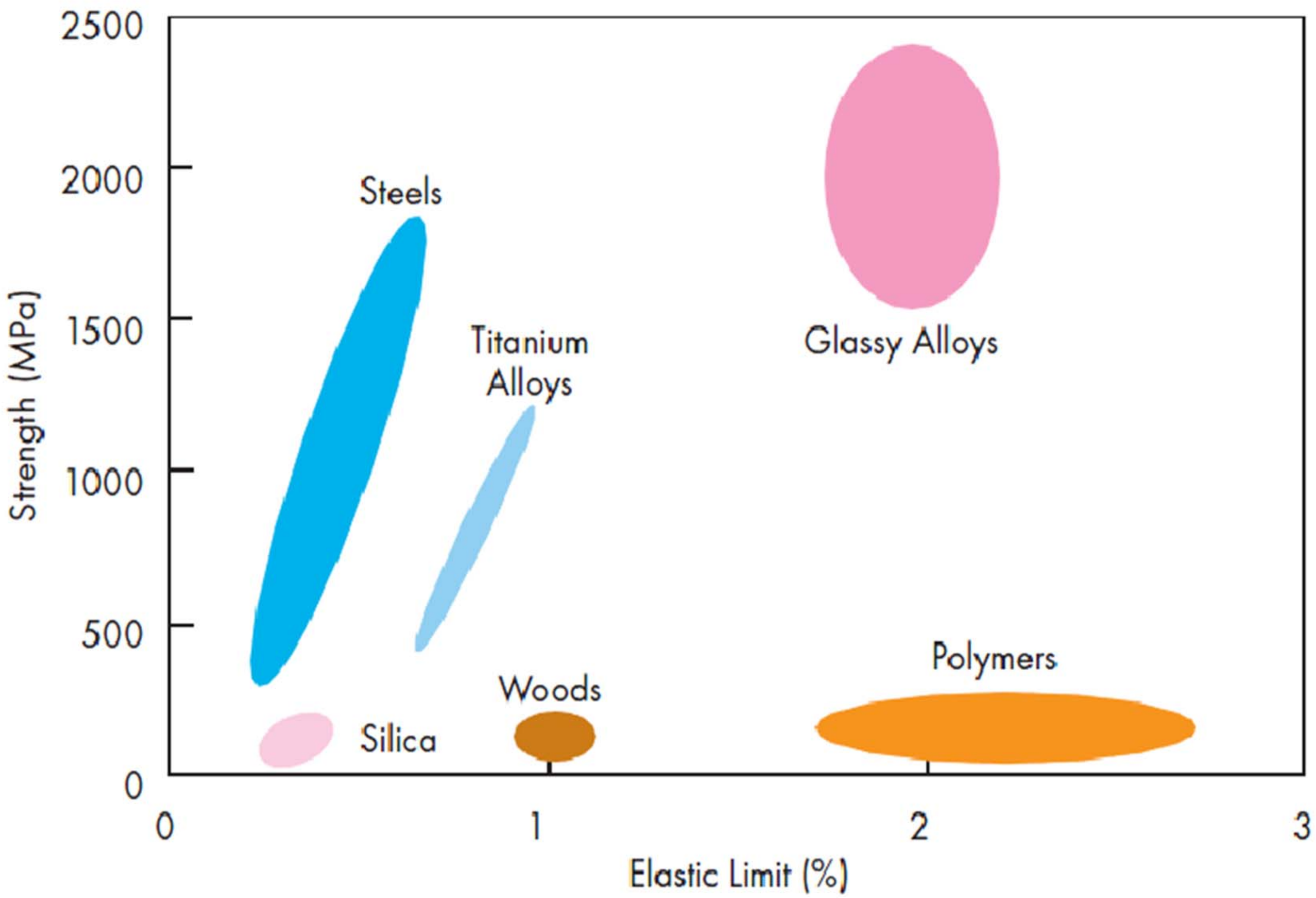



## 10.2 Special Characteristics of BMGs

# 4) Large elastic strain limit of about 2 % at room temperature



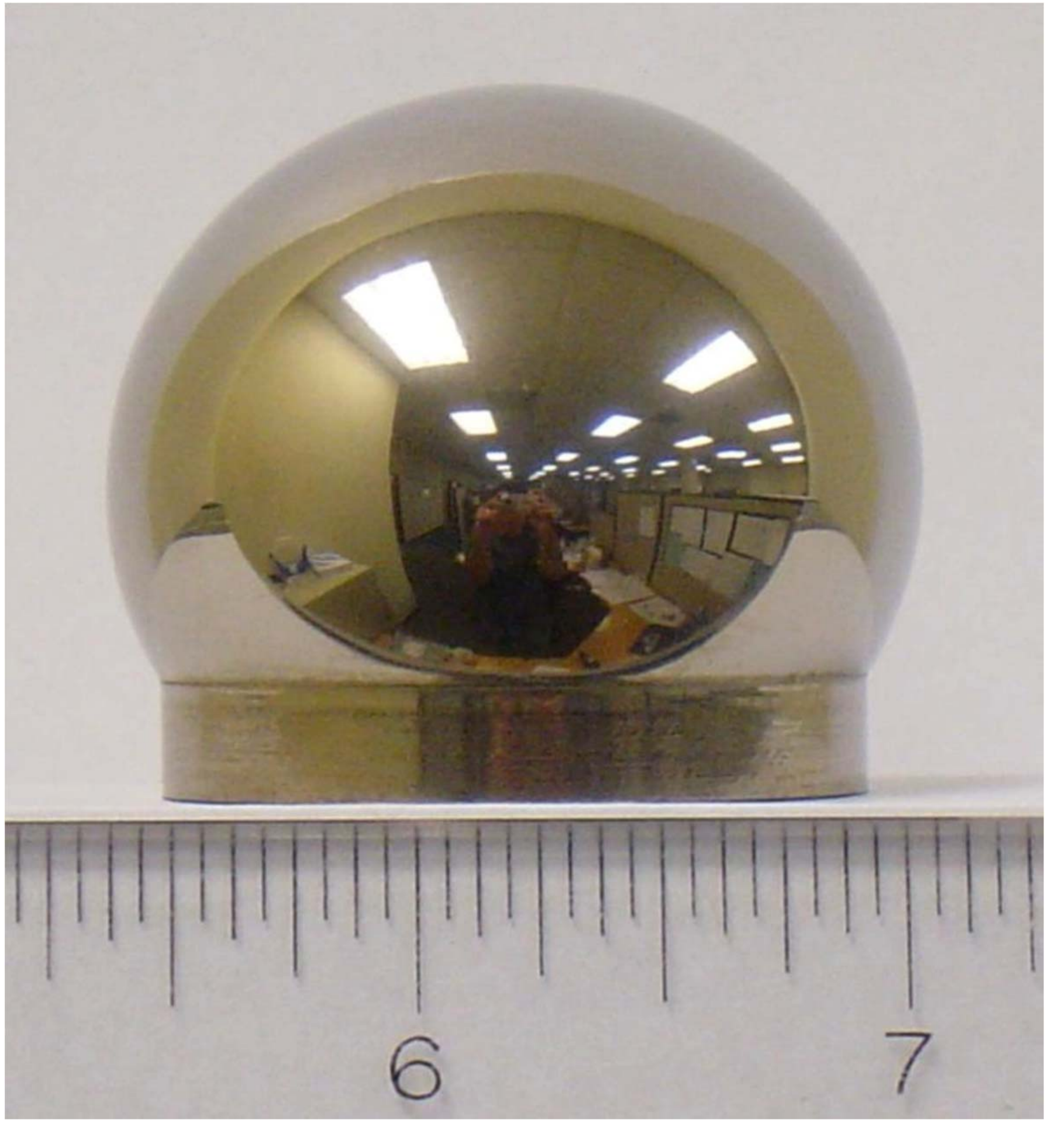
# Bulk metallic glasses with high strength & high elastic limit




**: Metallic Glasses Offer a Unique Combination of High Strength and High Elastic Limit**

## 5) Ability to achieve a very high surface finish

**: do not have microstructural features such as grains and grain boundaries**



## 10.2 Special Characteristics of BMGs

*** Different forms of the glassy materials: rods, sheets, plates, spheres , pipes, etc.**

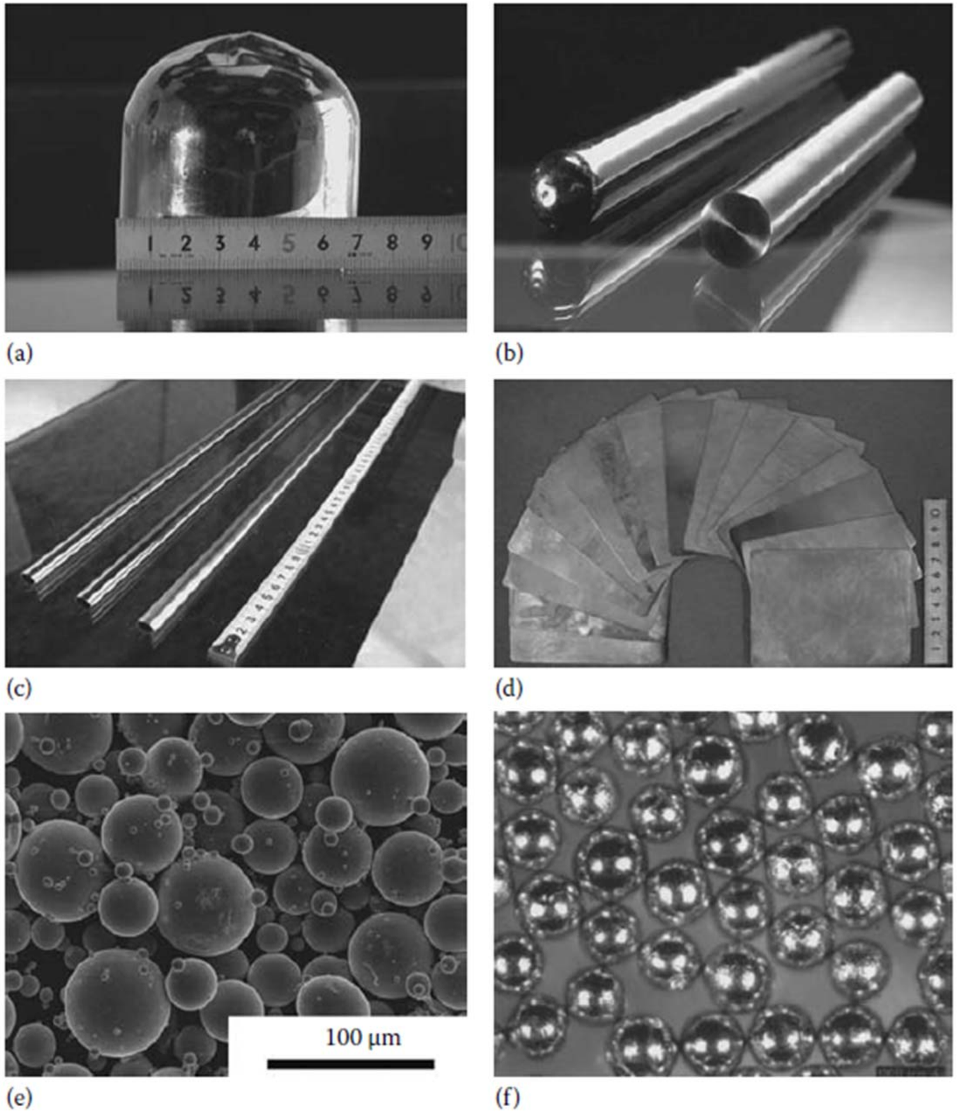



**FIGURE 10.1**
Different forms in which BMGs have been produced. (a) Cast cylinder, (b) rods, (c) pipes, (d) sheets, (e) powder, and (f) spheres.

## 10.3 Structural Applications: high yield (or fracture) strength, low Young's modulus, large elastic strain limit, and easy formability in the SCLR

### 10. 3. 1 Sporting Goods

*** Golf club: The repulsive efficiency (defined as the ratio of ball velocity/ club head velocity ) was found to 1.43 for the BMG alloy face, whereas it is only 1.405 for the Ti-alloy face. the overall flying distance was 225 mm for the BMG alloy face, whereas it is only 213 for the Ti-alloy face.**

the modulus of resilience, *U*,

$$U = \frac{1}{2}\sigma_y \cdot \varepsilon_y = \frac{1}{2}E\varepsilon_y^2$$

where

$\sigma_y$ and $\varepsilon_y$ are the yield stress and elastic strain limit, respectively

$E$ is the Young's modulus

**FIGURE 10.2**
Outer shapes of commercial golf club heads in wood-, iron-, and putter-type forms where the face materials are made of Zr-based BMG alloy. (Reprinted from Kakiuchi, H. et al., *Mater. Trans.*, 42, 678, 2001. With permission.)

## 10.3 Structural Applications: high yield (or fracture) strength, low Young's modulus, large elastic strain limit, and easy formability in the SCLR

### 10. 3. 1 Sporting Goods

- Striking face plate in golf clubs/ Frame in tennis rackets / Baseball and softball bats/ Skis and snowboards / Bicycle parts / Fishing equipment/ Marine applications


**FIGURE 10.3**
(a) Baseball bat and (b) tennis racket made of Liquidmetal (BMG) alloys.

## 10.3 Structural Applications: high yield (or fracture) strength, low Young's modulus, large elastic strain limit, and easy formability in the SCLR

### 10. 3. 2. Precision Gears

- No shrinkage during solidification
- No grain boundary – High flatness
- High strength

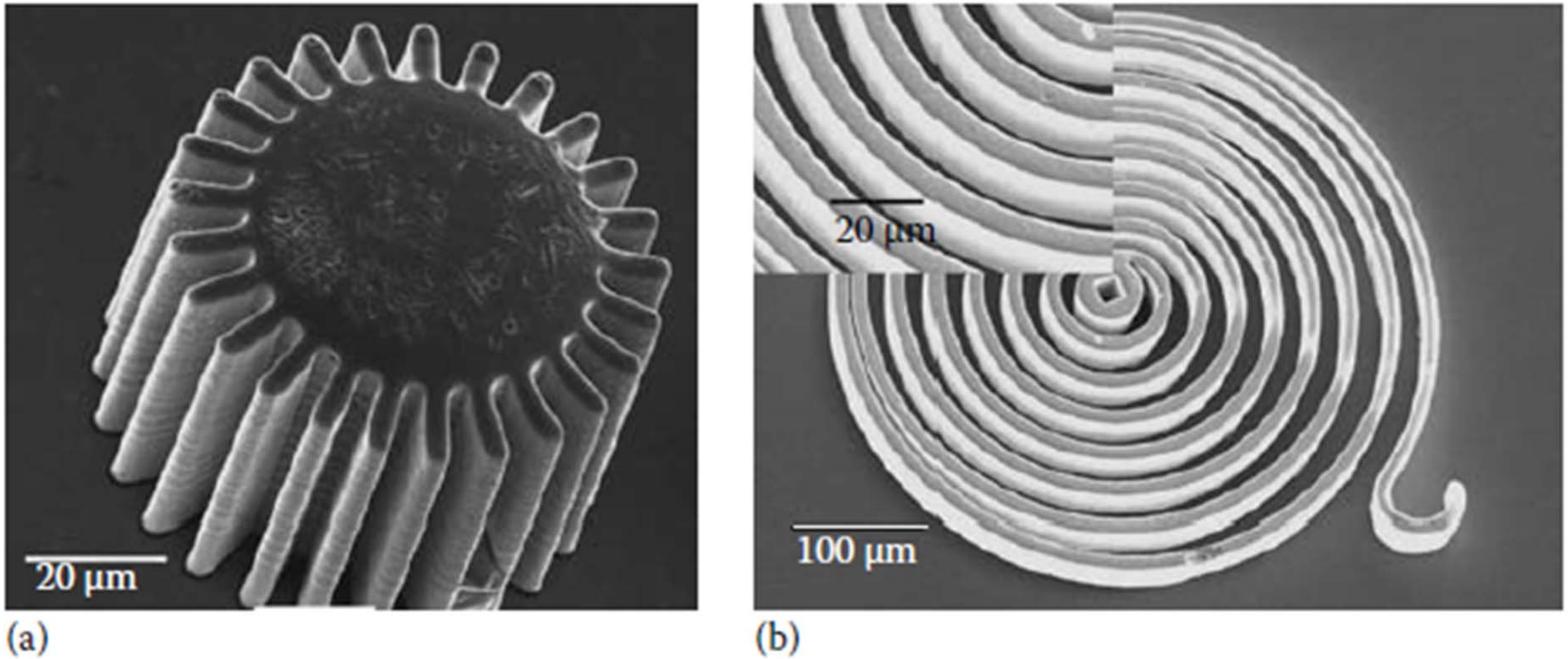



**FIGURE 10.5**
(a) A complex micro gear and (b) coil shape spring made from a $Zr_{44}Ti_{11}Cu_{10}Ni_{10}Be_{25}$ BMG alloy. (Reprinted from Schroers, J. et al., *Mater. Sci. Eng. A*, 449–451, 898, 2007. With permission.)

## 10.3 Structural Applications: high yield (or fracture) strength, low Young's modulus, large elastic strain limit, and easy formability in the SCLR

### 10. 3. 2. Precision Gears

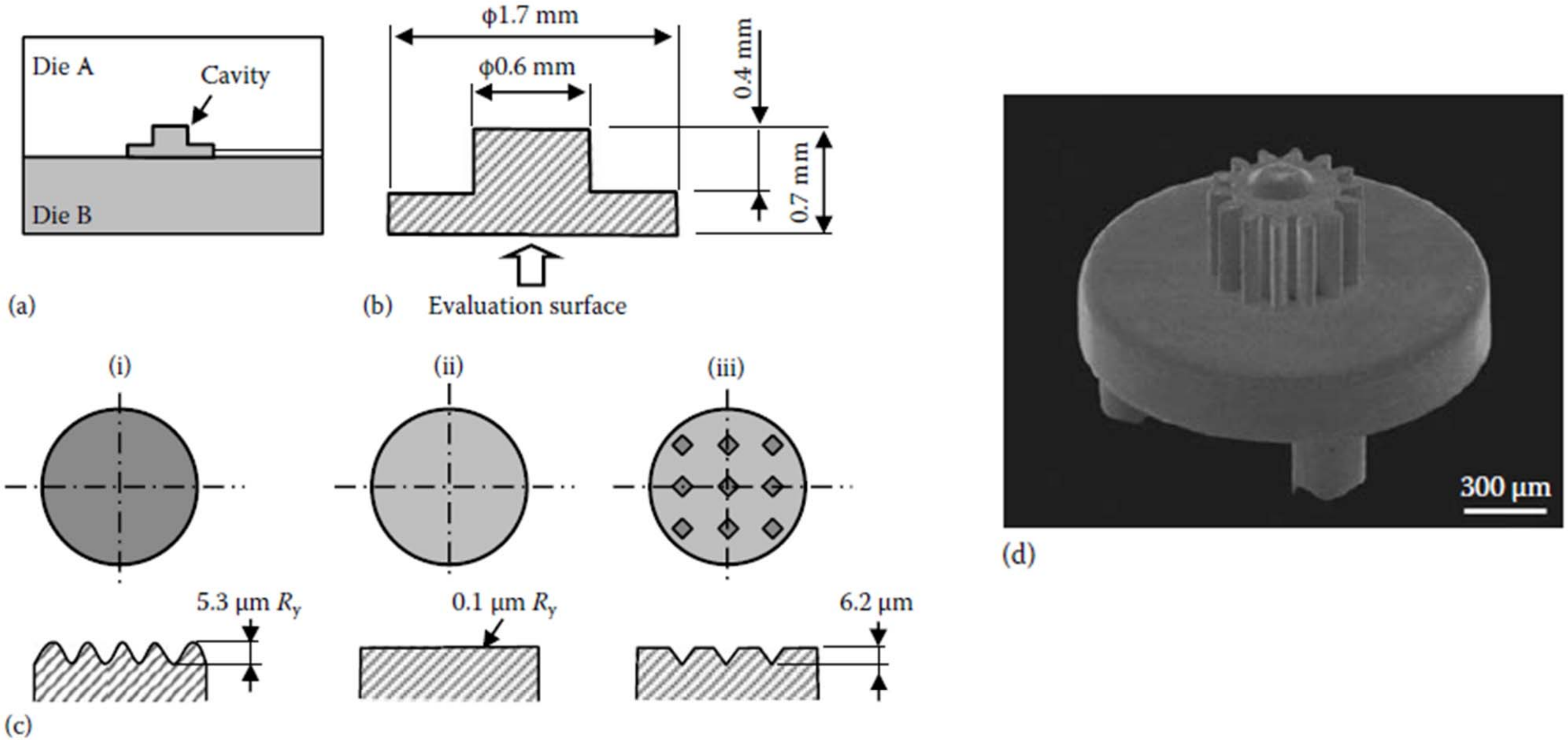
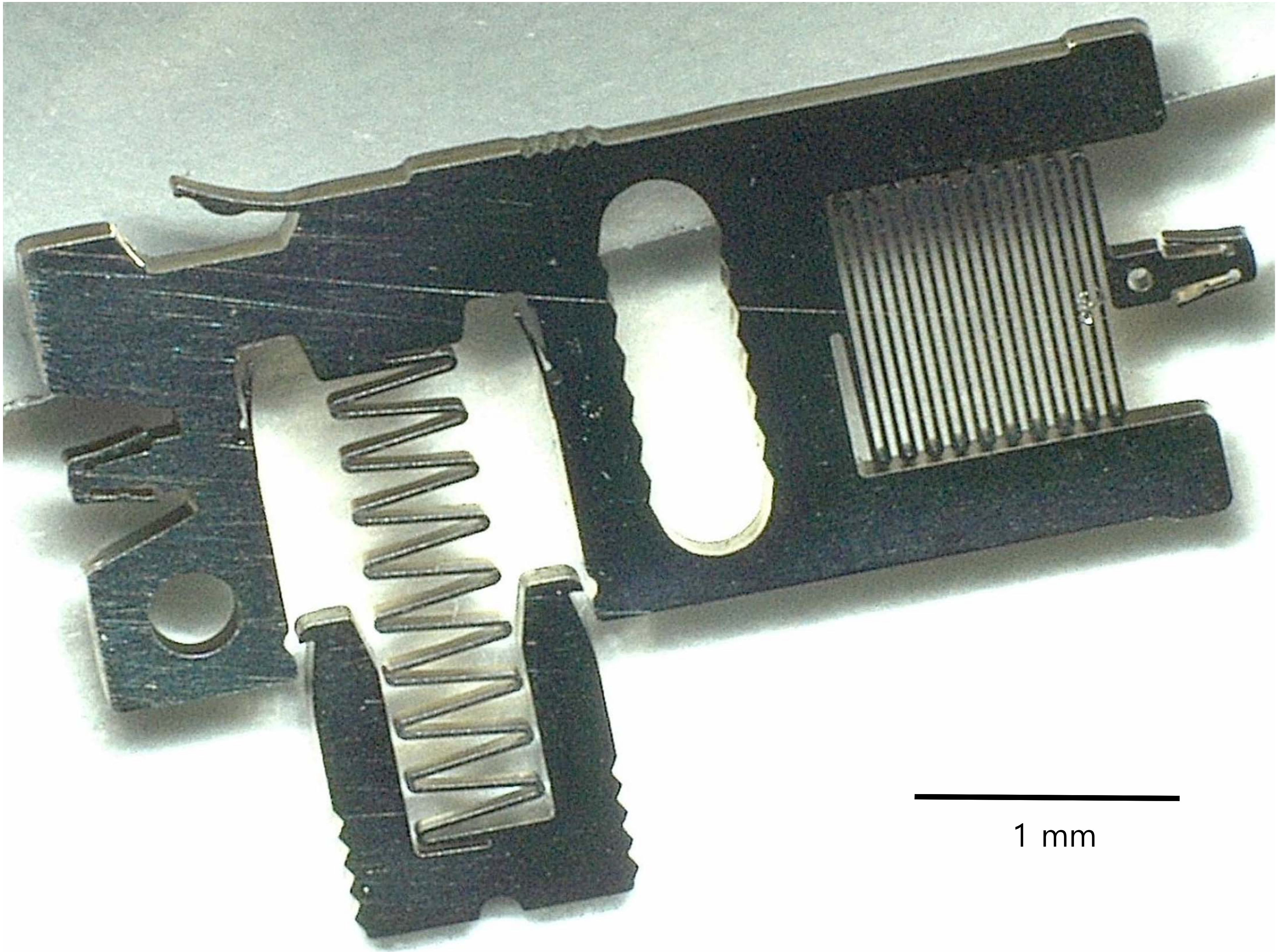
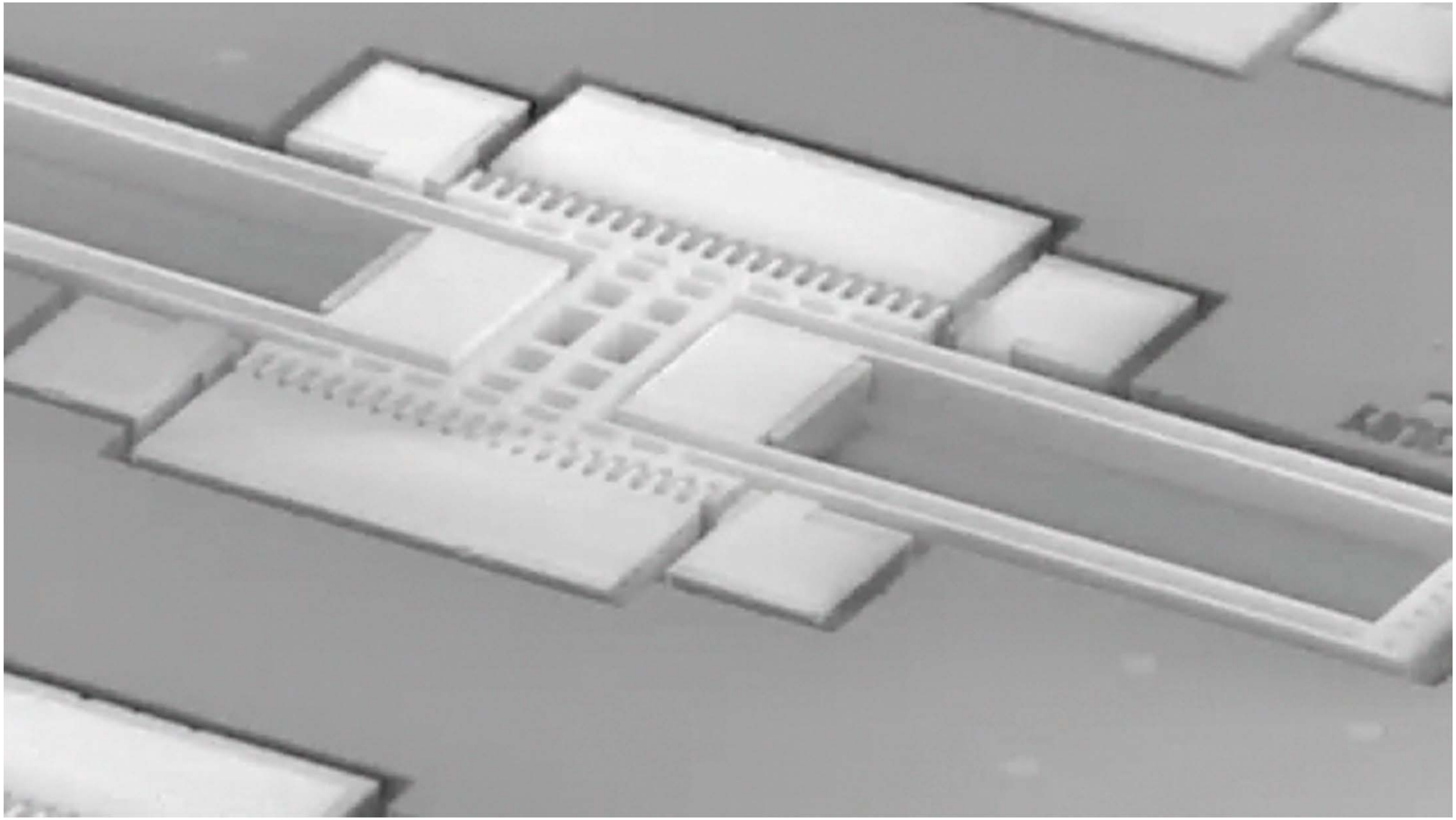



**FIGURE 10.4**
(a) Schematic illustration of the die assembly. (b) Schematic of the specimen with the dimensions indicated. (c) Schematic illustrations of the top surface of Die B prepared by (i) electro-discharge machining, (ii) polishing, and (iii) Vickers indentation. (d) External appearance of the Ni-based BMG sun-carrier fabricated by the precision die casting technique from an electro-discharge machined mold. (Reprinted from Ishida, M. et al., *Mater. Trans.*, 45, 1239, 2004. With permission.)

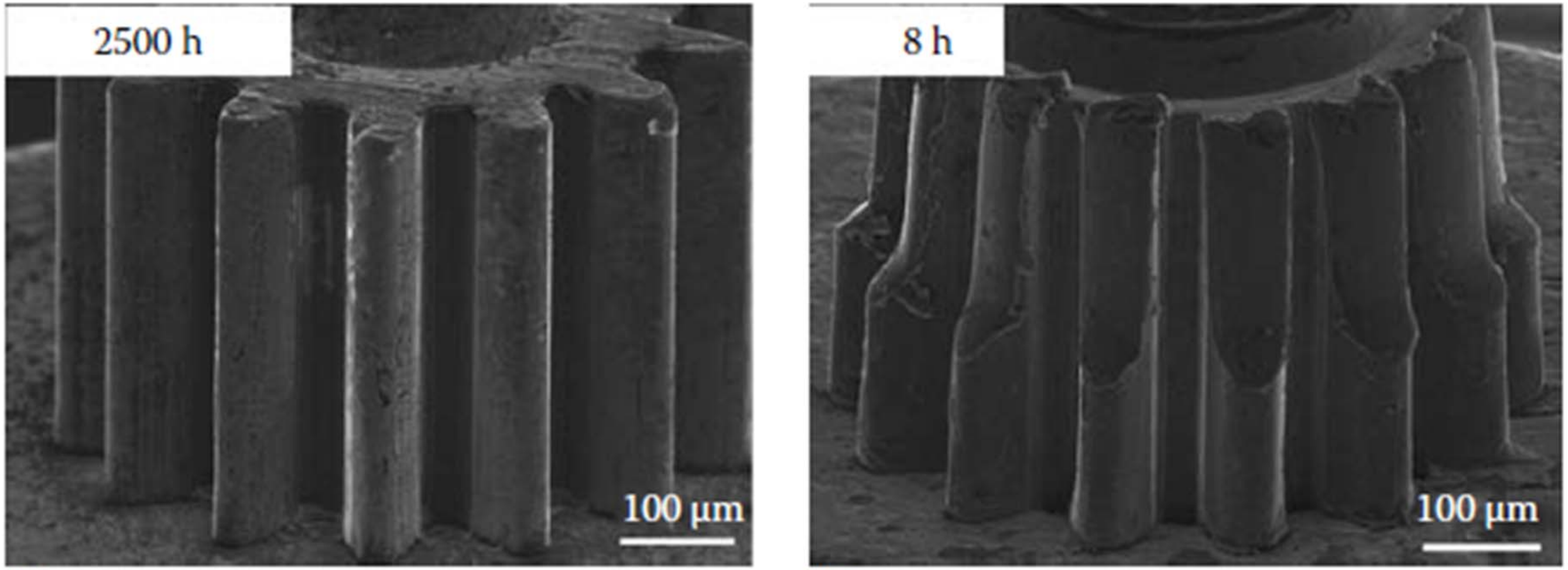

1 mm

# Fully functional MEMS device



## 10.3 Structural Applications: high yield (or fracture) strength, low Young's modulus, large elastic strain limit, and easy formability in the SCLR

### 10. 3. 3 Motors




(a) (b)

**FIGURE 10.6**
SEM images of the gears after the durability tests. (a) The gear made out of the Ni-based BMG alloy after 2500h of use (1875 million revolutions) and (b) the carbon steel gear after 8h of use (6 million revolutions). Notice the serious damage in the carbon steel gear even after just 8h of use, while the BMG gear is intact even after 2500h of use. (Reprinted from Ishida, M. et al., *Mater. Sci. Eng. A*, 449–451, 149, 2007. With permission.)

## 10.3 Structural Applications: high yield (or fracture) strength, low Young's modulus, large elastic strain limit, and easy formability in the SCLR

### 10. 3. 3 Motors

- Higher dimensional accuracy
- 313 times longer than conventional motor

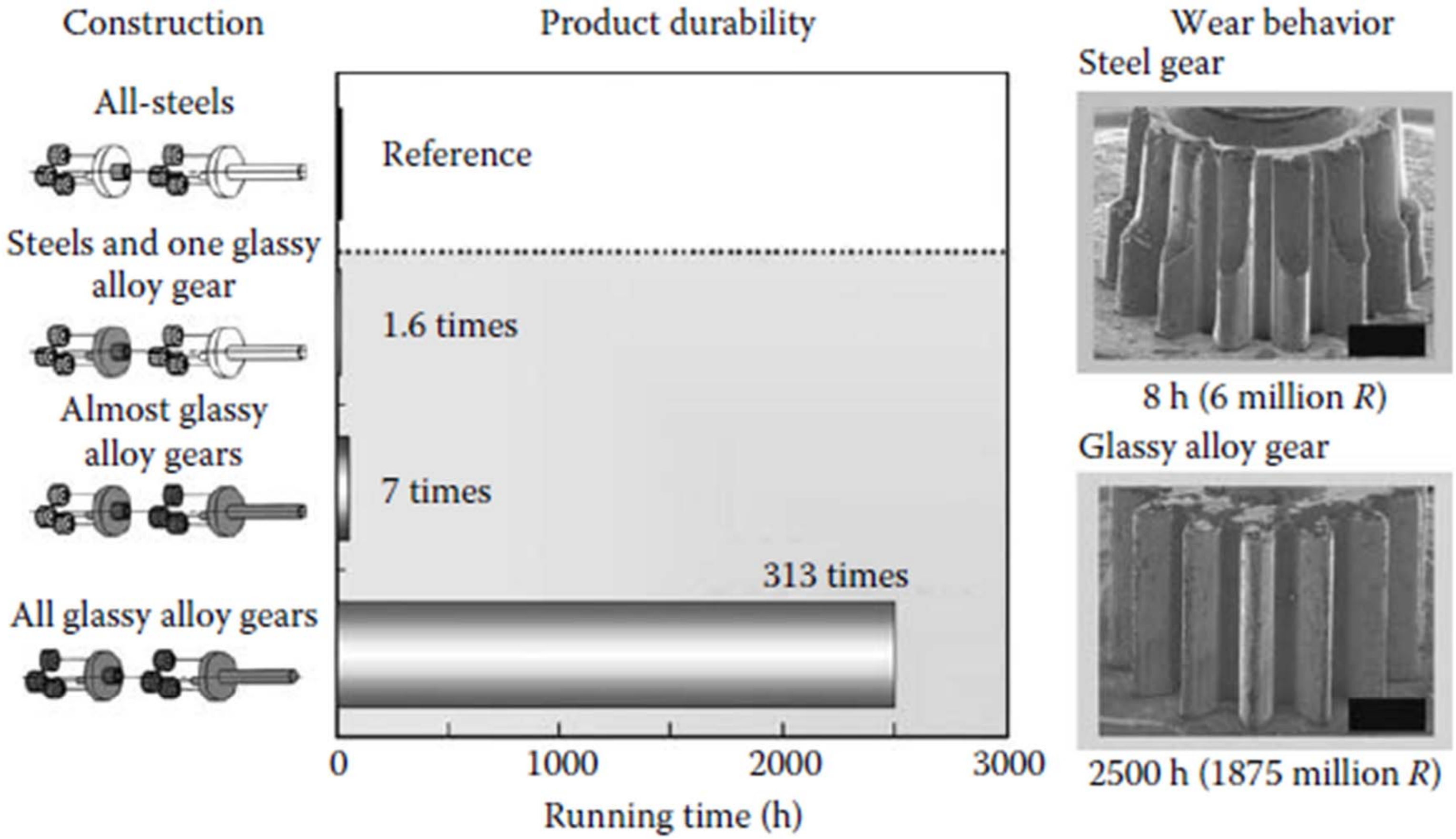



**FIGURE 10.7**
Comparative wear resistance behavior of gears made with different materials in a 2.4 mm diameter geared motor. (Reprinted from Inoue, A. et al., *Mater. Sci. Eng. A*, 441, 18, 2006. With permission.)

## 10.3 Structural Applications: high yield (or fracture) strength, low Young's modulus, large elastic strain limit, and easy formability in the SCLR

### 10. 3. 3 Motors

**With no shrinkage during solidification** → **Net-shape products** → **Low cost production**

**The lack of grain boundaries** → **Superior surface flatness** → **Reducing wear and energy loss by friction**

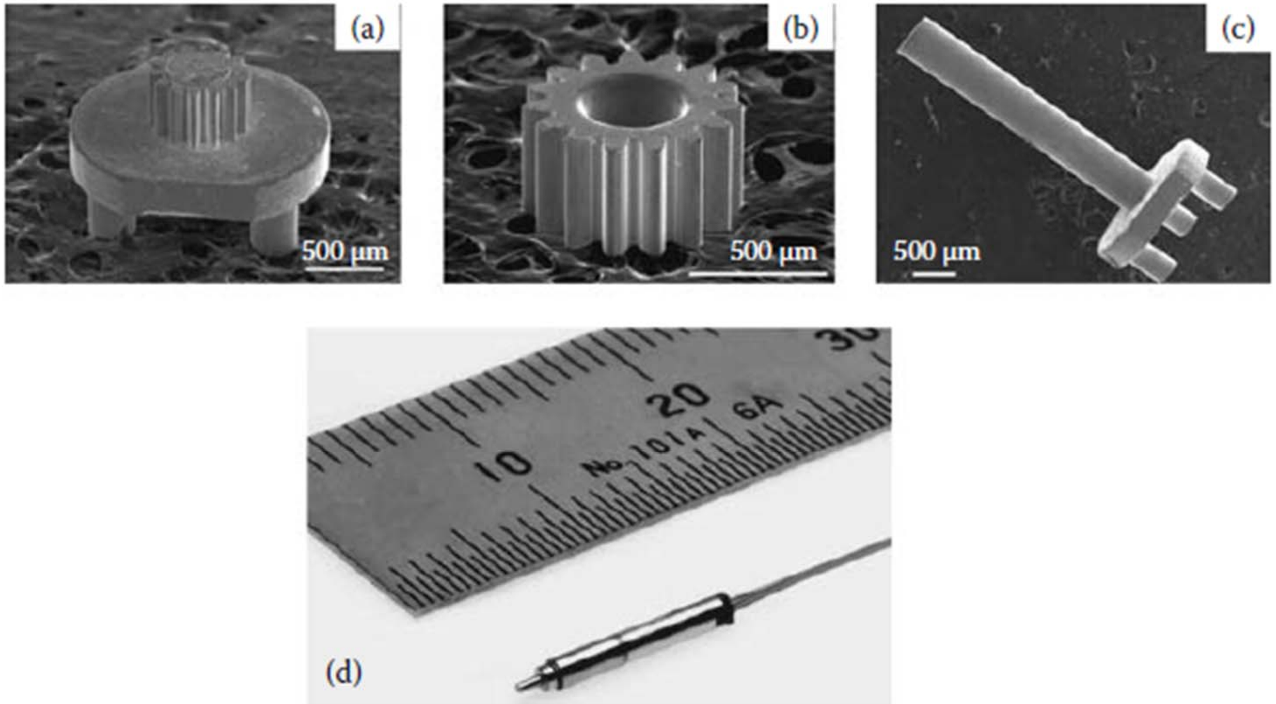



**FIGURE 10.8**
Precision microgear parts produced by injection casting of an $Ni_{53}Nb_{20}Zr_8Ti_{10}Co_6Cu_3$ BMG alloy: (a) sun-carrier, (b) planetary gear, and (c) an output shaft. (d) Micro-geared motor with a diameter of 1.5 mm and a length of 9.4 mm fabricated from the $Ni_{53}Nb_{20}Zr_8Ti_{10}Co_6Cu_3$ BMG alloy.

## 10.3 Structural Applications: high yield (or fracture) strength, low Young's modulus, large elastic strain limit, and easy formability in the SCLR

### 10. 3. 3 Motors

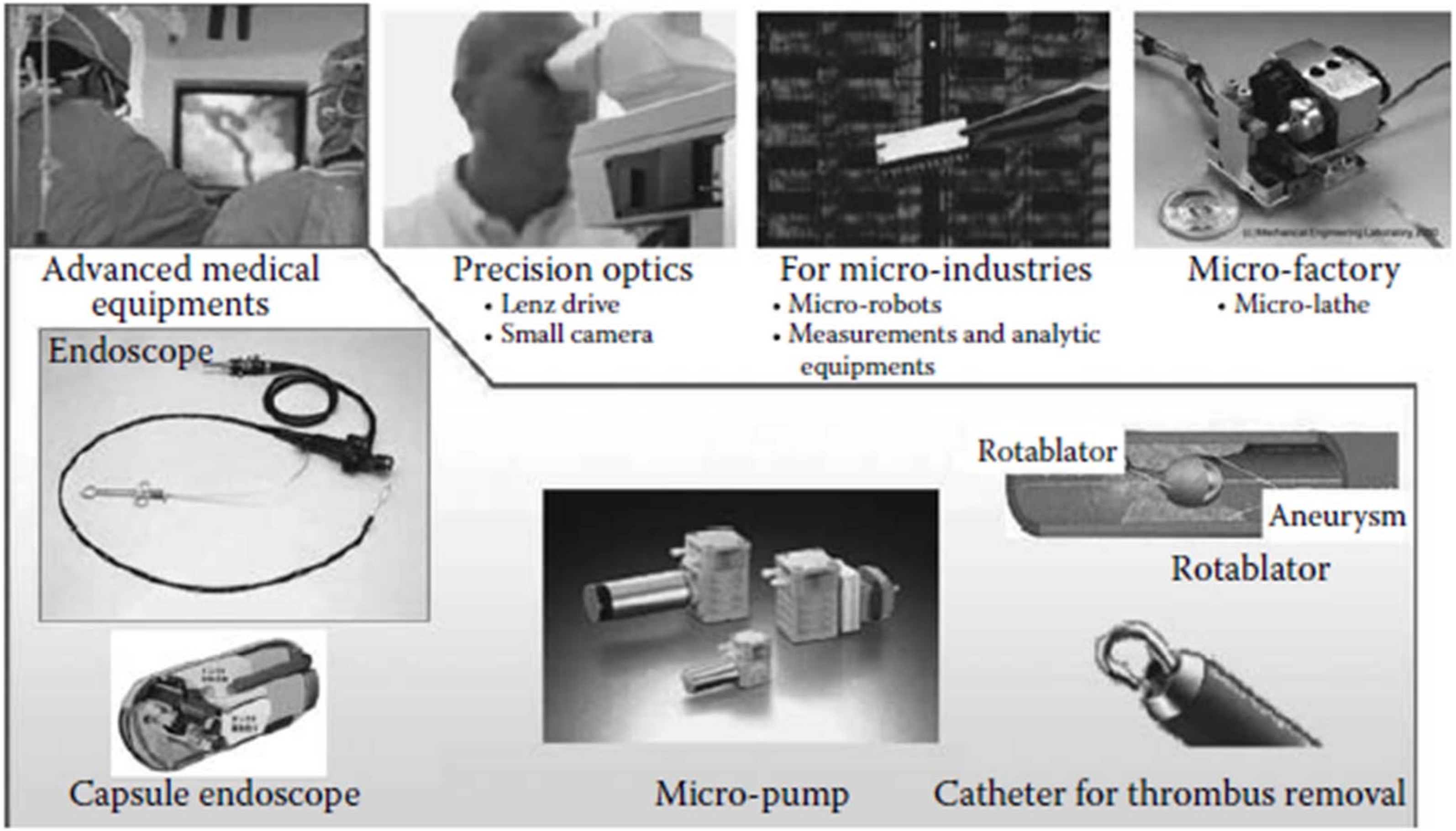
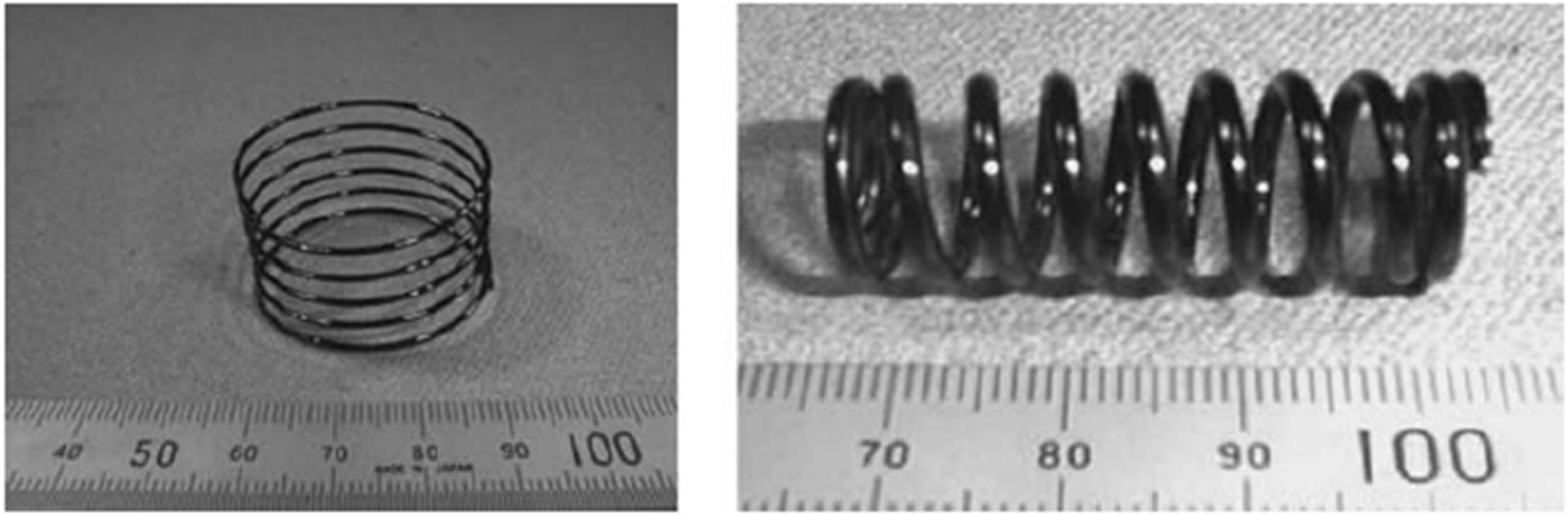



**FIGURE 10.9**
Projected application areas where micro-geared motors will find application.

## 10.3 Structural Applications: high yield (or fracture) strength, low Young's modulus, large elastic strain limit, and easy formability in the SCLR

### 10. 3. 4 Automobile Valve Springs

**: It was estimated that if the conventional valve springs made of oil-tempered and shot peened Si-Cr steel are replaced with Zr- or Ti-based BMGs, the overall weight of the engine will come down by 4 kg (about 10 lb).**




(a) (b)

**FIGURE 10.10**
Helical springs of $Zr_{55}Cu_{30}Al_{10}Ni_5$ BMG alloy produced by the coiling of wires of (a) 1 mm and (b) 2 mm in diameter. (Reprinted from Son, K. et al., *Mater. Sci. Eng. A*, 449–451, 248, 2007. With permission.)

## 10.3 Structural Applications: high yield (or fracture) strength, low Young's modulus, large elastic strain limit, and easy formability in the SCLR

### 10. 3. 5 Diaphragms for Pressure Sensors

| Requiring | material property |
|---|---|
| Miniaturized and high sensitivity | lower Young's modulus and higher strength |
| mass production a low-cost production and commercialization | Possible to net shaping |

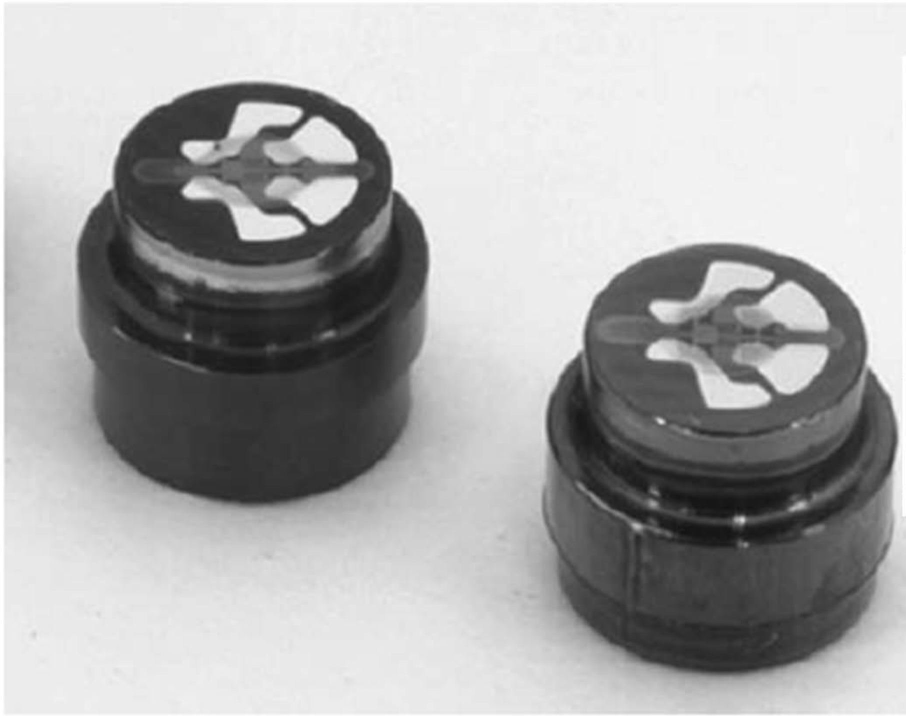


**TABLE 10.1**

Output Voltage for Pressure Sensors at a Testing Pressure of 20 MPa Using Commercial Stainless Steel (SUS 630) and Zr-Based $Zr_{55}Cu_{30}Al_{10}Ni_5$ BMG with Strain Gauges Deposited under Identical Conditions

| | Output Voltage (mV) Using | |
|---|---|---|
| Process | Stainless Steel (SUS 630) | Zr-Based $Zr_{55}Cu_{30}Al_{10}Ni_5$ BMG |
| Plasma CVD | 60 | — |
| Cat-CVD | 50 | 100 |
| Excimer laser annealing | 110 | 230 |

Sensitivity is 3.8 times greater than a conventional diaphragm

**FIGURE 10.11**
Zr-based BMG diaphragm with a strain gauge deposited at low temperatures. (Reprinted from Nishiyama, N. et al., *Mater. Sci. Eng. A*, 449–451, 79, 2007. With permission.)

## 10.3 Structural Applications: high yield (or fracture) strength, low Young's modulus, large elastic strain limit, and easy formability in the SCLR

### 10. 3. 5 Diaphragms for Pressure Sensors

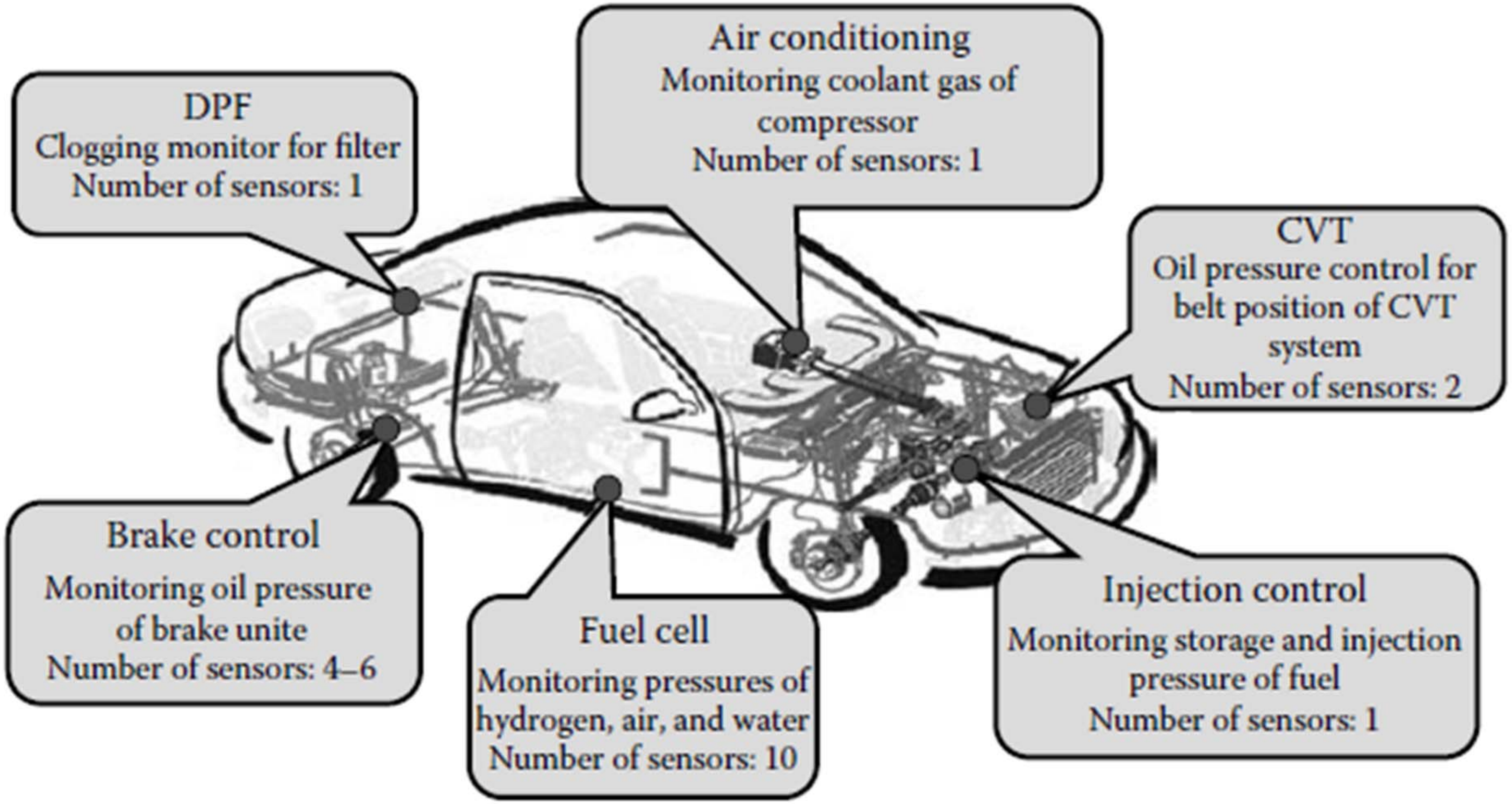



**FIGURE 10.12**
Expected market for pressure sensors to be used in different parts of an automobile.

## 10. 3. 6 Pipes for a Coriolis Mass Flow meter

**: CFM determined by the density, Young's modulus, and strength of the materials used in the measurement pipe**

**: Young's modulus ↓ → elastic deformation↑ for the same applied force**
**→ measurement of super-small liquid flow**

**high strength of BMGs** → **Pipes with thinner walls**
**high strength of BMGs** → **Resulting in larger elastic deformation**
**high strength of BMGs** → **More sensitivity**

(b)

**FIGURE 10.13**
Ti-based BMG pipes with outer diameters of (a) 6 and (b) 2 mm. (Reprinted from Nishiyama, N. et al., *J. Non-Cryst. Solids*, 353, 3615, 2007. With permission.)

## 10.3 Structural Applications: high yield (or fracture) strength, low Young's modulus, large elastic strain limit, and easy formability in the SCLR

### 10. 3. 6 Pipes for a Coriolis Mass Flow meter

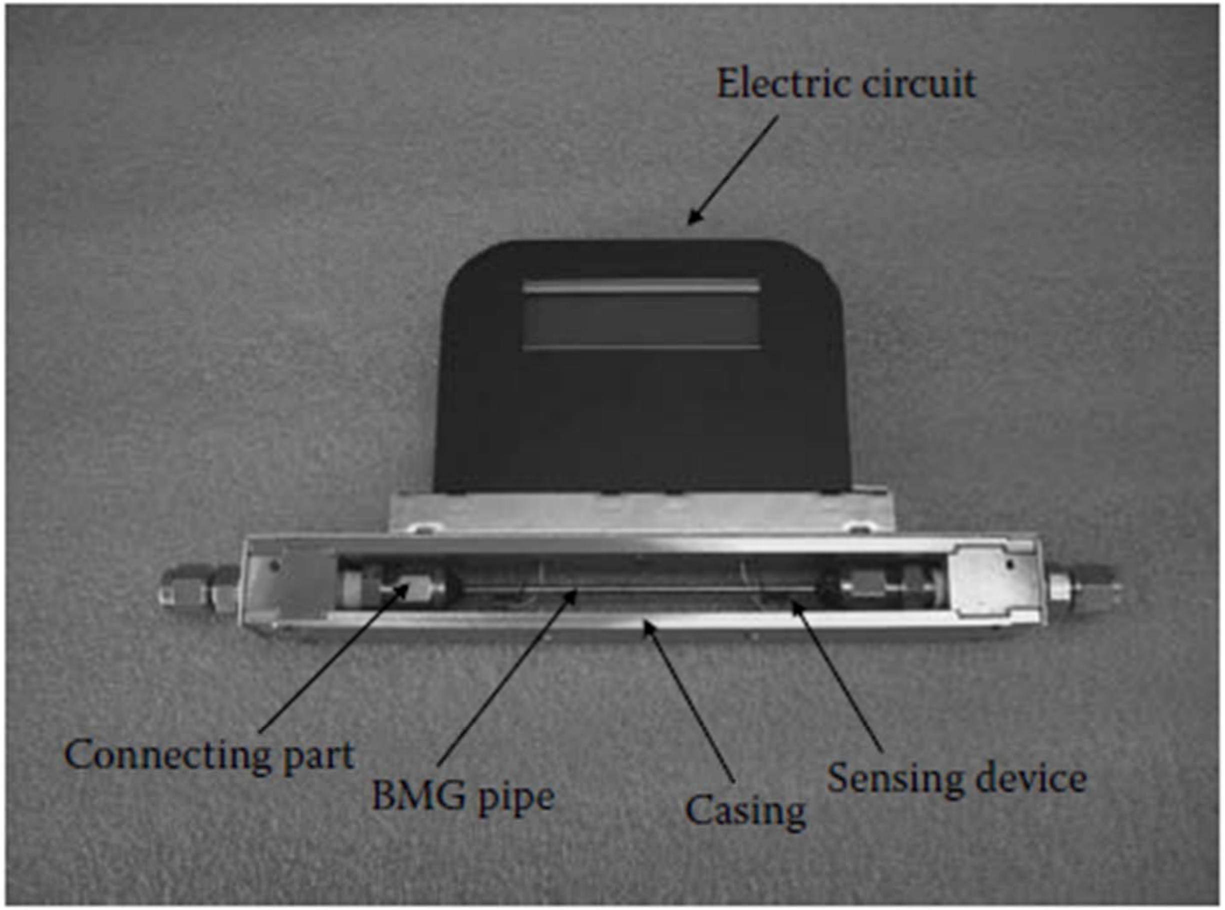



**FIGURE 10.14**
CMF developed using the Ti-based BMG pipes.

## 10.3 Structural Applications: high yield (or fracture) strength, low Young's modulus, large elastic strain limit, and easy formability in the SCLR

### 10. 3. 6 Pipes for a Coriolis Mass Flow meter

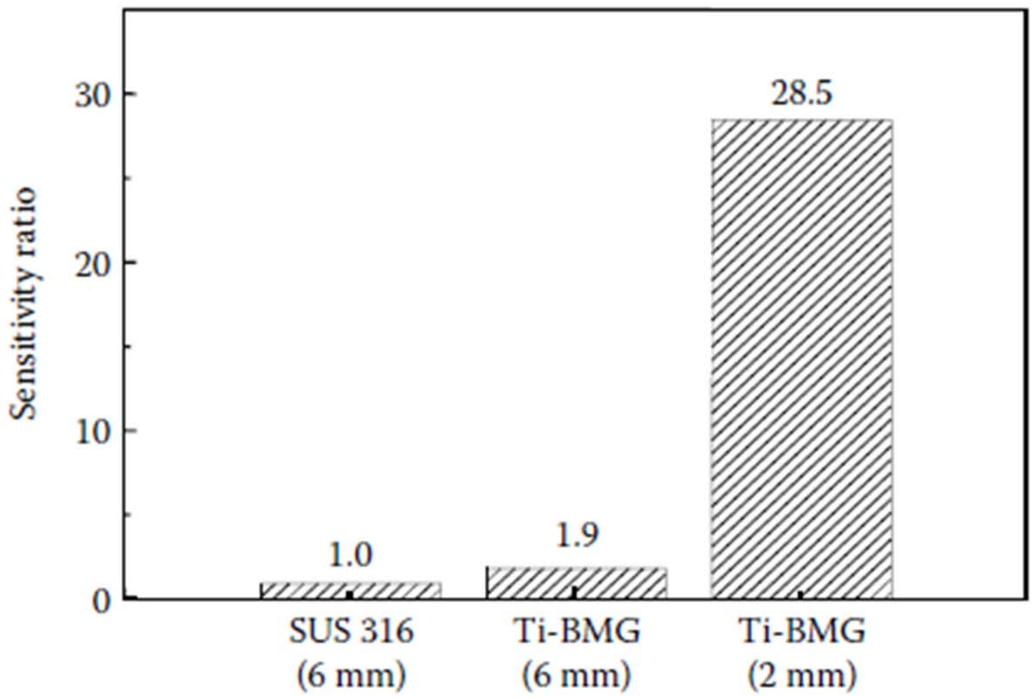


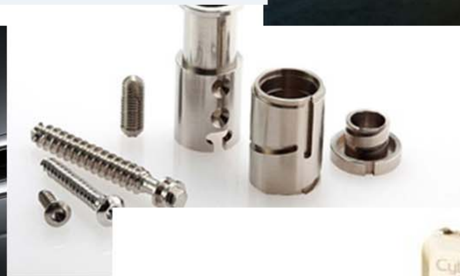

**FIGURE 10.15**
Sensitivity obtained by the CMF using the Ti-based BMG with diameters of 2 and 6 mm. Their sensitivity is compared with that of commercial stainless steel (SUS 316L) pipe with a diameter of 6 mm. (Reprinted from Ma, C.L. et al., *Mater. Sci. Eng. A*, 407, 201, 2005. With permission.)

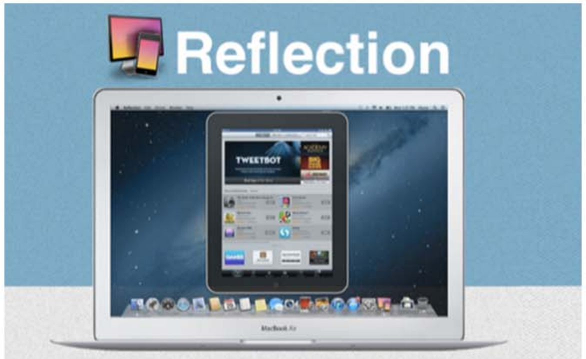
## 10. 3. 7 Optical Mirror Devices : Optical coating

- Ideal isotropic material have no grain boundary (Polymer and oxide glass)
- Have Metallic luster - Reflective parts of optical device, Optical Mirror

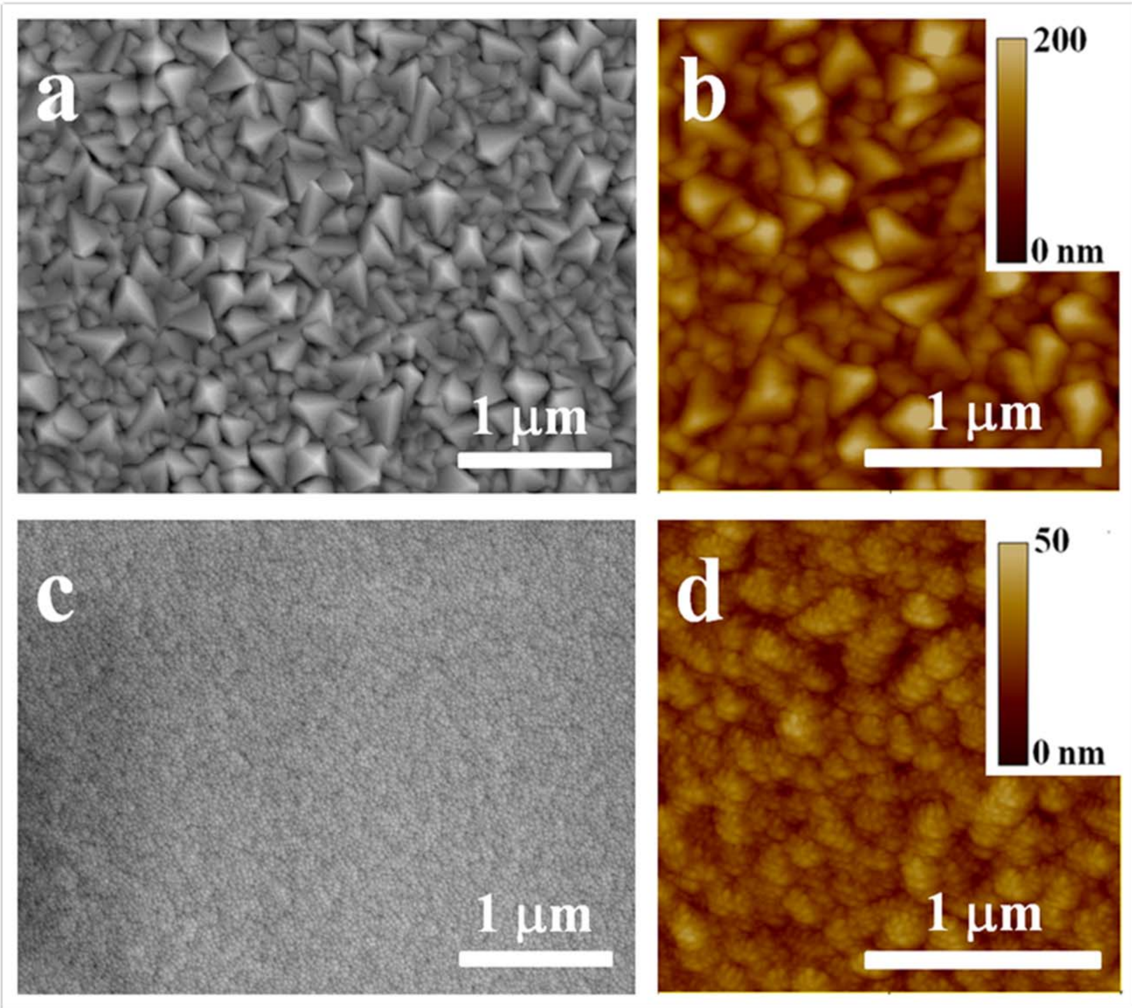


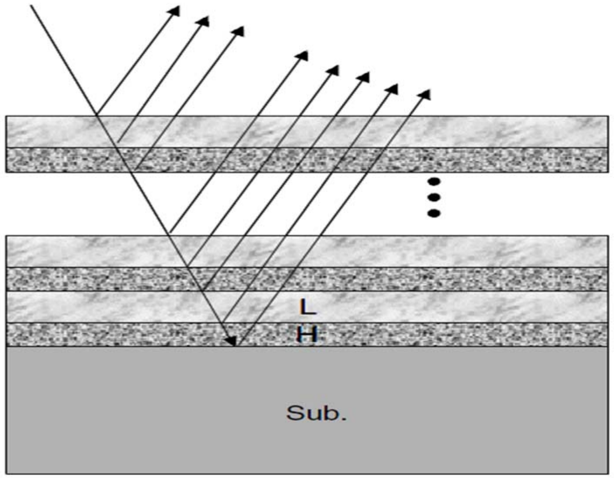
- **LED display**
- **Solar cell, light collector**
- **3C enclosure**
- **Lighting, high refection**
- **Tool coating**

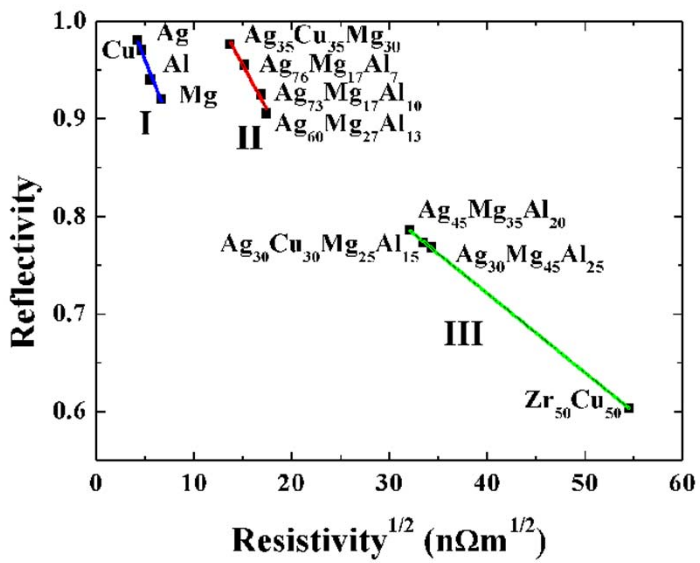




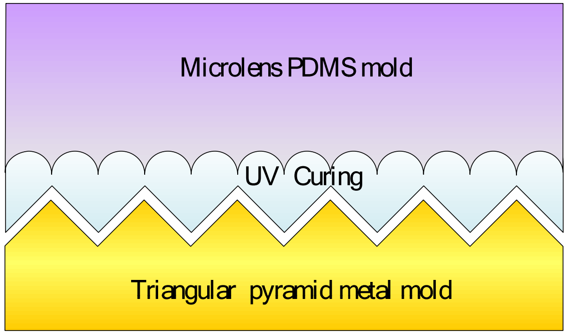

# High light reflection TFMG coating

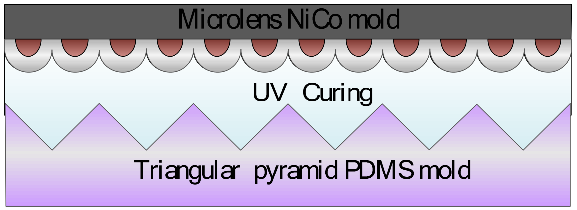


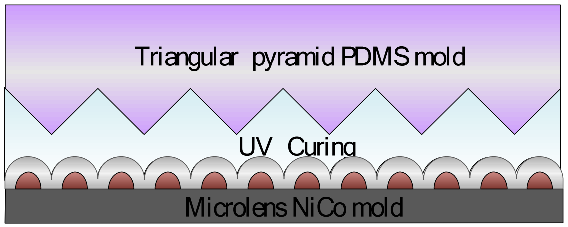



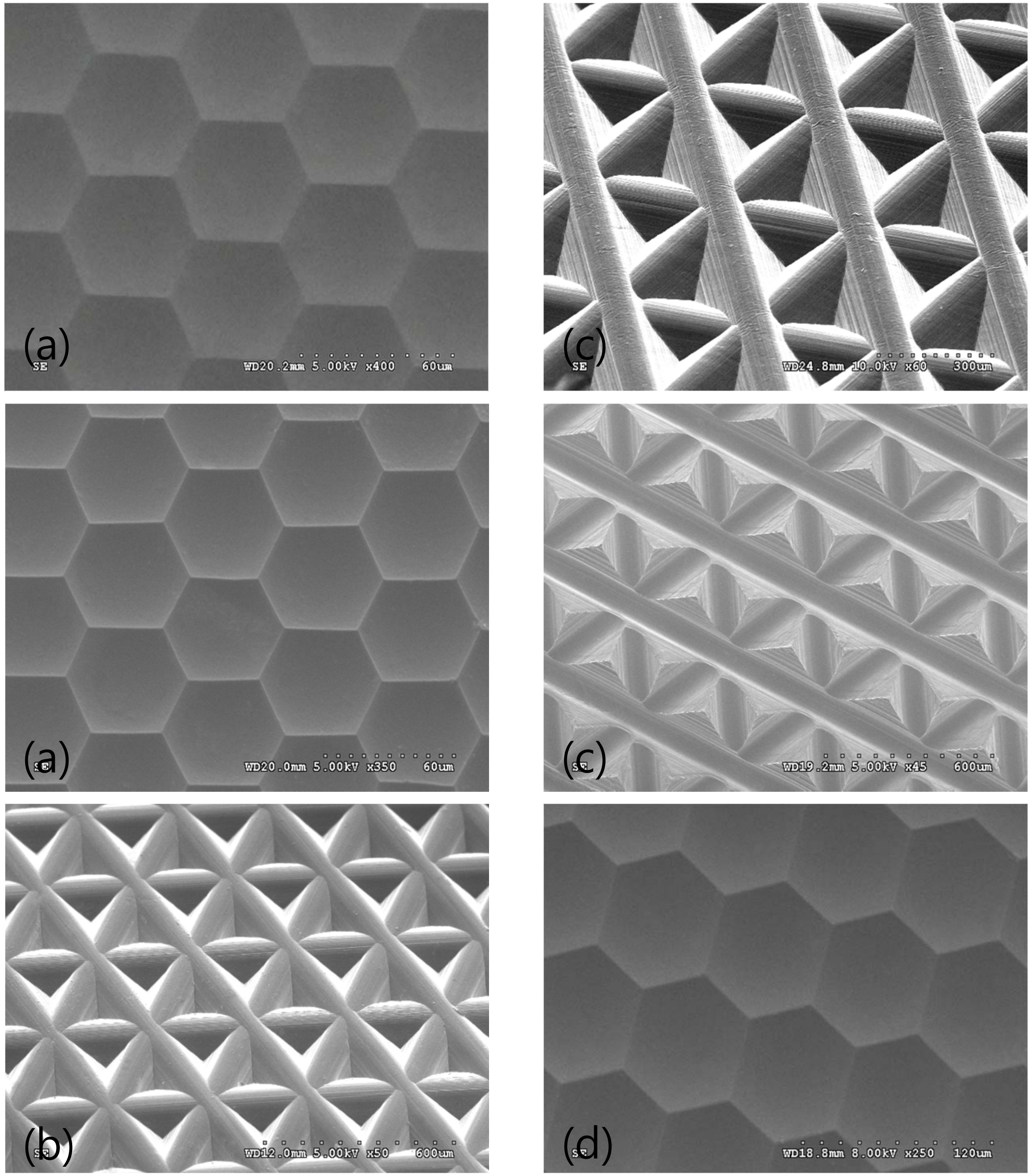



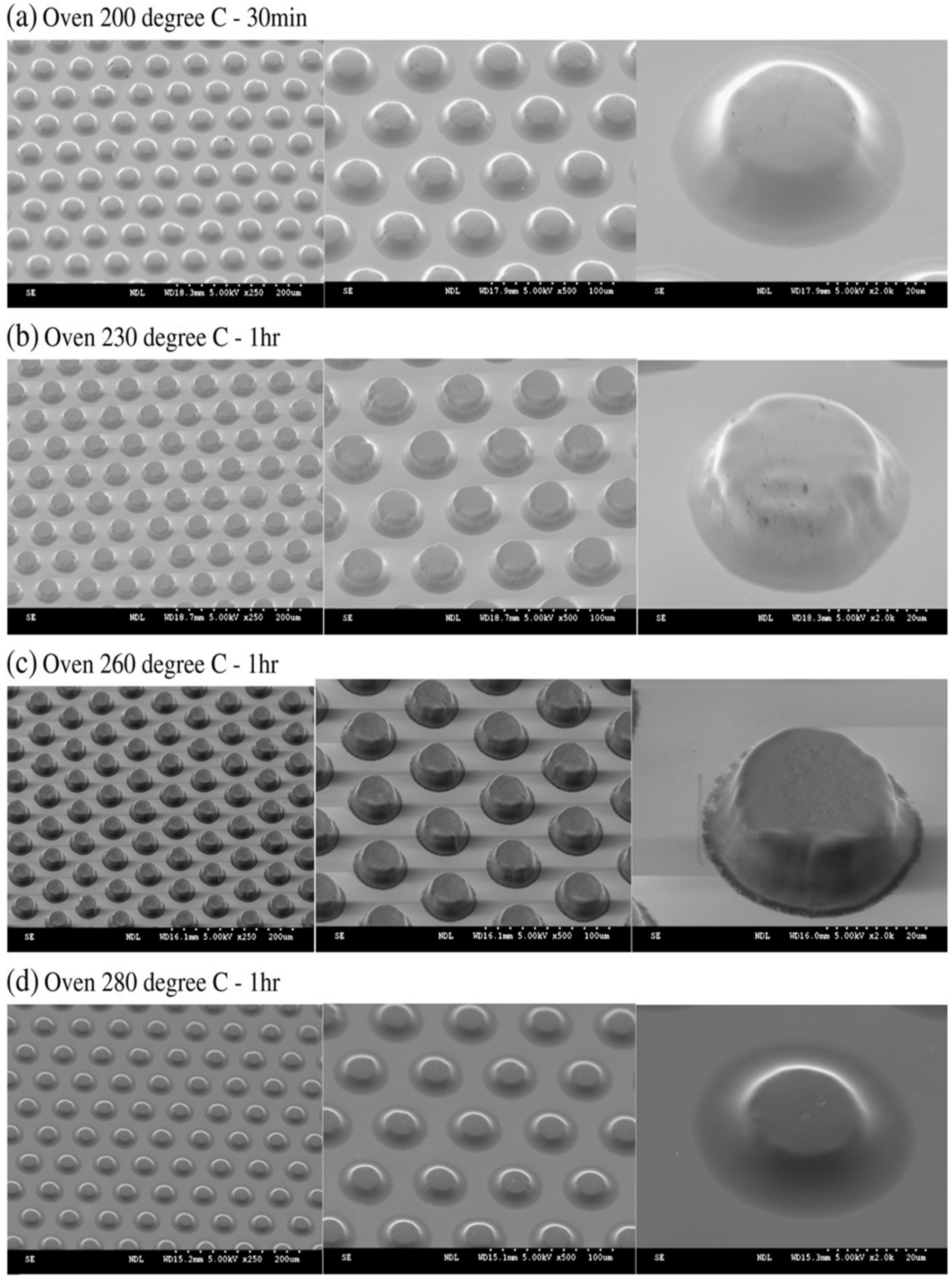
# Optical lens for light con/diverging

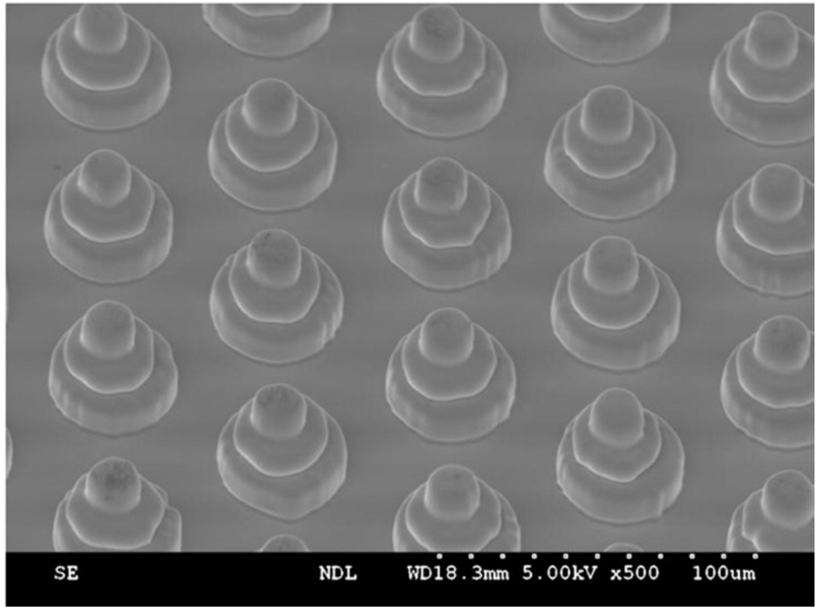


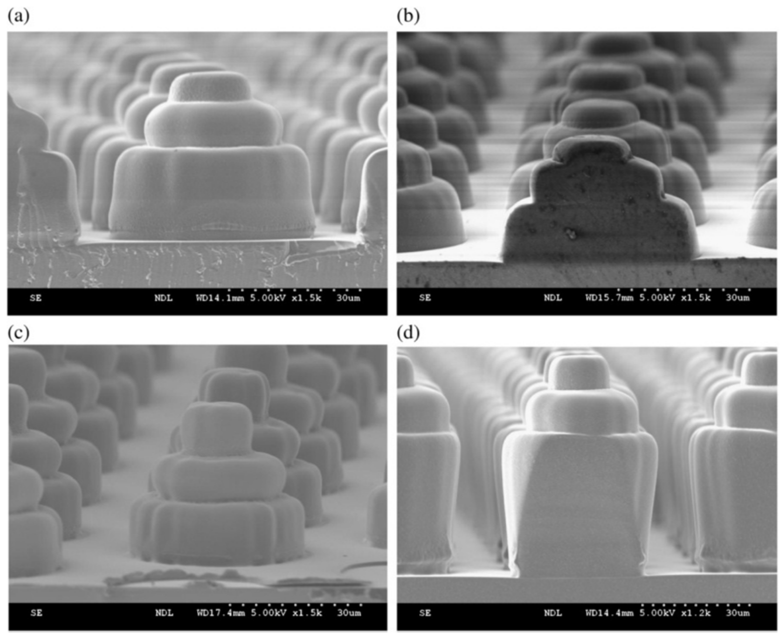



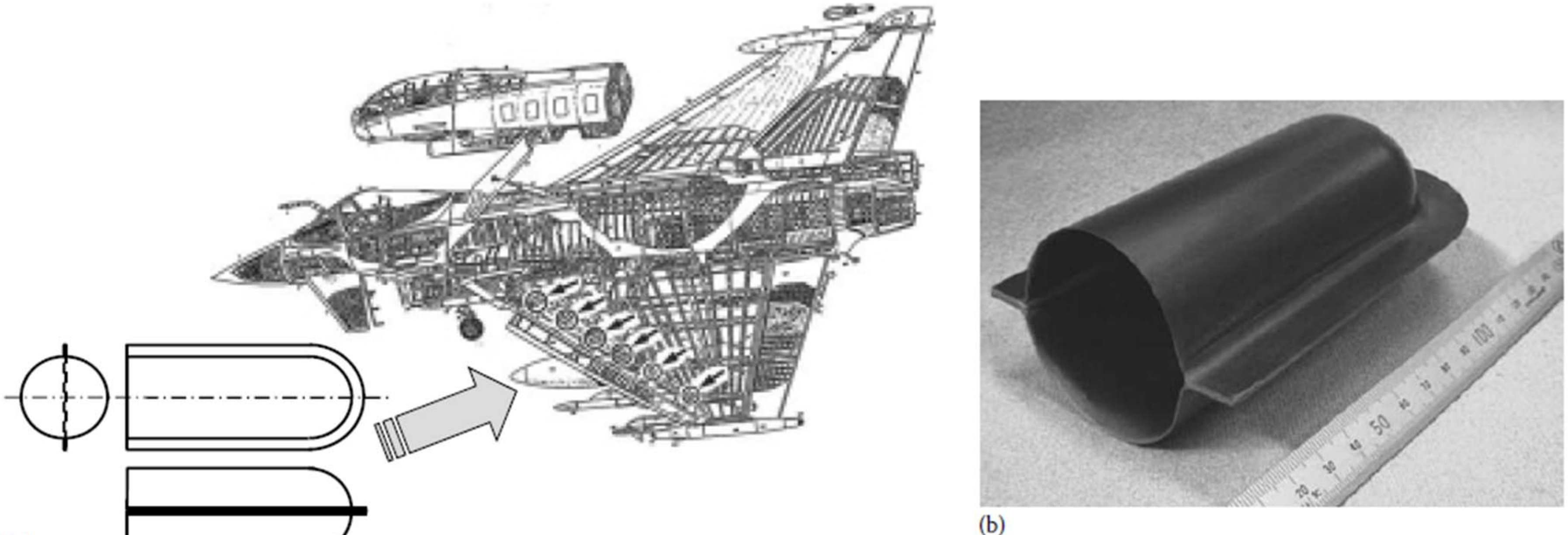

(a) Oven 200 degree C - 30min
(b) Oven 230 degree C - 1hr
(c) Oven 260 degree C - 1hr
(d) Oven 280 degree C - 1hr


SE
NDL
WD18.3mm 5.00kV x500 100um


(a)
(b)
(c)
(d)

## 10. 3. 8 Structural Parts for Aircraft: slat-track over surrounding a set of guide rails at the front of the wings_high formability and corrosion resistance (exposure to ambient atmosphere moistened by rain or seawater)

| | | | | |
|---|---|---|---|---|
| high strength and<br>low Young's modulus | → | spring wires to be slimmer<br>springs themselves to be shorter | → | possible to improve<br>fuel consumption |
| engines may be lightened by<br>miniaturizing cylinder heads | | increasing the revolution limit of<br>engines by reducing their inertial mass | | |



(a) (b)

**FIGURE 10.16**
(a) Some areas (see small arrows) of an aircraft in which BMGs could be exploited. (b) Slat track cover fabricated by joining two identical parts obtained by viscous flow forming of a $Zr_{55}Cu_{30}Al_{10}Ni_{5}$ BMG plate.

## 10.3 Structural Applications: high yield (or fracture) strength, low Young's modulus, large elastic strain limit, and easy formability in the SCLR

### 10. 3. 9 Shot Peeing Balls: high strength, good ductility, high endurance against cyclic bombadment load, and high corrosion resistance

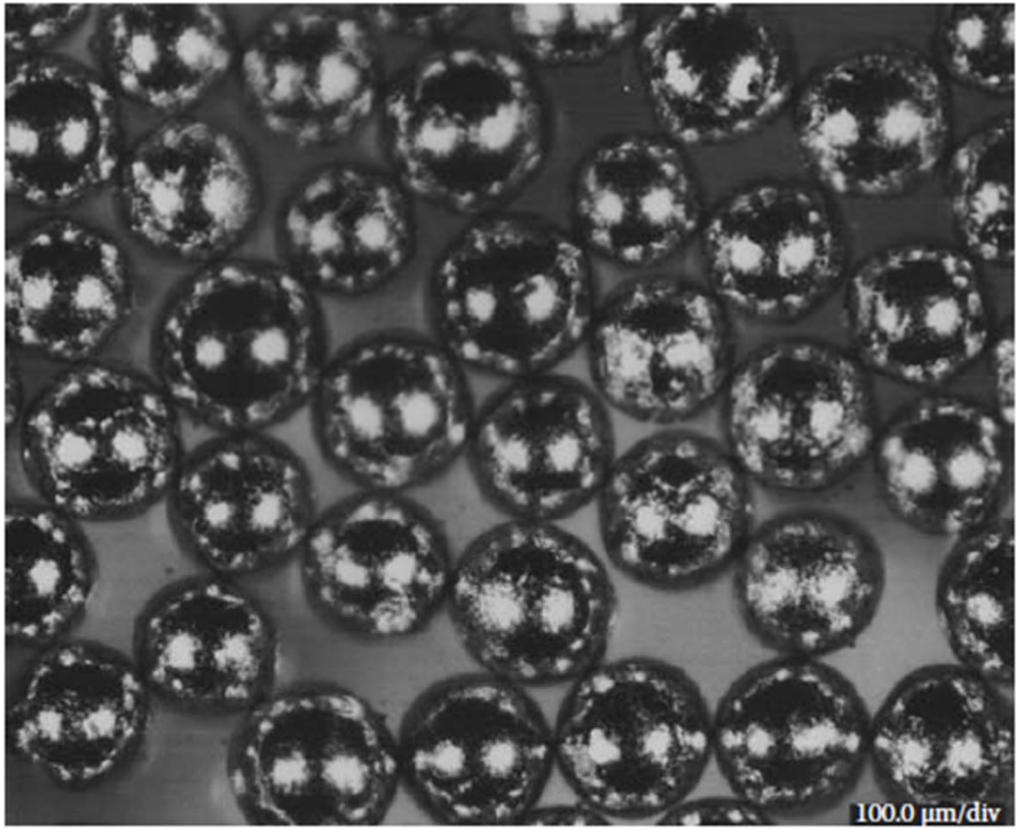



**FIGURE 10.17**
Size and surface finish of commercial $Fe_{44}Co_5Ni_{24}Mo_2B_{17}Si_8$ glassy alloy shots of 80 μm diameter produced by water atomization. (Reprinted from Inoue, A. et al., *Mater. Trans.*, 44, 2391, 2003. With permission.)

**10.3 Structural Applications: high yield (or fracture) strength, low Young's modulus, large elastic strain limit, and easy formability in the SCLR**

**10. 3. 9 Shot Peeing Balls: high strength, good ductility, high endurance against cyclic bombadment load, and high corrosion resistance**

**TABLE 10.2**

Mechanical Properties of the Fe-Based BMG and Two Other Cast Steel Shots Used in the Investigation

| Property | Fe-Based BMG $Fe_{44}Co_5Ni_{24}Mo_2B_{17}Si_8$ | High-Speed Steel Fe–1.15C–4Cr–5Mo–2.5V–6.5W–8Co (wt.%) | Cast Steel Fe–1C–0.9Si–0.7Mn (wt.%) |
|---|---|---|---|
| Young's modulus (GPa) | 80 | 215 | 210 |
| Fracture strength (MPa) | 3200 | 2100 | 1100 |
| Vickers hardness | 930 | 815 | 810 |
| Density (g $cm^{-3}$) | 7.4 | 7.7 | 7.55 |

**TABLE 10.3**

Effects of Bombardment with Fe-Based BMG Alloy Shots and Cast Steel Shots for 40 s on Two Commercial Steel Sheets

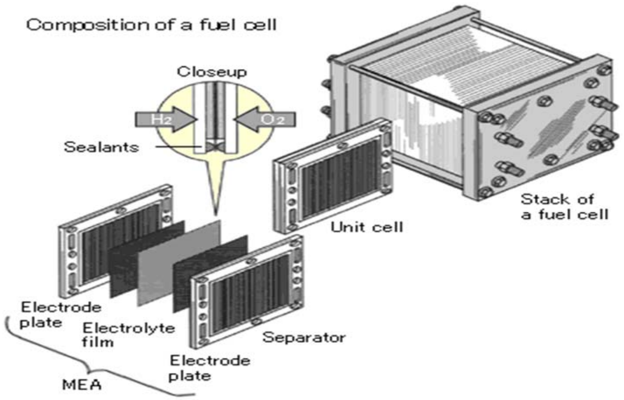
| Attribute | Fe-Based BMG | Cast Steel |
|---|---|---|
| Crater size (μm) | 20 | 7 |
| Average crater height (μm) | 15 | 5 |
| Depth of affected region (μm) | 100 | 45 |
| Surface Vickers hardness | 510 | 480 |
| Maximum compressive stress on the surface (MPa) | 1600 | 1470 |
| Depth (μm) of the region at which the compressive stress was 500 MPa | 27 | 18 |
| Endurance time needed to final rupture of the peening shots (h) | 28 | — |

# Chemical Applications

Very hard, high strength | High corrosion resistance | Viscous deformability → Chemical Applications

## 1) Fuel cell separator

Lower interfacial contact resistances
higher corrosion resistance
high strength

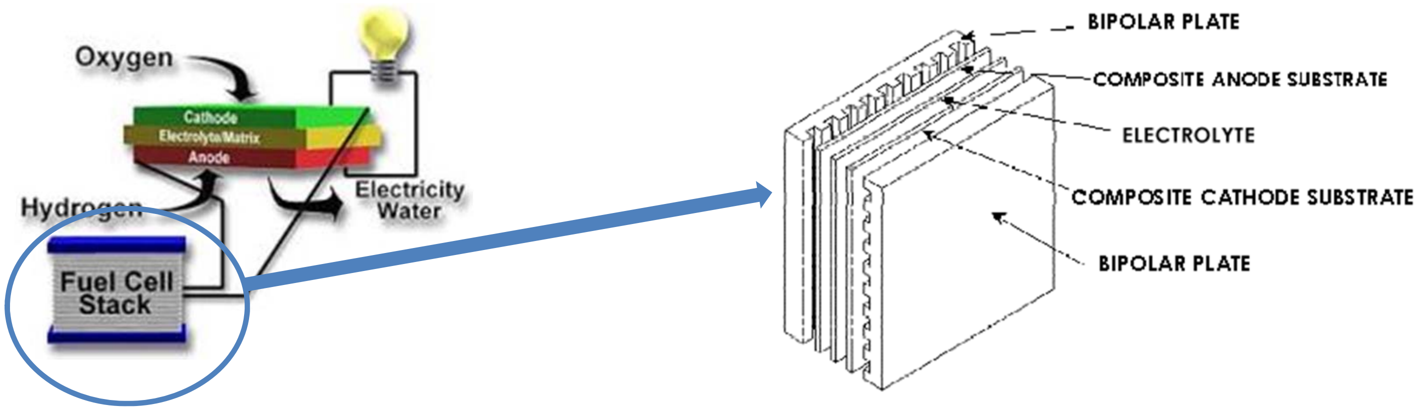



## 2) hydrogen-permeable membrane

Defect-free film growth
High strength and ductility
Corrosion resistance
Good H2 solubility

→

Withstanding repeated cycling, high temperature, high pressure
Compositional flexibility and homogeneity
High catalytic surface activities for H2 interactions



## 10. 4 Chemical Applications: a) Fuel cell separators_high strength, superior corrosion resistance, and excellent formability in SCLR

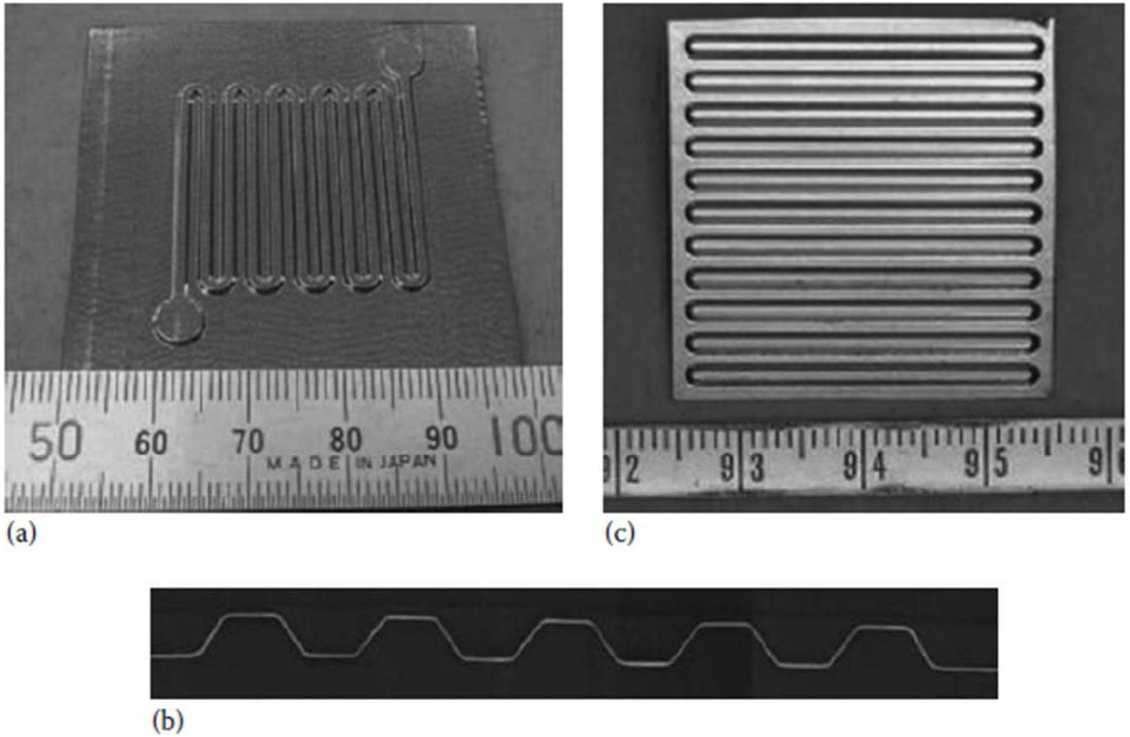



**FIGURE 10.18**
(a) Prototype fuel cell separator using a Ni-based BMG sheet, (b) cross-sectional morphology of the groove-formed specimen, and (c) appearance of the BMG separator after power generation for 350 h. (Reprinted from Inoue, A. et al., *Mater. Trans.*, 46, 1706, 2005. With permission.)

## b) Hydrogen separating membrane:

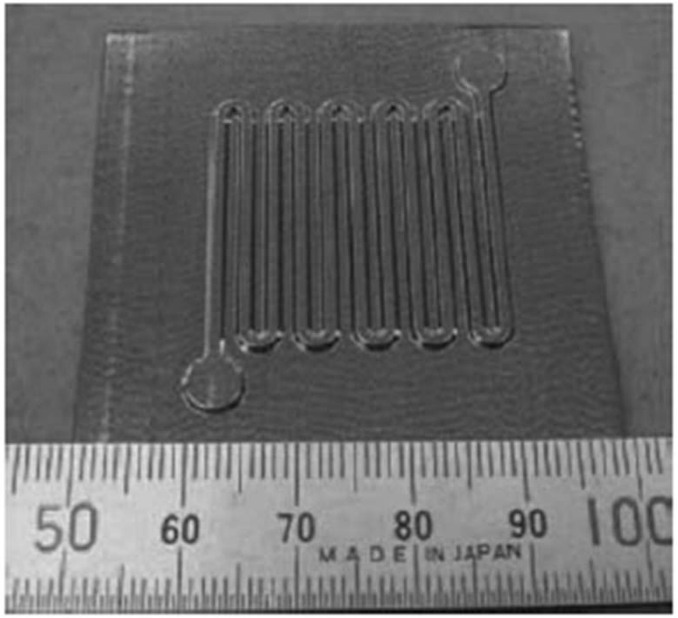
Good hydrogen permeability + melt-spun
→ Possible to mass-production technique by using amorphous hydrogen permeable membranes

Fig, Photograph of the melt-spun Ni-Nb-Zr-Co amorphous alloy of 100mm in width.

**10. 4 Chemical Applications: Fuel cell separators_high strength, superior corrosion resistance, and excellent formability in SCLR**

BMG

- High strength
- Superior corrosion resistance
- Viscous deformability



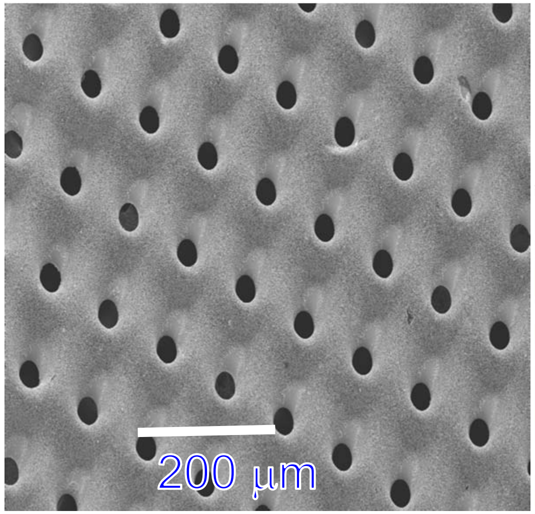

Stainless steel: drastic drop of output voltage

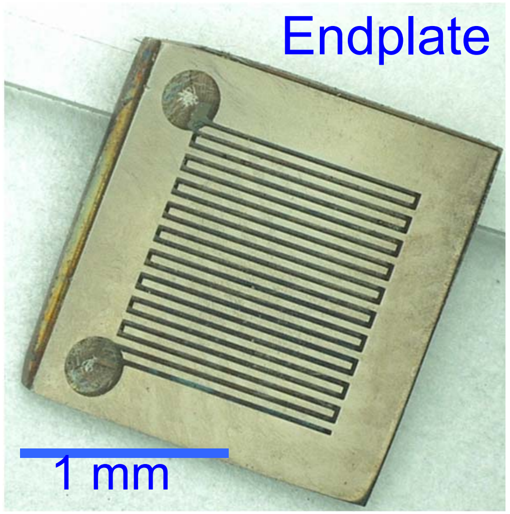
↓

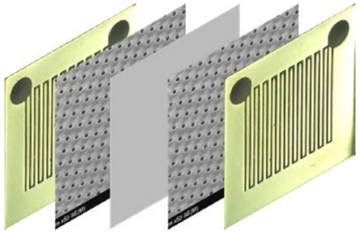
BMG: System smaller
lighter
low product cost
High voltage output
Slow degradation

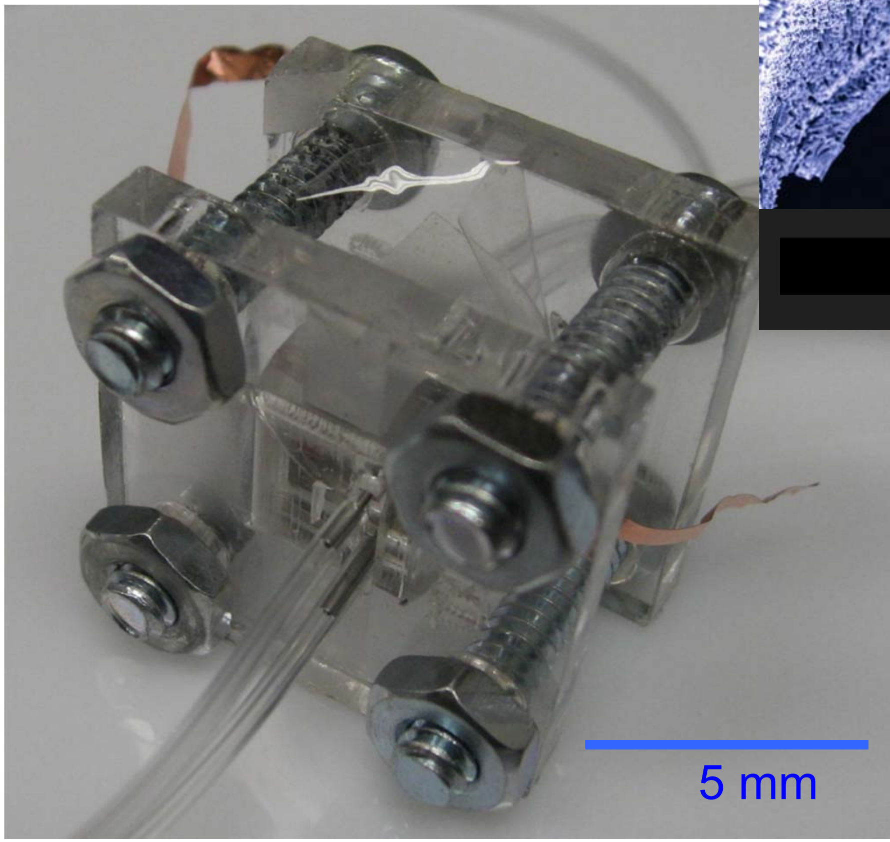
# Metallic Glass Fuel Cell

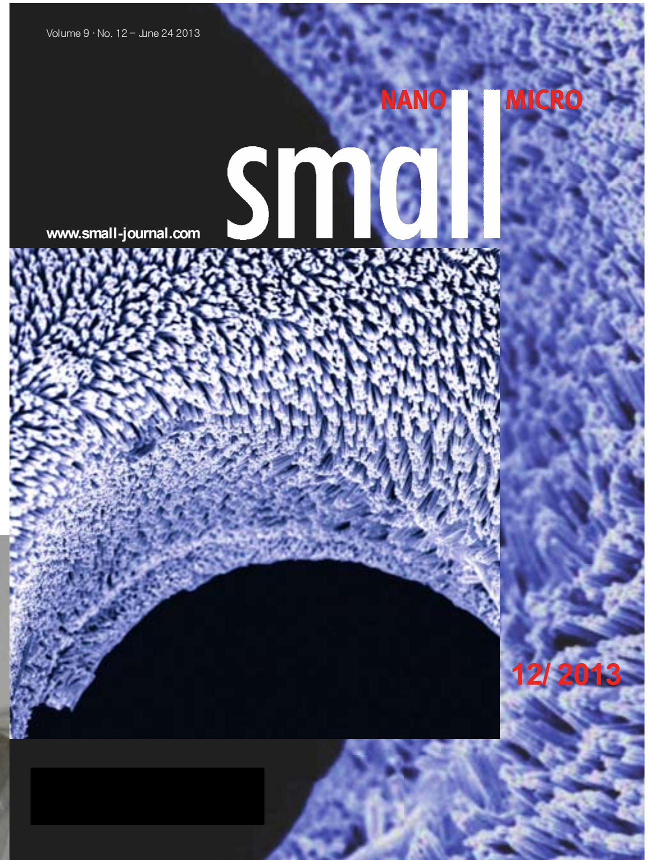
Electrode, Catalyst



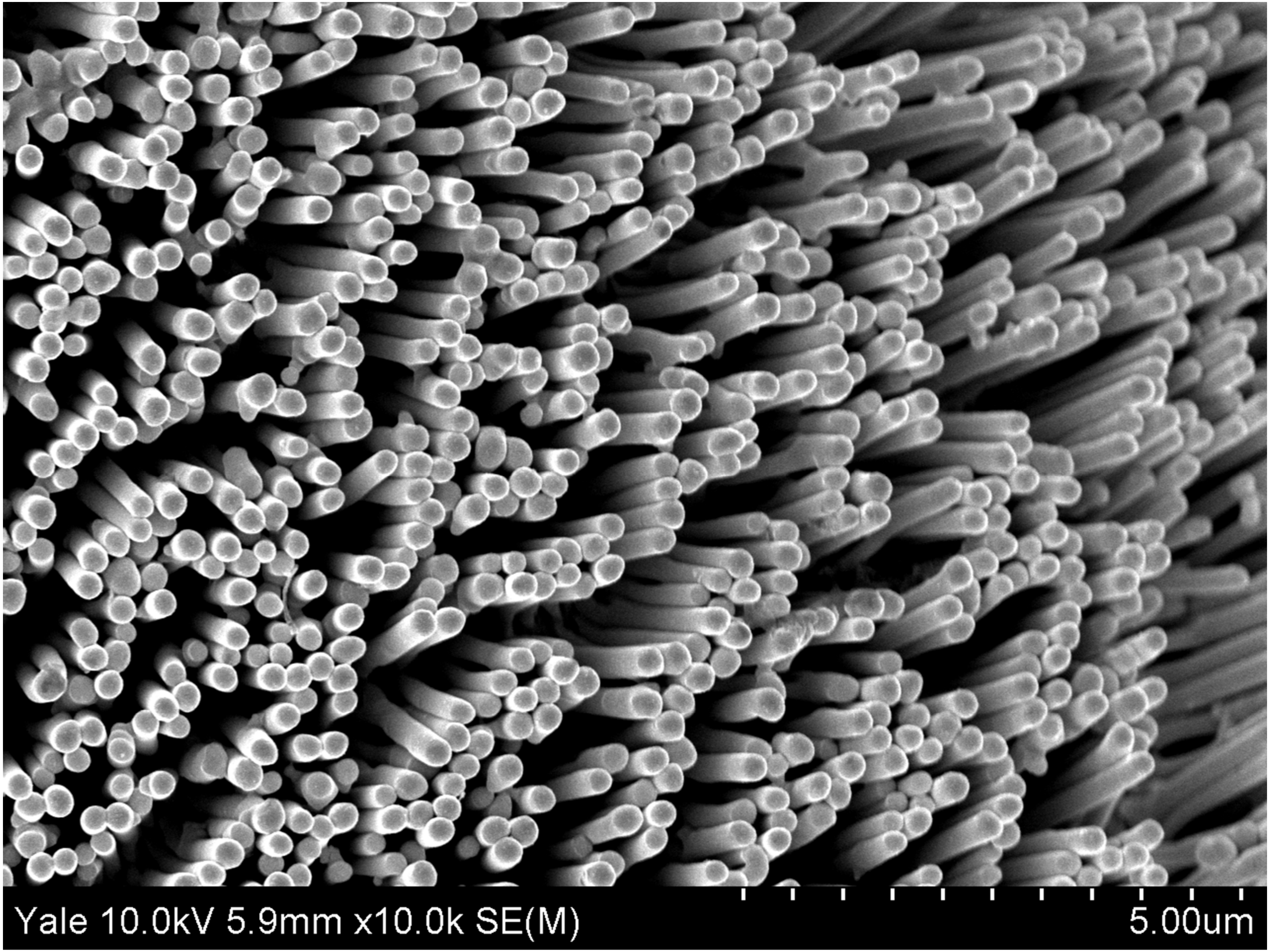






**R. C. Sekol, M. Carmo, G. Kumar, J. Schroers, and A. D. Taylor, Small 9, 2081 (2013)**


Yale 10.0kV 5.9mm x10.0k SE(M)
5.00um

## 10. 5. Magnetic Applications:

**BMG**

High permeability

Low coercivity

* $Fe_{73}Ga_4P_{11}C_5B_4Si_3$ BMG plates
( 30 mm long, 20 mm wide and 1 mm thick )

* Fe-Ga-Al-P-C BMG : Low core loss
610 kW/m$^3$ at 100kHz (High freq.)

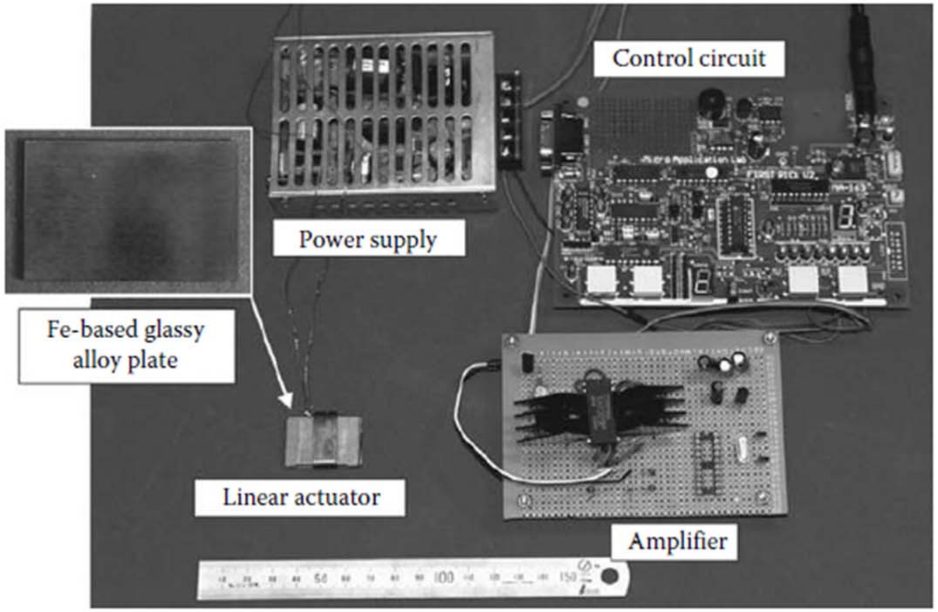
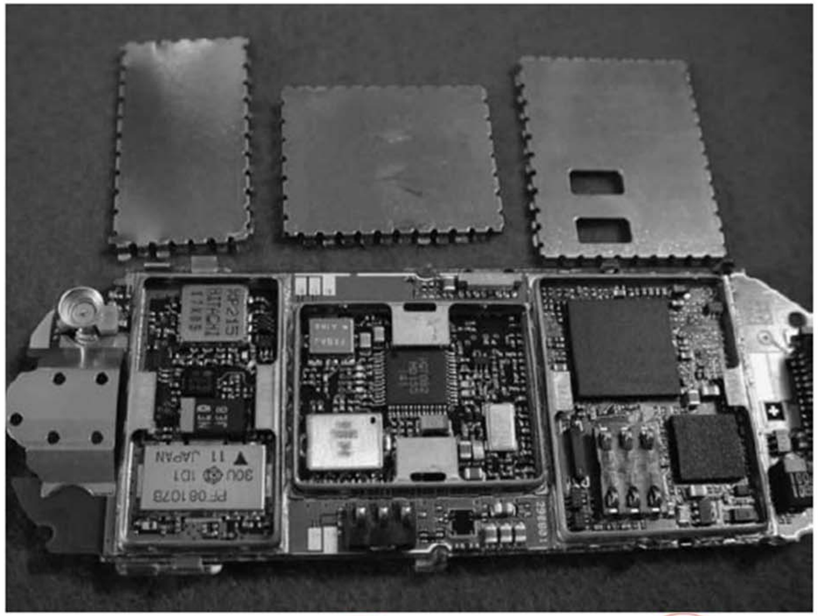
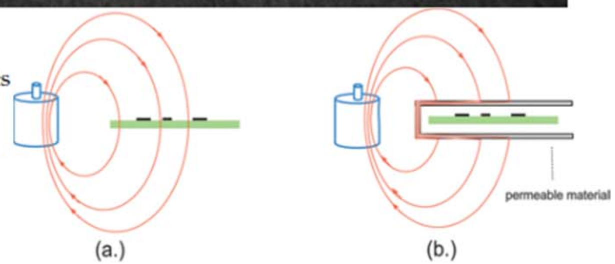



FIGURE 10.19
Magnetic yoke made of an $Fe_{73}Ga_4P_{11}C_5B_4Si_3$ BMG plate for a prototype linear actuator.



IGURE 10.20
MG magnetic shielding sheets



# Magnetic Applications

Very soft magnetic material | High electrical resistivity → Magnetic Applications

## 1) Sensor

- Sensitivity: ferrite < amorphous alloy < superconductor
- Operating temp.: amorphous alloy > ferrite , superconductor
- Compactness: amorphous alloy , ferrite > superconductor
- Reliability: amorphous alloy, ferrite>>ferrite>superconductor

| Shape | Dimension | Fabrication | Applications | compositions |
|---|---|---|---|---|
| Ribbon | 15~30 $\mu$mt<br>0.1~200mm W | Melt spinning<br>(single roll technique) | Magnetic hand<br>Cartridge<br>Torque sensor<br>Data tablet<br>Magnetic-field sensor<br>Current sensor | CoFeSiB<br>FeSiB |
| Wire | 90~160$\mu$m φ | In-rotating water<br>Melt quenching | Magnetic-field sensor<br>Current sensor<br>Security sensor<br>Rotation sensor<br>Displacement sensor | CoFeMSiB |
| Thin film | 500~400Å t | Sputtering | Pressure sensor<br>Magnetic head | FeB<br>CoFeMSiB |
| Composite | 10~30$\mu$m t | Laser-quenching | Torque sensor | FeBsi |

# Magnetic Applications

Very soft magnetic material | High electrical resistivity → Magnetic Applications

## 1) Sensor

- Sensitivity: ferrite < amorphous alloy < superconductor
- Operating temp.: amorphous alloy > ferrite , superconductor
- Compactness: amorphous alloy , ferrite > superconductor
- Reliability: amorphous alloy, ferrite >> ferrite > superconductor

| | | |
|---|---|---|
| **Zero-magnetostrictive alloy** | Magnetic head sensor | |
| | Data tablet(Matteucci effect) | |
| | Magnetic cartridge | |
| | Magnetic-field sensor | Magnetometer , Current sensor, Direction sensor<br>Displacement sensor, Card reader, Security sensor<br>Motor-flux sensor, Eddy-current sensor →proximity sensor |
| **High-magnetostrictive alloy** | Stress-magnetic effect | Torque sensor, pressure sensor, shock sensor |
| | Magnetoelastic wave propagation effect | Data tablet, frost sensor<br>Distance sensor, touch sensor |
| | Large Barkhausen effect | Security sensor, rotation speed sensor, distance sensor |
| | Matteucci effect | degitizer |

**10. 6 Miscellaneous Applications: The high strength and wear resistance of BMGs along with their biocompatiability, smooth surface finish, and aesthetic appearance determine the type of material to be used and the appropriate applications.**

## 10. 6. 1 Jewelry

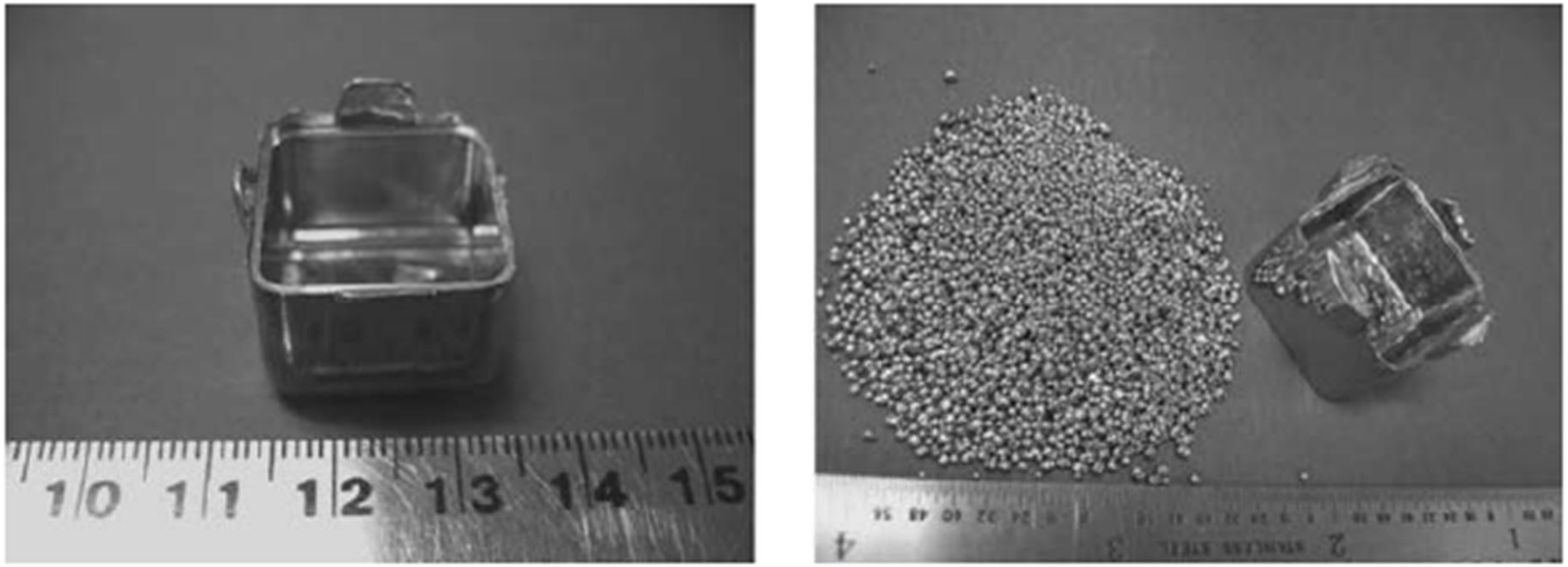
**TABLE 10.4**

Selected Properties of Au-Based and Pt-Based BMGs and Their Approximate Crystalline Counterparts

| Material | Density ($g\ cm^{-3}$) | Yield Strength (MPa) | Elastic Elongation (%) | Hardness | $S = \Delta T_x/(T_\ell - T_g)$ |
|---|---|---|---|---|---|
| $Au_{49}Ag_{5.5}Pd_{2.3}Cu_{26.9}Si_{16.3}$ (LM18kAu) | 11 | 1200 | 1.5 | 360 | 0.24 |
| Au–Ag–Cu (18k) | 15.4 | 350 | <0.5 | 150 | — |
| $Pt_{57.5}Cu_{14.7}Ni_{5.3}P_{22.5}$ (LM850Plat) | 15.3 | 1400 | 1.3 | 402 | 0.34 |
| Pt/Ir850/150 | 21.5 | 420 | <0.5 | 160 | — |

**10. 6 Miscellaneous Applications: The high strength and wear resistance of BMGs along with their biocompatiability, smooth surface finish, and aesthetic appearance determine the type of material to be used and the appropriate applications.**

## 10. 6. 1 Jewelry




(a) (b)

**FIGURE 10.21**

Net shape formability using Au-based and Pt-based BMG alloys. (a) The Au-based alloy was formed at 150°C for 200s under a pressure of 100 MPa. (b) The Pt-based alloy formed at 270°C for 100s under a pressure of 28 MPa using pellets as feedstock material. (Reprinted from Schroers, J. et al., *Mater. Sci. Eng. A*, 449–451, 235, 2007. With permission.)

**10. 6 Miscellaneous Applications: The high strength and wear resistance of BMGs along with their biocompatiability, smooth surface finish, and aesthetic appearance determine the type of material to be used and the appropriate applications.**

## 10. 6. 2. Biomedical Applications

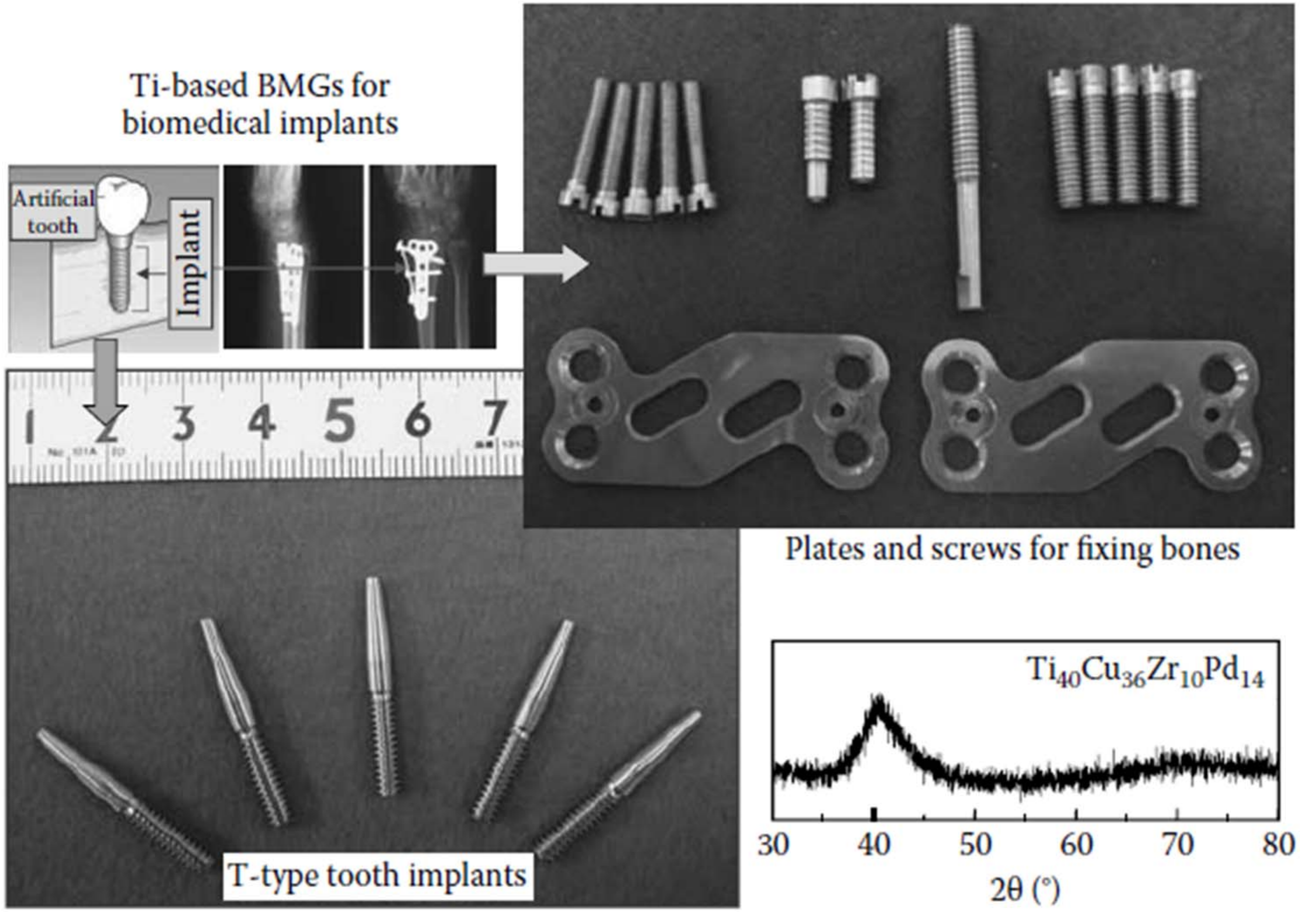



**FIGURE 10.22**

$Ti_{40}Zr_{10}Cu_{36}Pd_{14}$ BMG alloy implants for T-type teeth and plates and screws for fixing bones.

**10. 6 Miscellaneous Applications: The high strength and wear resistance of BMGs along with their biocompatiability, smooth surface finish, and aesthetic appearance determine the type of material to be used and the appropriate applications.**

### 10. 6. 2. Biomedical Applications

# Enveloped Cast Technique for BMG Parts (hip joint)

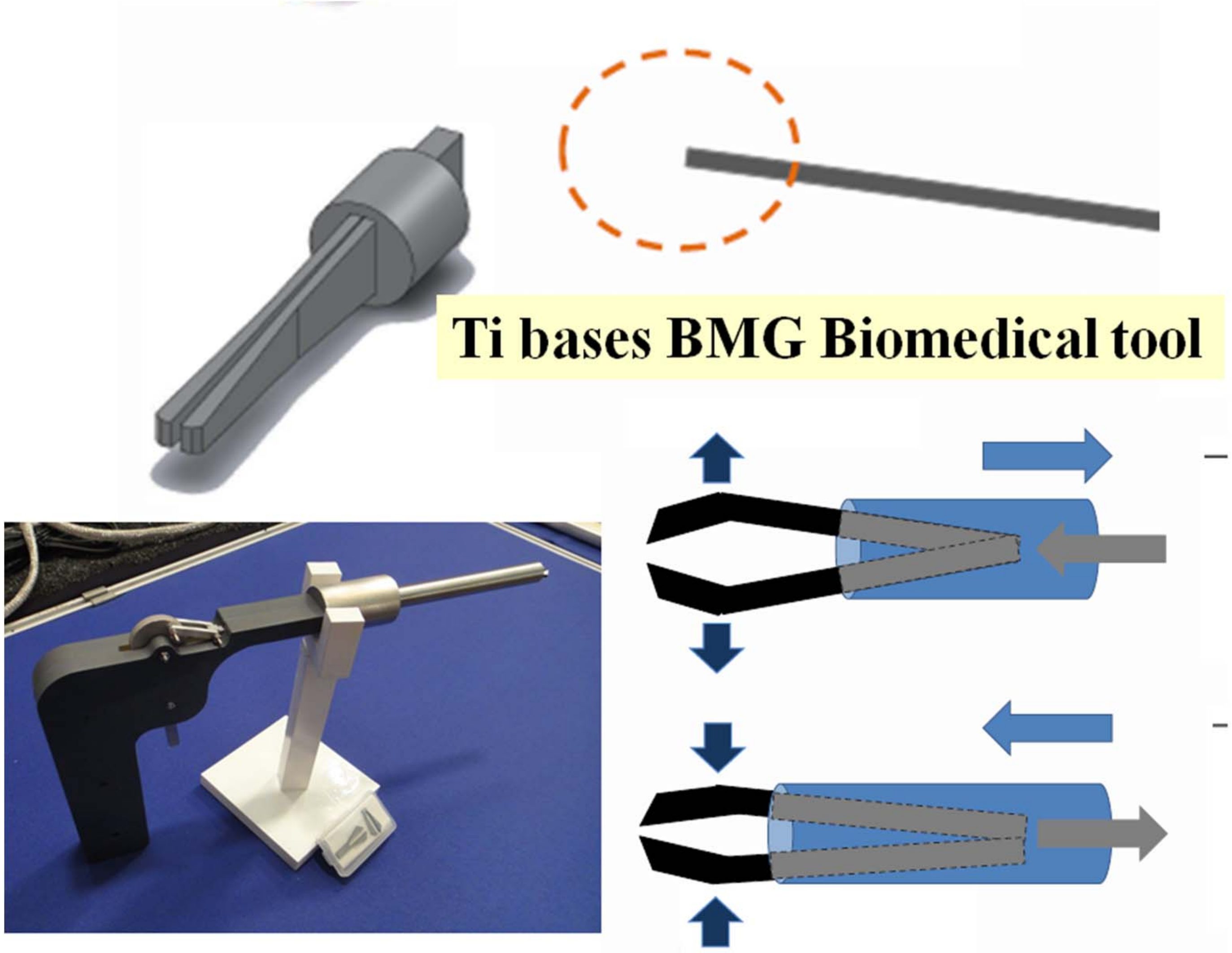
**For biomedical use**


**Stainless Steel (core)**

**Ball head was covered by BMG with enveloped casting (thickness 3 mm)**

10. 6 Miscellaneous Applications: The high strength and wear resistance of BMGs along with their biocompatiability, smooth surface finish, and aesthetic appearance determine the type of material to be used and the appropriate applications.

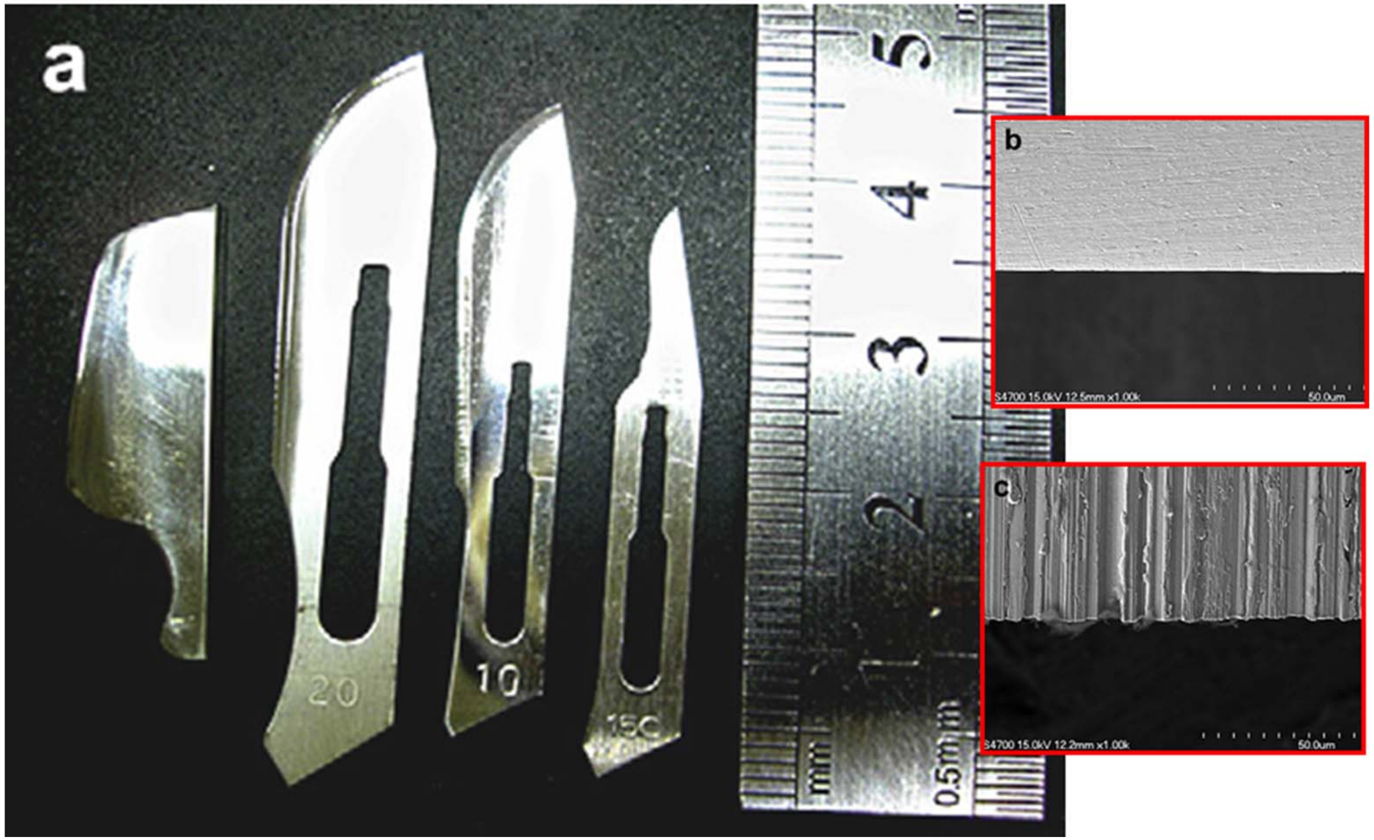
## 10. 6. 2. Biomedical Applications



**10. 6 Miscellaneous Applications: The high strength and wear resistance of BMGs along with their biocompatiability, smooth surface finish, and aesthetic appearance determine the type of material to be used and the appropriate applications.**

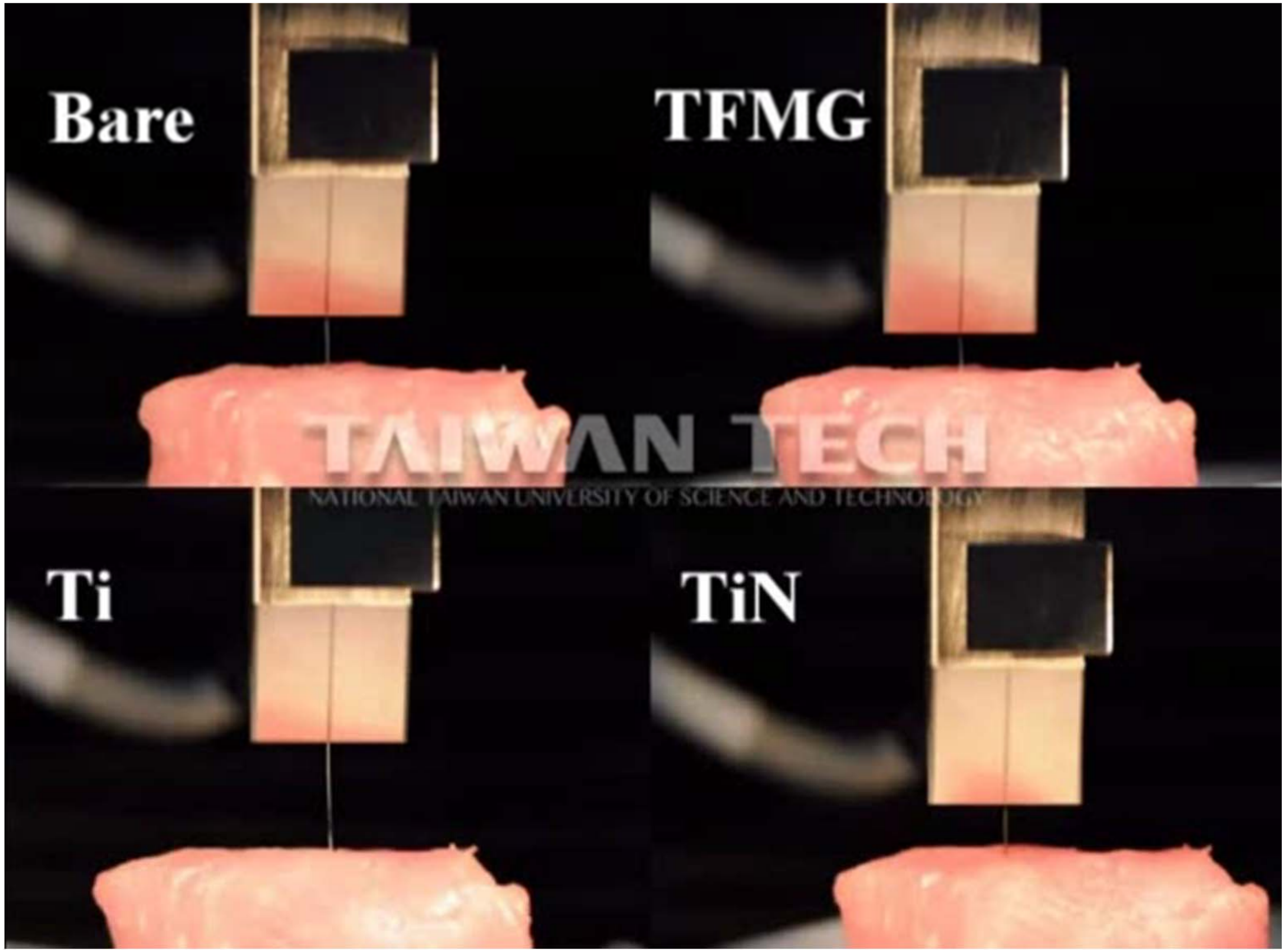
## 10. 6. 3. Medical Devices

# Anti-microbial surgical tools



**10. 6 Miscellaneous Applications: The high strength and wear resistance of BMGs along with their biocompatiability, smooth surface finish, and aesthetic appearance determine the type of material to be used and the appropriate applications.**

## 10. 6. 3. Medical Devices



# Zr-based alloy

## ❖ Catching solar wind

As part of NASA's Discovery Program, August 2001 saw the launch of the $200 million Genesis spacecraft(Fig. a) with the aim of collecting samples of solar wind22. Orbiting the Lagrange point, Genesis is expected to capture 10-20 μg of solar wind particles and ions using five, 1 m diameter circular passive collector arrays.

Zr-Nb-Cu-Ni-Al

10㎝

X 55 → Circular passive collector array

Absorbing and retaining noble gases He and Ne

↓

Bring collectors to Earth and acid etching

↓

Captured higher ions

↓

<u>[higher-energy ions] differ in composition from the solar wind</u>

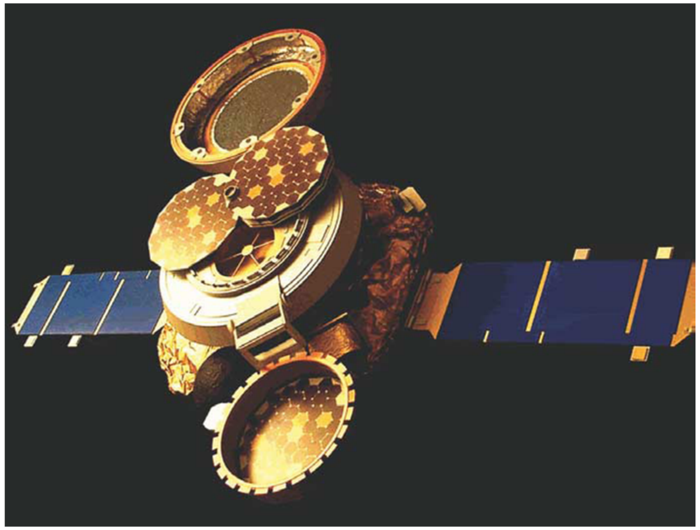
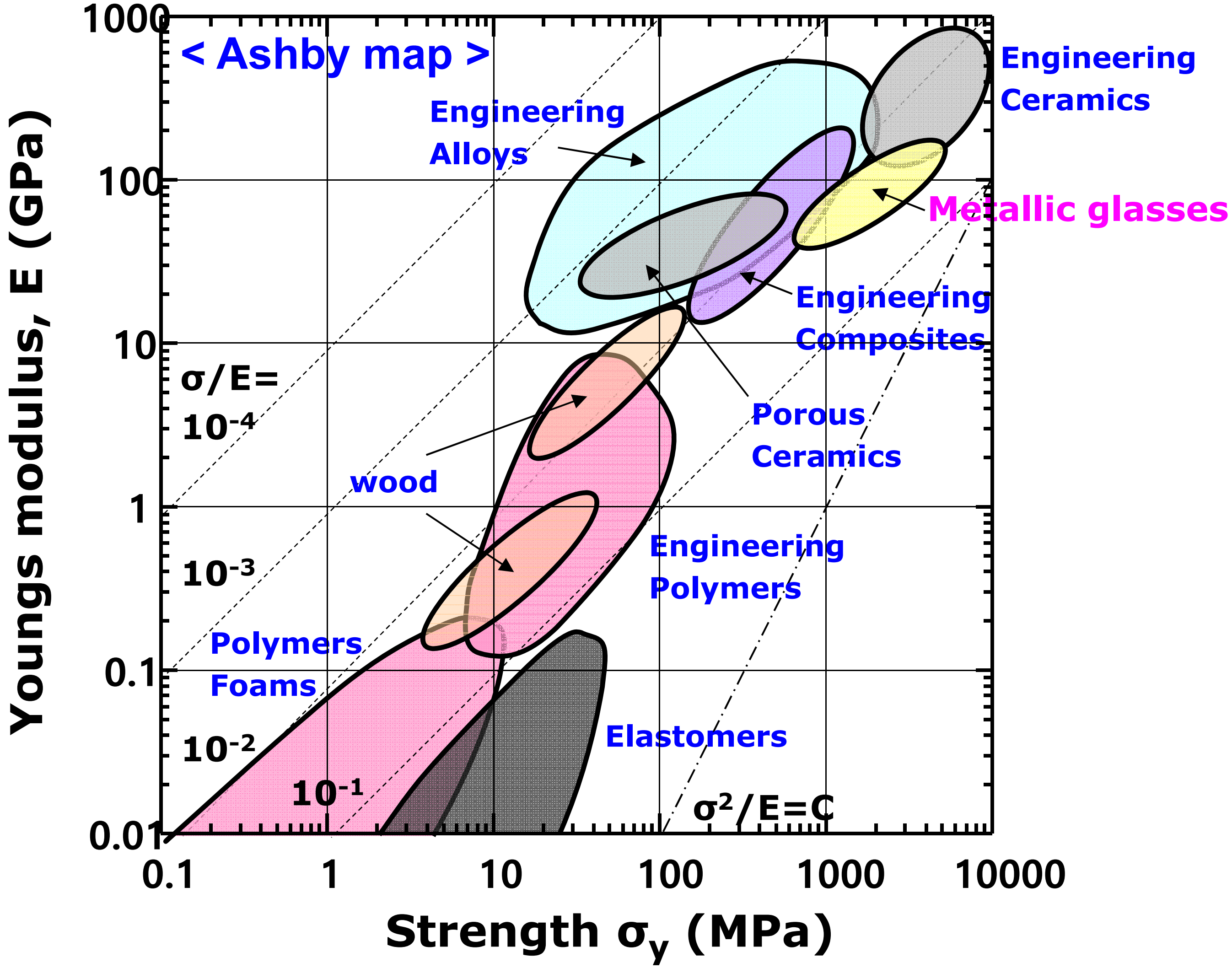


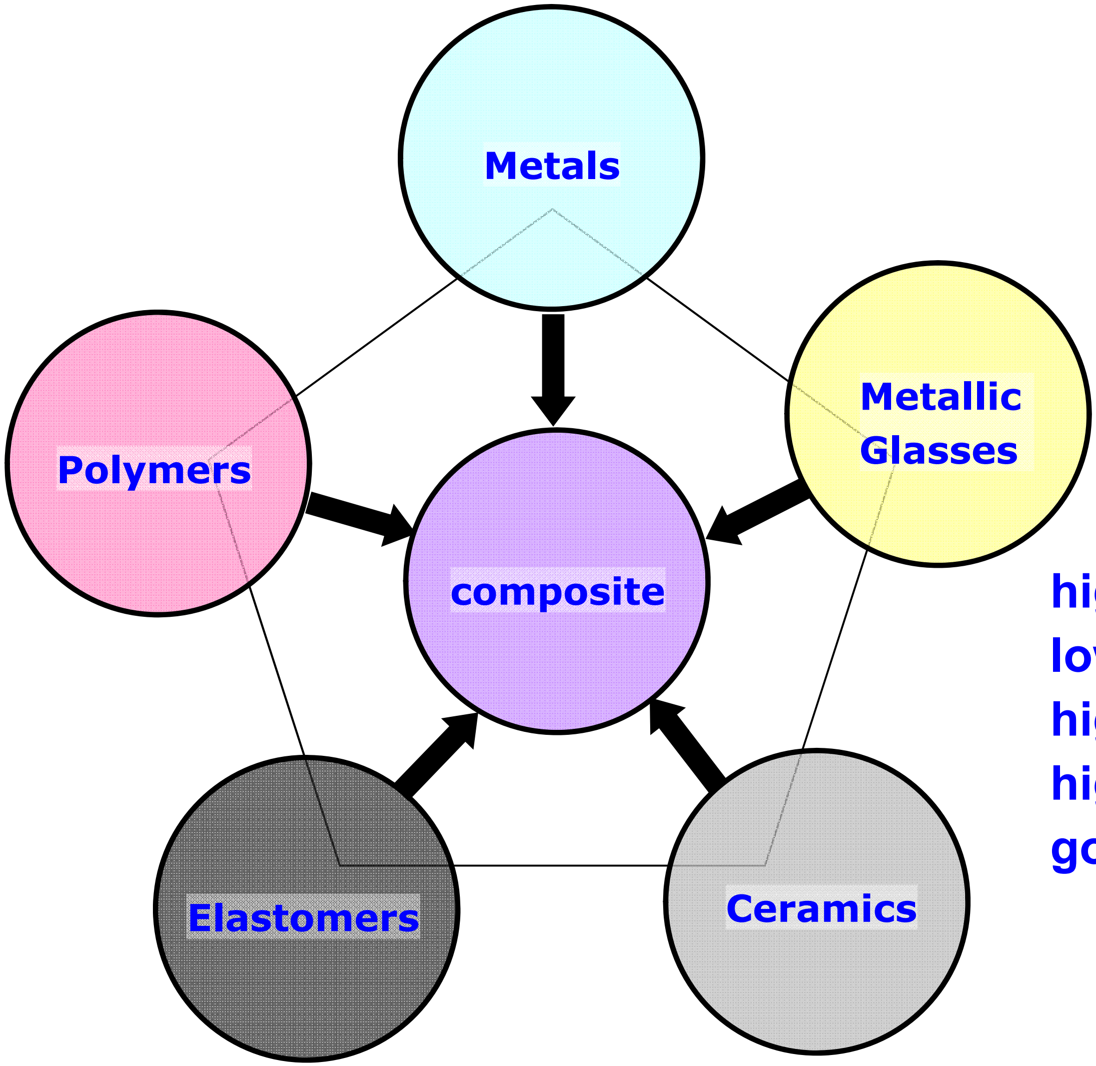
*Fig. (a) Artist's impression of the Genesis spacecraft in collection mode, opened up to collect and store samples of solar wind particles. The cover of the canister contains one collector array and the body of a stack of four arrays that can be rotated out when the spacecraft begins its orbit. (b) Genesis' array, held by Andy Stone of the Jet Propulsion Laboratory, showing the collector materials. [(a) courtesy of JPL; (b) courtesy of NASA Johnson Space Center.]*

# The beginning of a new era in metallic materials

# Ashby map


< Ashby map >
Youngs modulus, E (GPa)
Strength $\sigma_y$ (MPa)
1000
100
10
1
0.1
0.01
0.1
1
10
100
1000
10000
Engineering Ceramics
Engineering Alloys
Metallic glasses
Engineering Composites
Porous Ceramics
wood
Engineering Polymers
Polymers Foams
Elastomers
σ/E=
10-4
10-3
10-2
10-1
σ²/E=C

# Menu of engineering materials



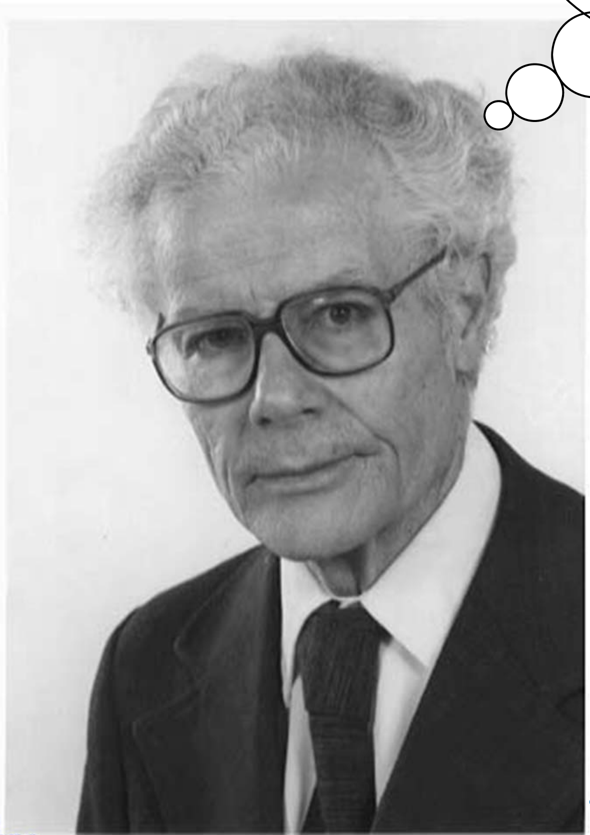

High GFA

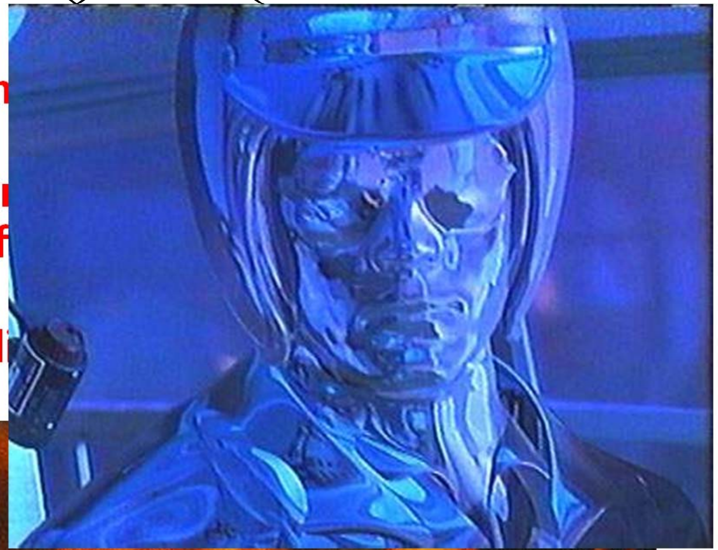
High plasticity

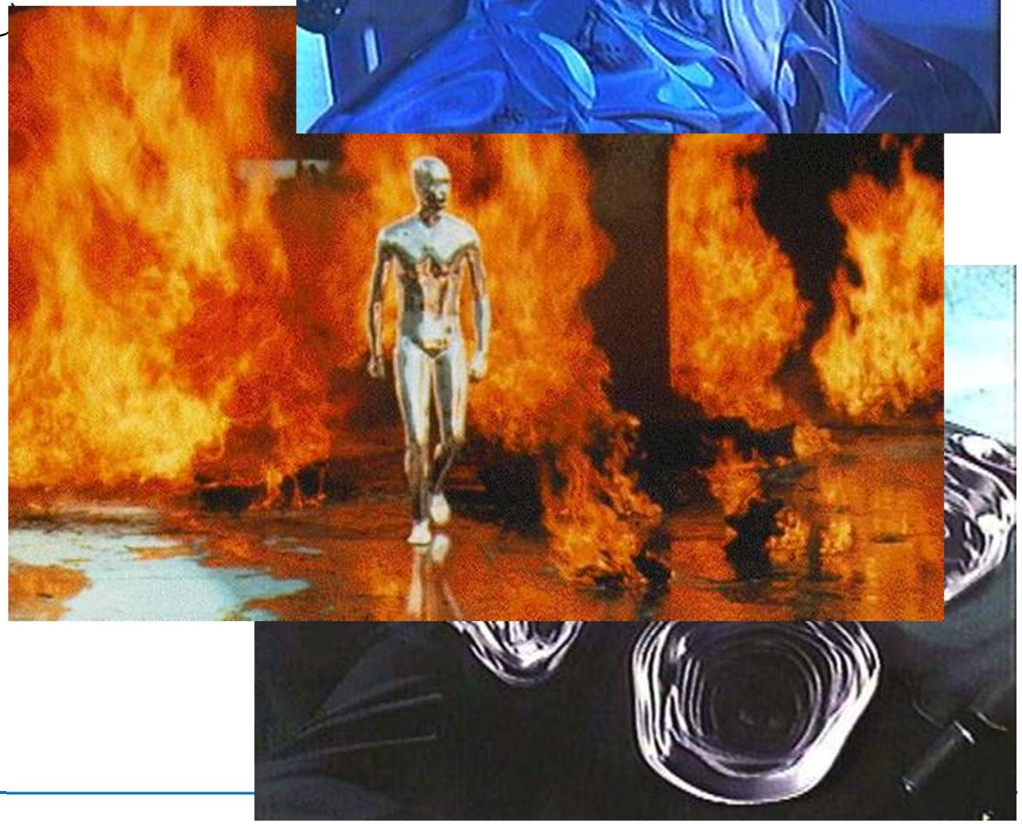
higher strength
lower Young's modulus
high hardness
high corrosion resistance
good deformability
•
•
•

# At the Cutting Edge of Metals Research: Bulk Metallic Glasses

By eliminating or reducin
the effectiveness of
heterogeneous nucleatio
it should be possible to f
bulk metallic glasses
with virtually unlimited di







## *Schedule*

week 1 Ch1. Introduction to amorphous materials
week 2 Ch2. Metallic Glasses_Glass formation
week 3 Ch2. Metallic Glasses_Thermodynamics of glass formation
week 4 Ch2. Metallic Glasses_Kinetics of glass formation
week 5 Ch2. Metallic Glasses_Methods to synthesize metallic glasses
week 6 Ch3. Glass-Forming Ability of Alloys _ Glass-forming ability
week 7 Ch3. Glass-Forming Ability of Alloys _ GFA parameters
week 8 Ch3. Glass-Forming Ability of Alloys _ Development of GFA parameters
week 9 Ch4. Synthesis of Bulk Metallic Glasses
week 10 Ch4. Synthesis of Bulk Metallic Glasses
week 11 Ch4. Synthesis of Bulk Metallic Glasses_BMG composites
week 12 Ch5. Crystallization Behavior_Crystallization modes
week 13 Ch5. Crystallization Behavior_Annealing of BMGs
week 14 Ch. 8 Mechanical Behavior_Deformation maps
week 15 Ch. 8 Mechanical Behavior_Improvement of Plasticity in BMGs
week 16 Ch 10. Potential Applications of BMGs

H: Explain the role of pressure to improve GFA.

H: Study and summary for Voronoi Polyhedra and
submit as a ppt file (under 5 pages)

H: Summary (page 265 – page 360)

Chapter 6_Physical Properties & Chapter 7_Corrosion Behavior

H: Find out a novel application of bulk metallic glass and

submit as a ppt file (under 3 pages)

**Final: 25th June (Monday) 9 AM – 11 AM (Lunch)**

**Scope: text 145~ 513 pages (except Chapter 9)**

**Teaching note: #12~ #22 and references**