Metallic Glasses I:

Overview of mechanical properties

A. L. Greer
Dept. of Materials Science & Metallurgy
University of Cambridge

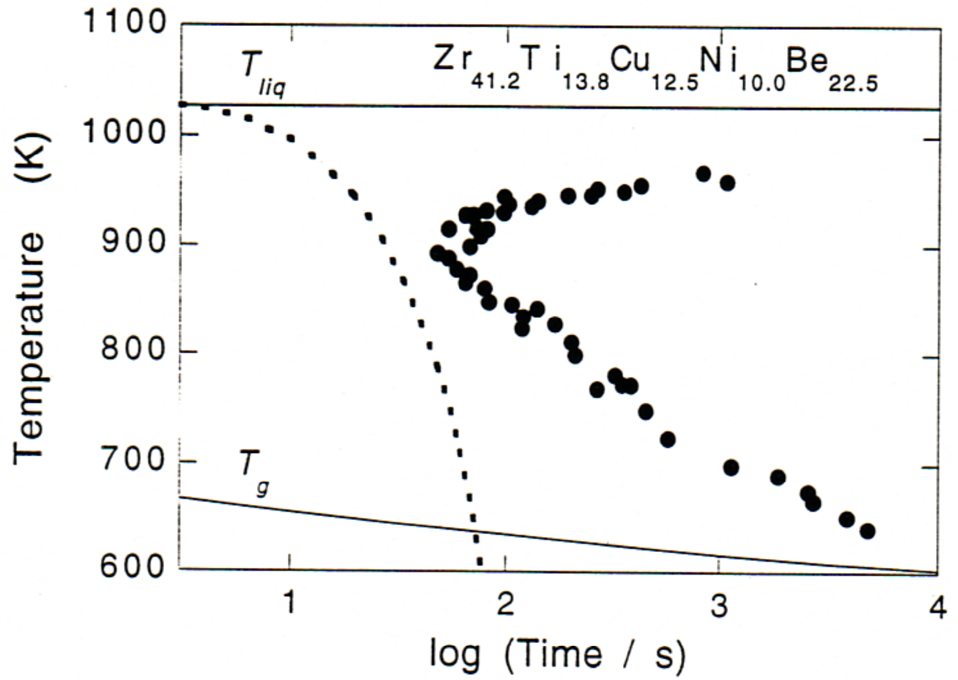
School on Glass Formers and Glasses
JNCASR, Bengaluru, 4–20 January 2010

Outline

- elasticity
- yield strength
- formability
- elastic strain limit
- elastic energy storage
- losses
- toughness
- shear bands and work softening
- brittleness and plasticity
- effects of plastic deformation on structure

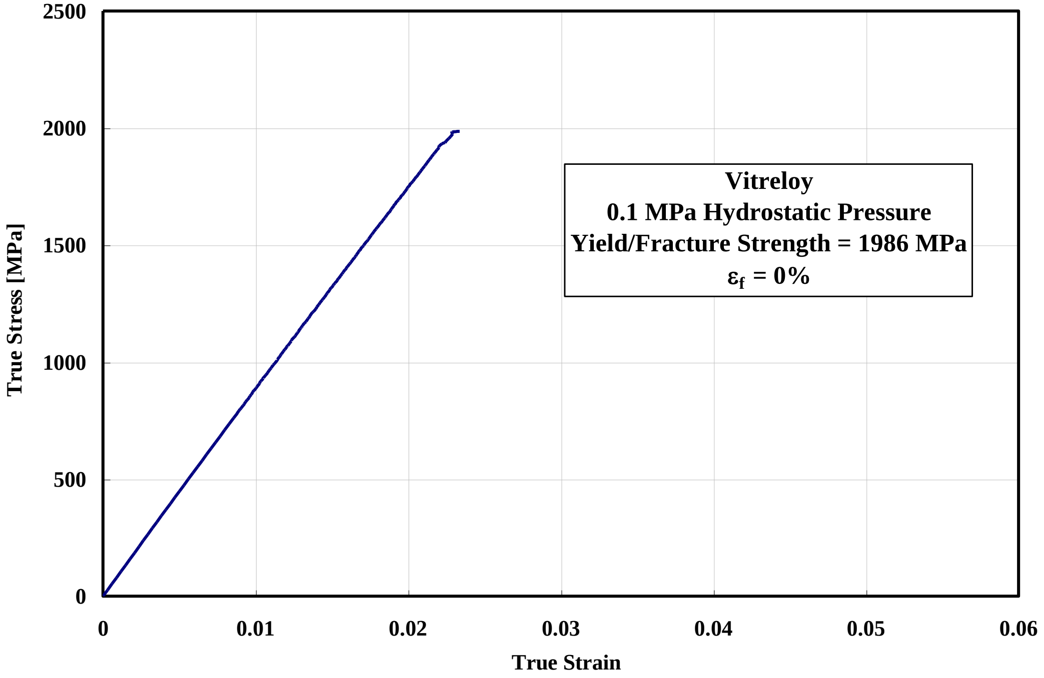
— and overall a look at applications

Bulk Metallic Glasses



- multicomponent compositions aid glass formation
- the critical cooling rate is low (~1 K s^{-1})
- glasses can be formed in bulk

(maximum diameters mm up to a few cm)



J.J. Lewandowski

— can perform macroscopic mechanical tests

Measuring strain distributions in amorphous materials

HENNING F. POULSEN[1]*, JOHN A. WERT[1], JÖRG NEUEFEIND[2], VEIJO HONKIMÄKI[3] AND MARK DAYMOND[4]

[1]Materials Research Department, Risø National Laboratory, DK-4000 Roskilde, Denmark

[2]SNS, Oak Ridge National Laboratory, PB 2008, MS 6474, Oak Ridge, Tennessee, 37922, USA

[3]European Synchrotron Radiation Facility, BP 220, F-38043 Grenoble, France

[4] ISIS Rutherford Appleton Laboratory, Oxfordshire OX11 0QX, UK

*e-mail: henning.friis.poulsen@risoe.dk

AMORPHOUS MATERIALS

NEWS & VIEWS

Characterizing amorphous strain

The engineering performance of materials is controlled to a large extent by their elastic stress/strain response. The first X-ray strain measurements in amorphous metals allow for new understanding of complex glassy materials.

GENE ICE is at the Oak Ridge National Laboratory, Bethel Valley Rd, Oak Ridge, Tennessee 37831-6118, USA.
e-mail: IceGE@ornl.gov

- can measure elastic strain from $g(r)$
- linear elasticity
- can map the strain distribution
- stiffness of nearest-neighbour shell is 2.7× that of the bulk

$Zr_{57}Ti_5Cu_{20}Ni_8Al_{10}$ BMG in compression

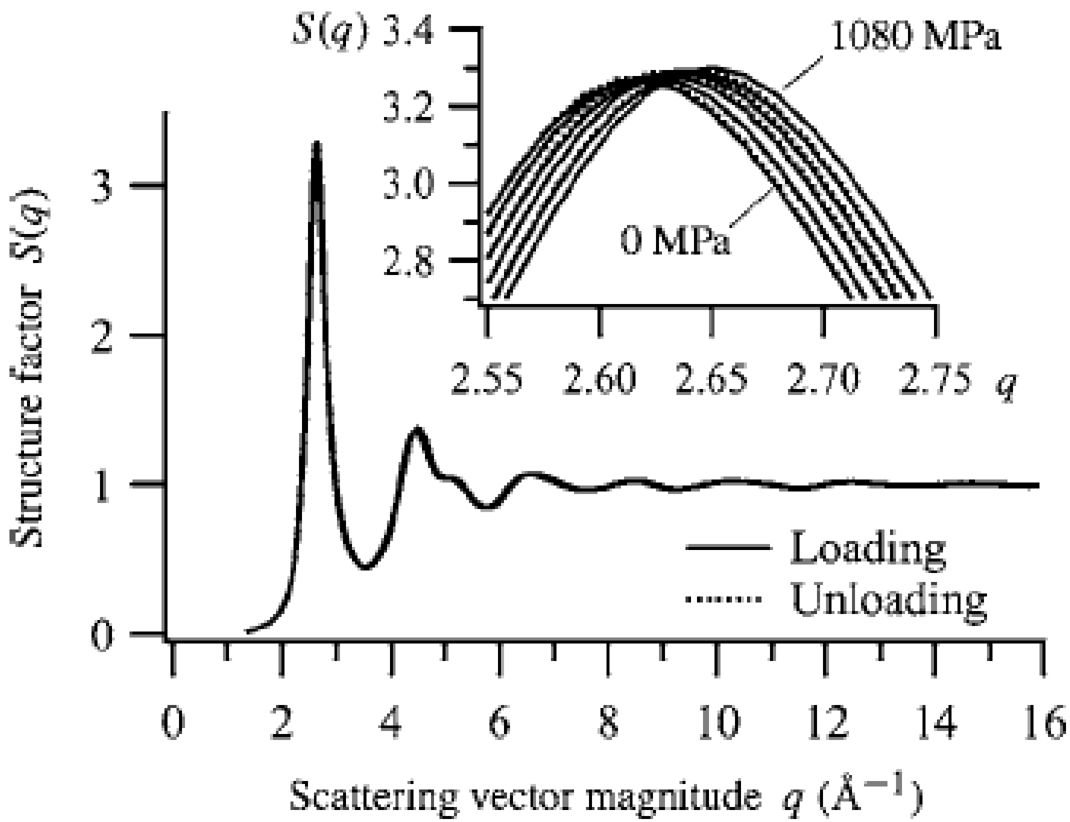


FIG. 1. Structure factor $S(q)$ parallel to the loading direction from 11 scattering patterns collected during incremental loading and unloading. Inset: top of the main peak, showing the shift of the peak in $S(q)$ to larger q with increasing compressive stress.

- shifts of first peak give a good measure of elastic strain
- can use $I(q)$

Hufnagel et al. *Phys. Rev. B* **73** (2006) 064204

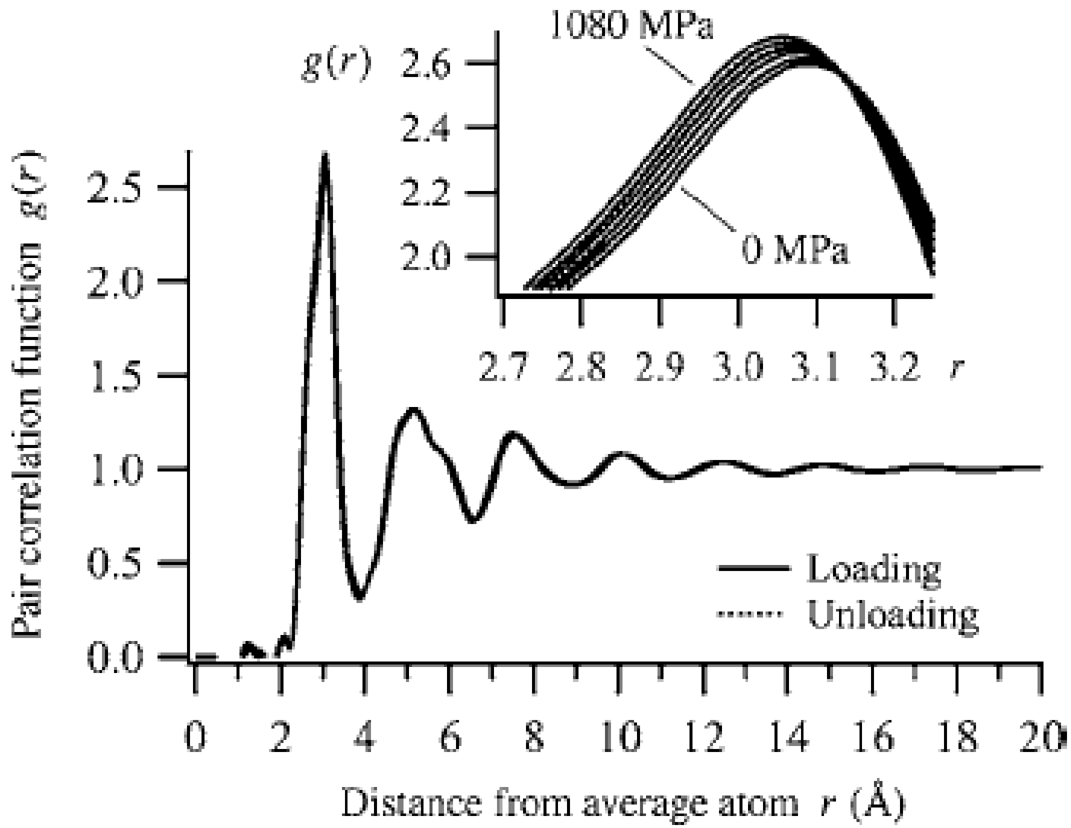


FIG. 3. Pair correlation functions $g(r)$ calculated from the $S(q)$ data in Fig. 1 (parallel to the loading direction). Inset: shift in the first peak in $g(r)$ to smaller r with increasing compressive stress.

- elastic strain can also be obtained from the pair distribution function *g*(*r*)

Hufnagel et al. *Phys. Rev. B* **73** (2006) 064204

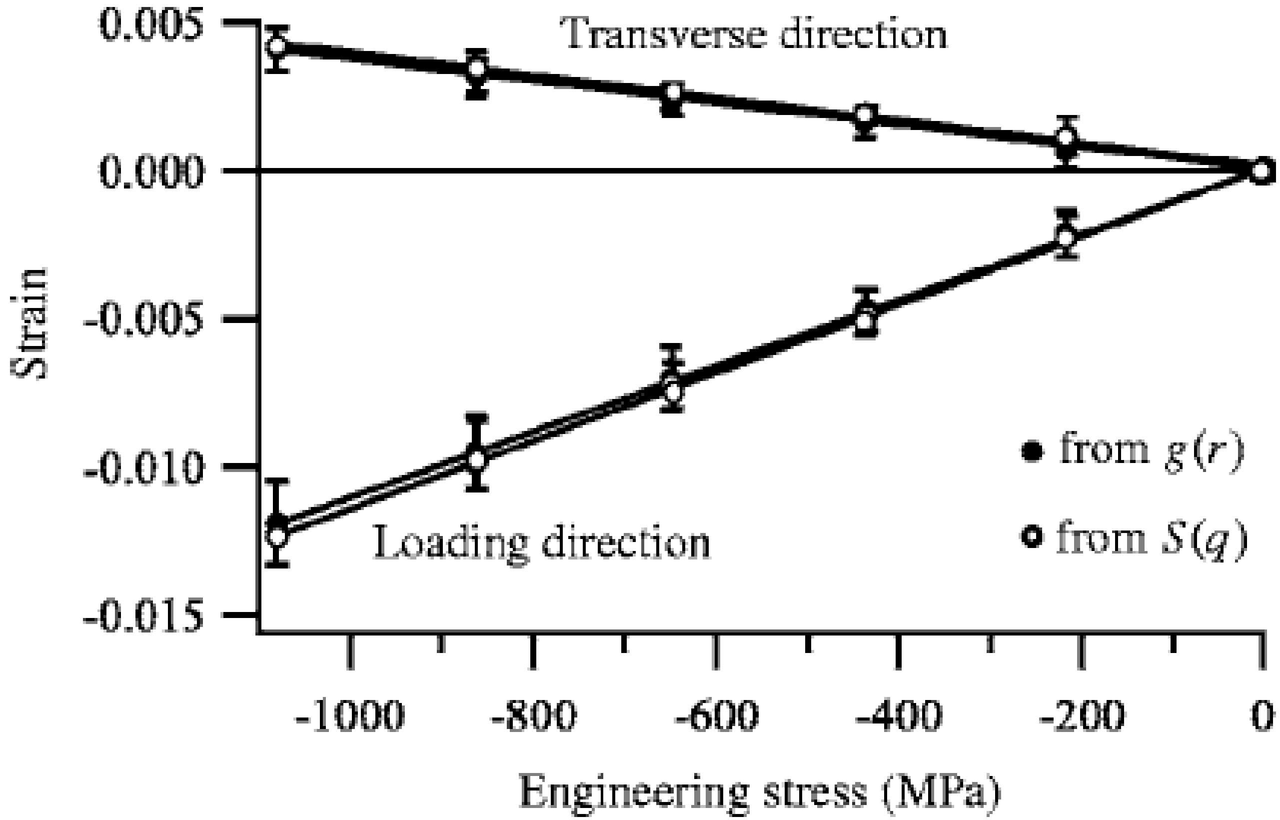
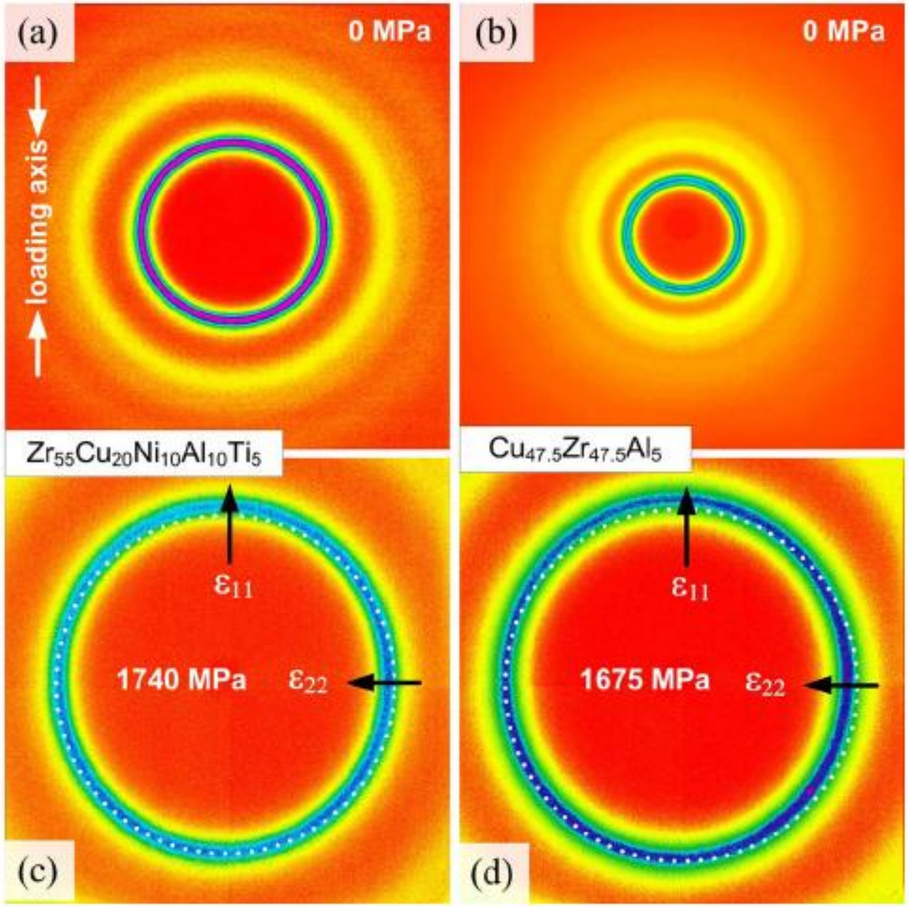


FIG. 2. Strain determined from the structure factor $S(q)$ in reciprocal space and from the pair correlation function $g(r)$ in real space.

Hufnagel et al. *Phys. Rev. B* **73** (2006) 064204

Compressive loading of BMG samples



Das et al. *Phys. Rev. B* **76** (2007) 092293.

FIG. 1. (Color online) The diffraction patterns of $Zr_{55}Cu_{20}Ni_{10}Al_{10}Ti_5$ and $Cu_{47.5}Zr_{47.5}Al_5$ before [(a) and (b)] and after employing stress [(c) and (d)] near plastic yielding, showing a very clear change from circular to elliptical shape. A dotted circle is shown to reveal that the average interatomic spacing decreases along the loading axis (ϵ_{11}) and increases along the transverse direction (ϵ_{22}).

apparent strain is ~30% less for *r* < 4 Å

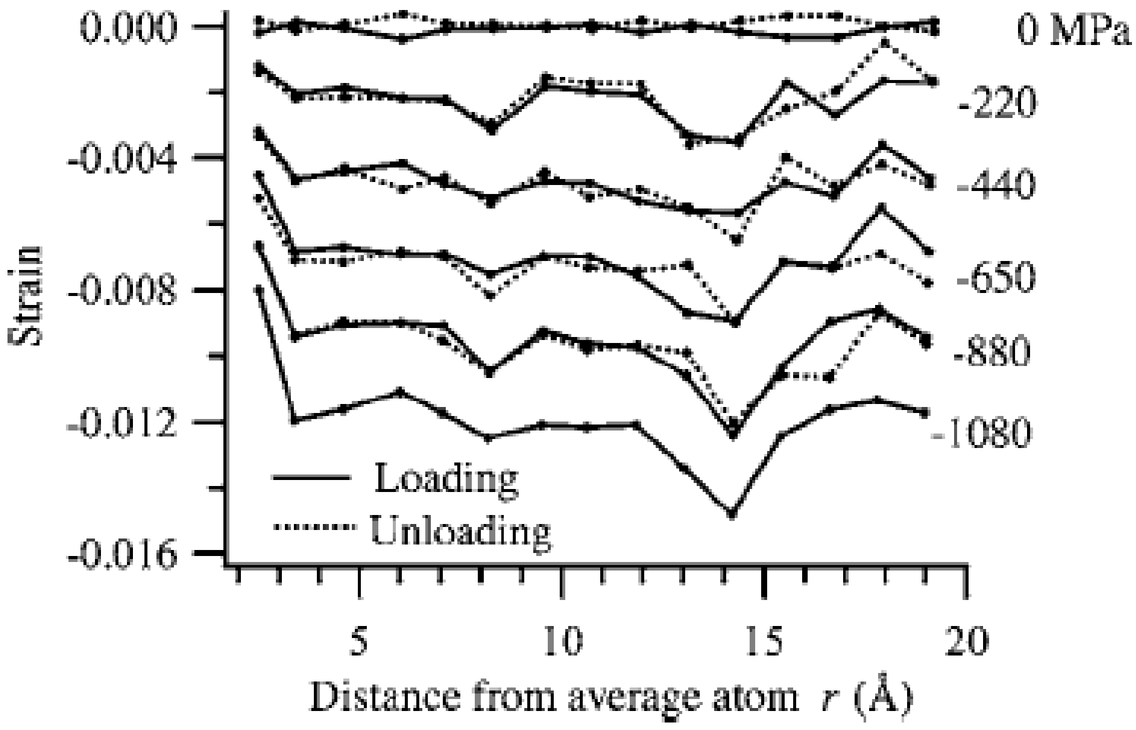


FIG. 4. Strain determined from pair correlation functions $g(r)$ at several stresses.

Hufnagel et al. *Phys. Rev. B* **73** (2006) 064204

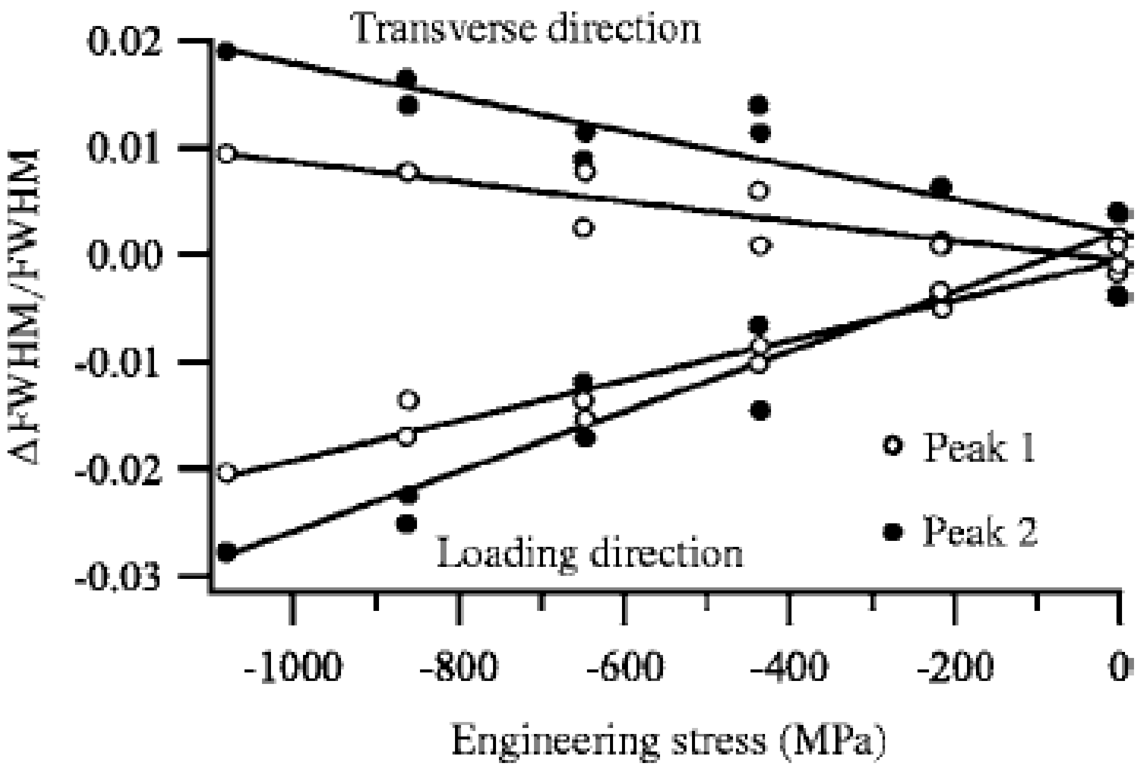
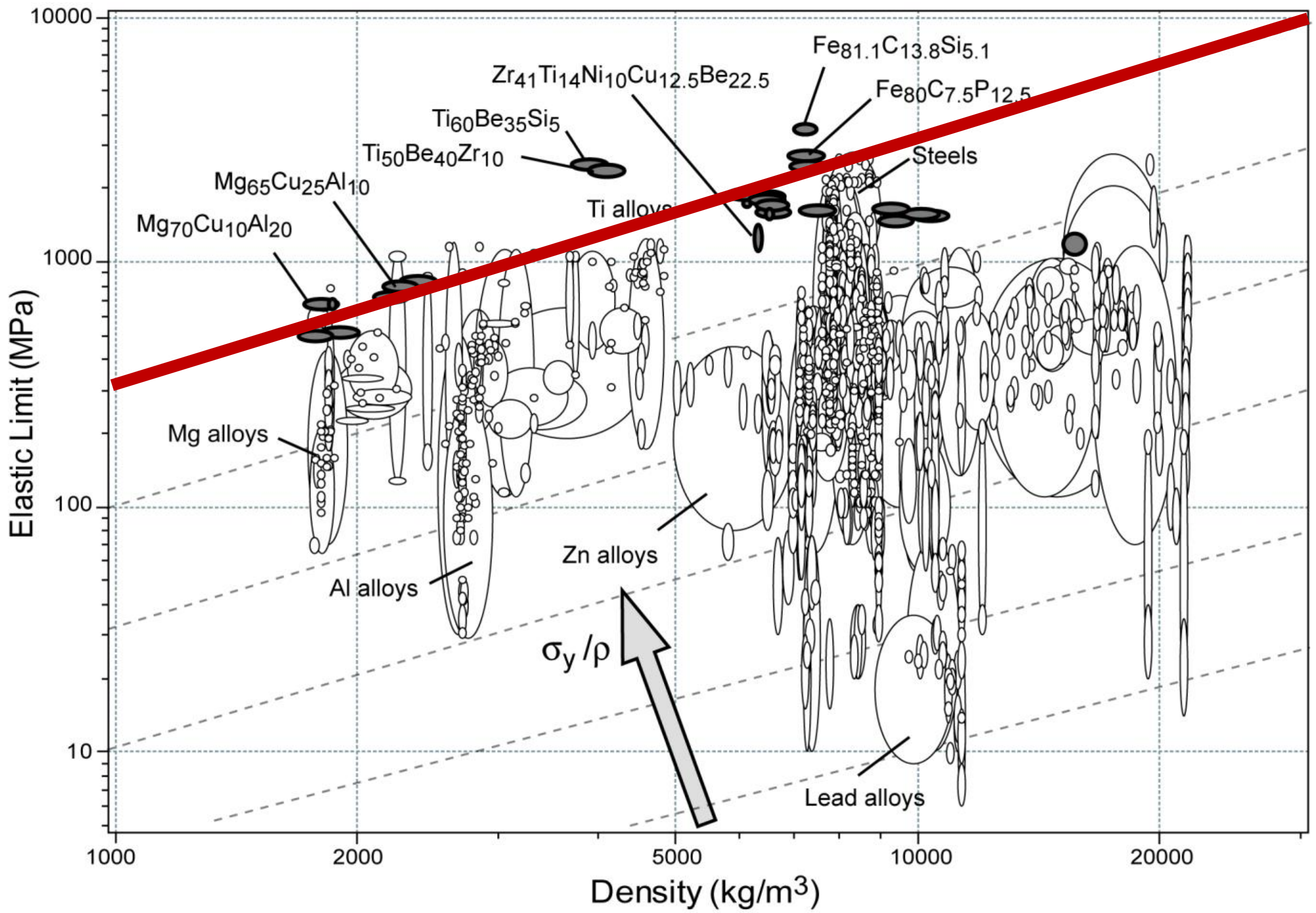


FIG. 7. Change in the widths (FWHM) of the two overlapping peaks in the RDF (Fig. 5).

- overall peak narrowing under stress
- stressed sample has lower entropy
- analogous to "entropy spring" familiar for polymers

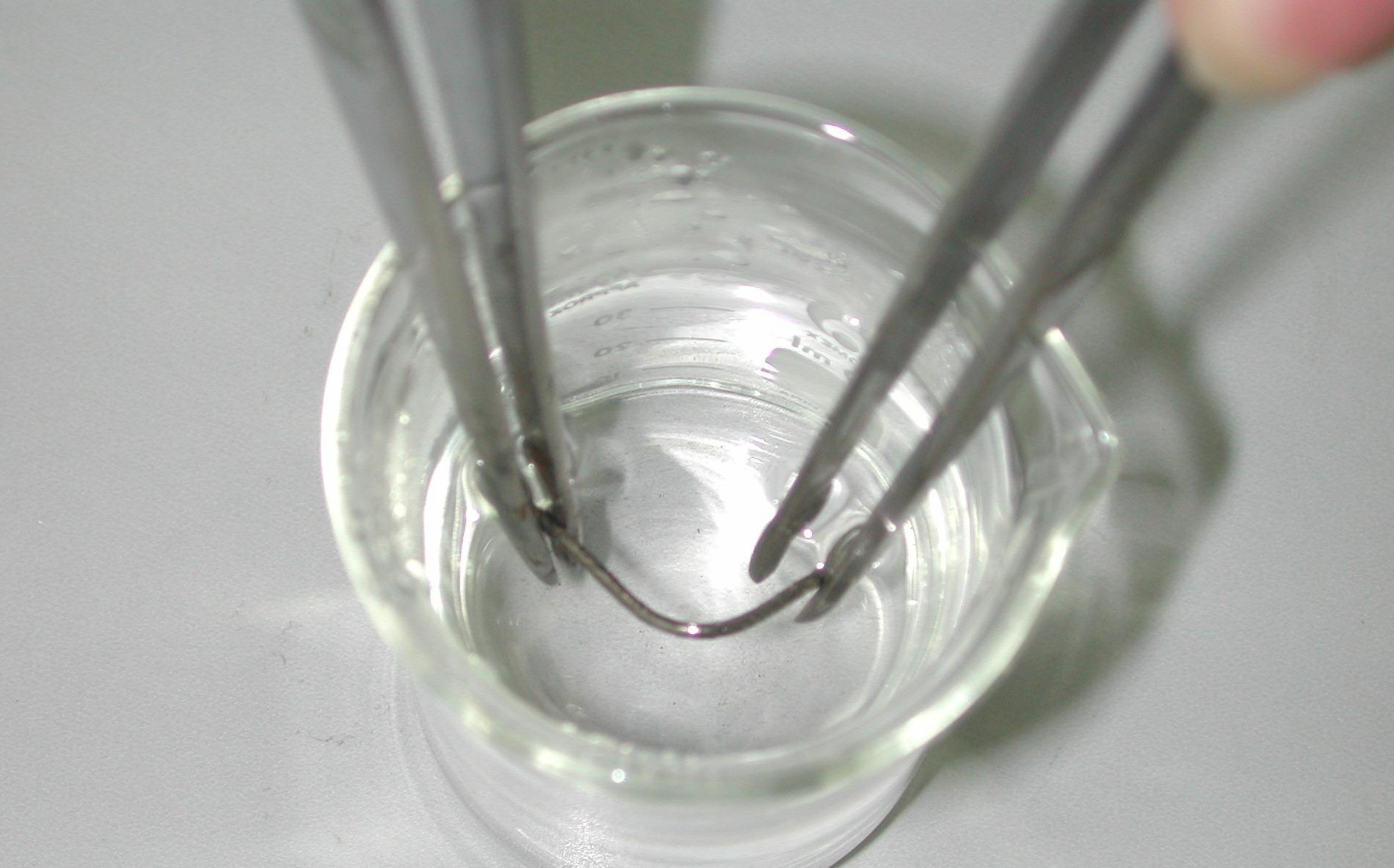
Hufnagel et al. *Phys. Rev. B* **73** (2006) 064204

Metallic glasses for structural applications



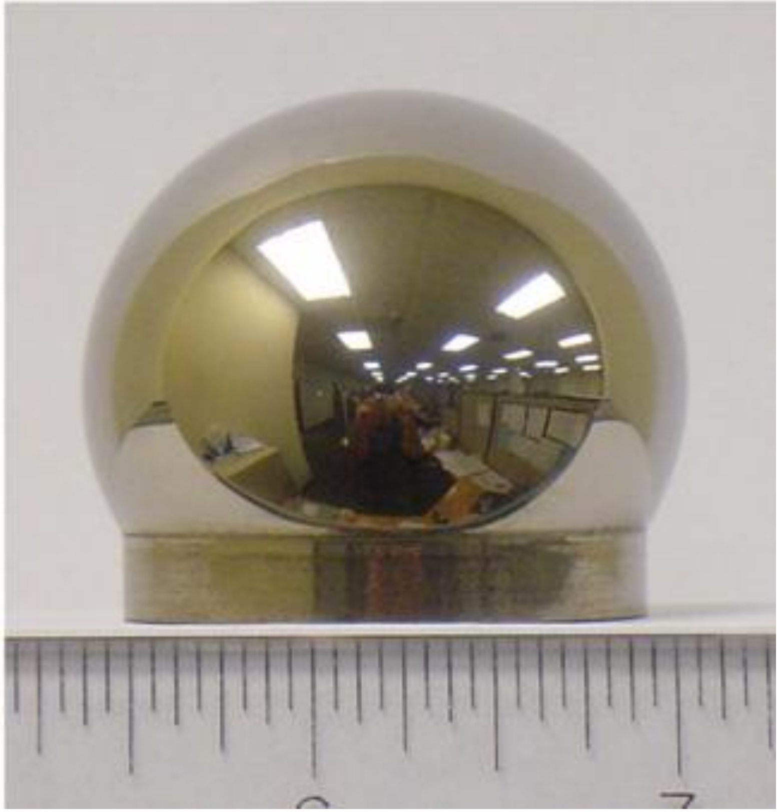
Elastic limit σ_y plotted against **density** ρ for 1507 metals, alloys, metal-matrix composites and metallic glasses. The contours show the **specific strength** σ_y/ρ.

M.F. Ashby & A.L. Greer: *Scripta Materialia* **54** (2006) 321.
(in Viewpoint Set on *Mechanical Behavior of Metallic Glasses*, edited by T.C. Hufnagel)

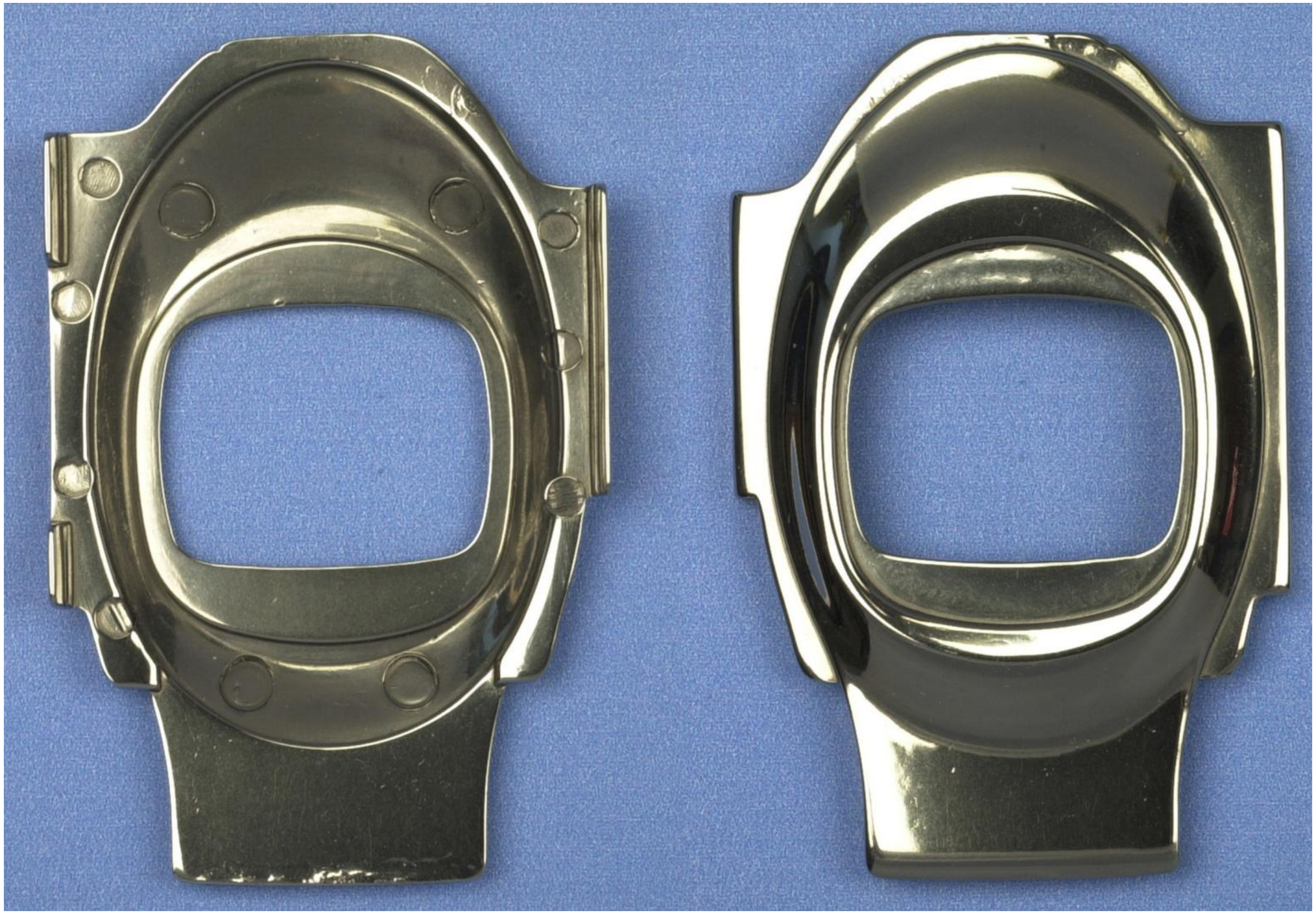


$Ce_{70}Al_{10}Cu_{20}$ — T_g = 338 K, T_x = 390 K

B. Zhang, D.Q. Zhao, M.X. Pan, W.H. Wang & A.L. Greer:
"Amorphous metallic plastic", *Phys. Rev. Lett.* **94** (2005) 205502.

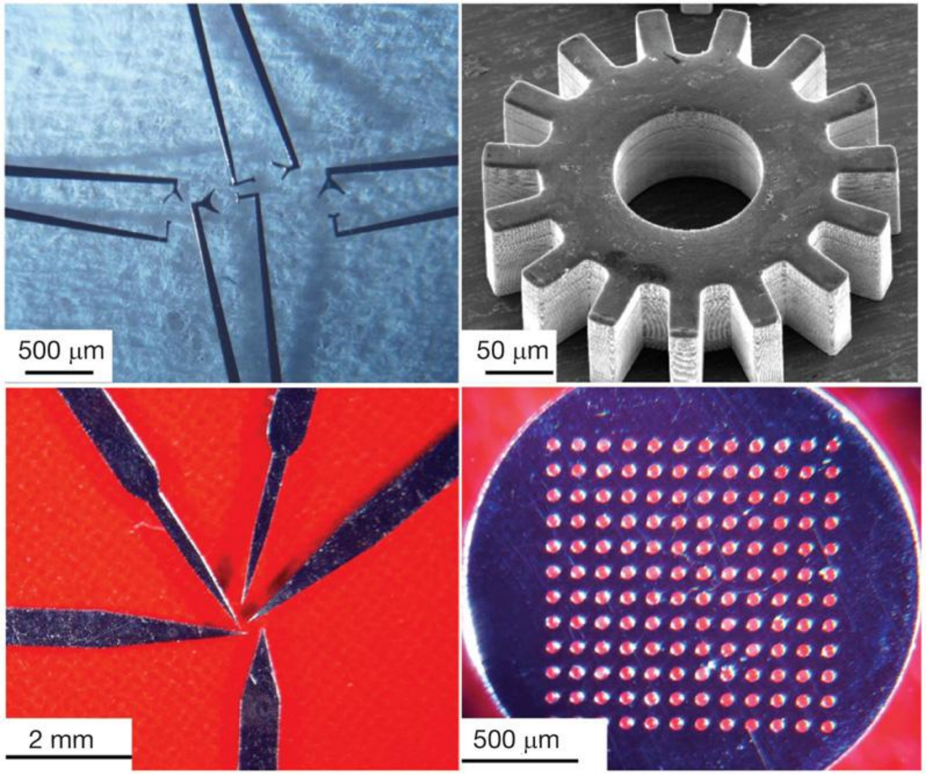


J Schroers *et al*., *Scripta Mater*. (2007) **57**, 341



Nanomoulding with amorphous metals

Optical and scanning electron microscope images of three-dimensional microparts, including tweezers (top left), scalpels (bottom left), a gear (top right) and a membrane (bottom right).



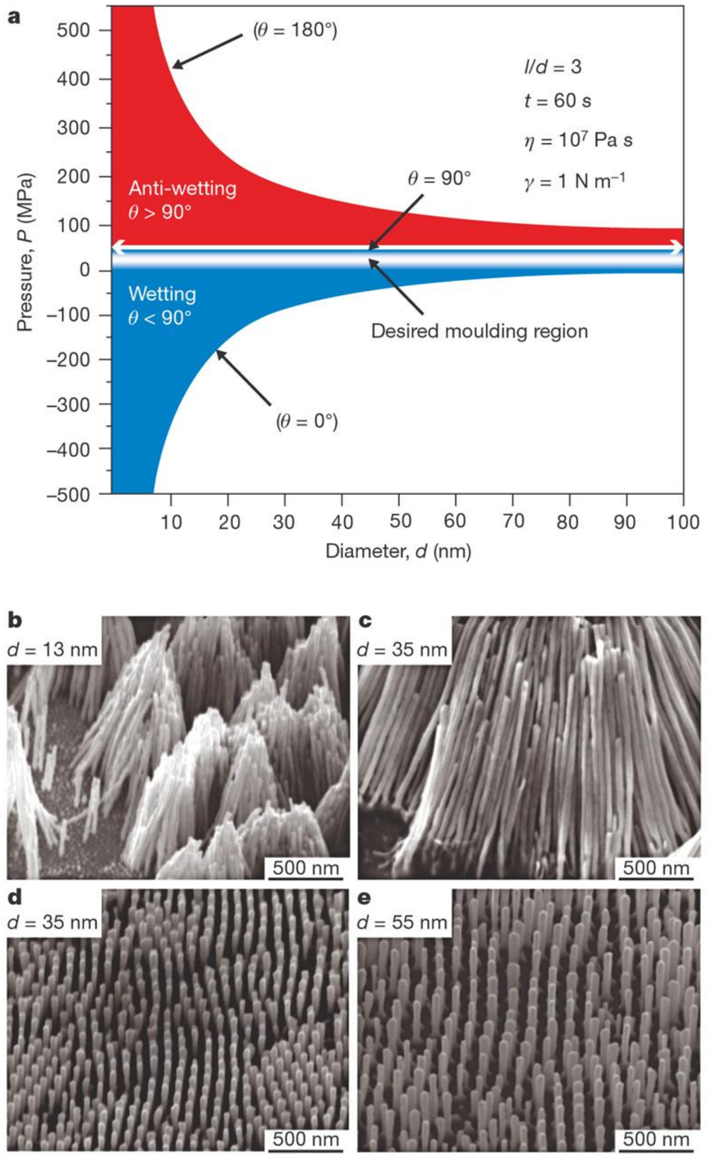
G Kumar, HX Tang & J. Schroers, *Nature* **457**, 868-872 (2009)

nature

Nanomoulding with amorphous metals

Controlling metallic glass moulding on scales smaller than 100 nm

Pt-based BMG



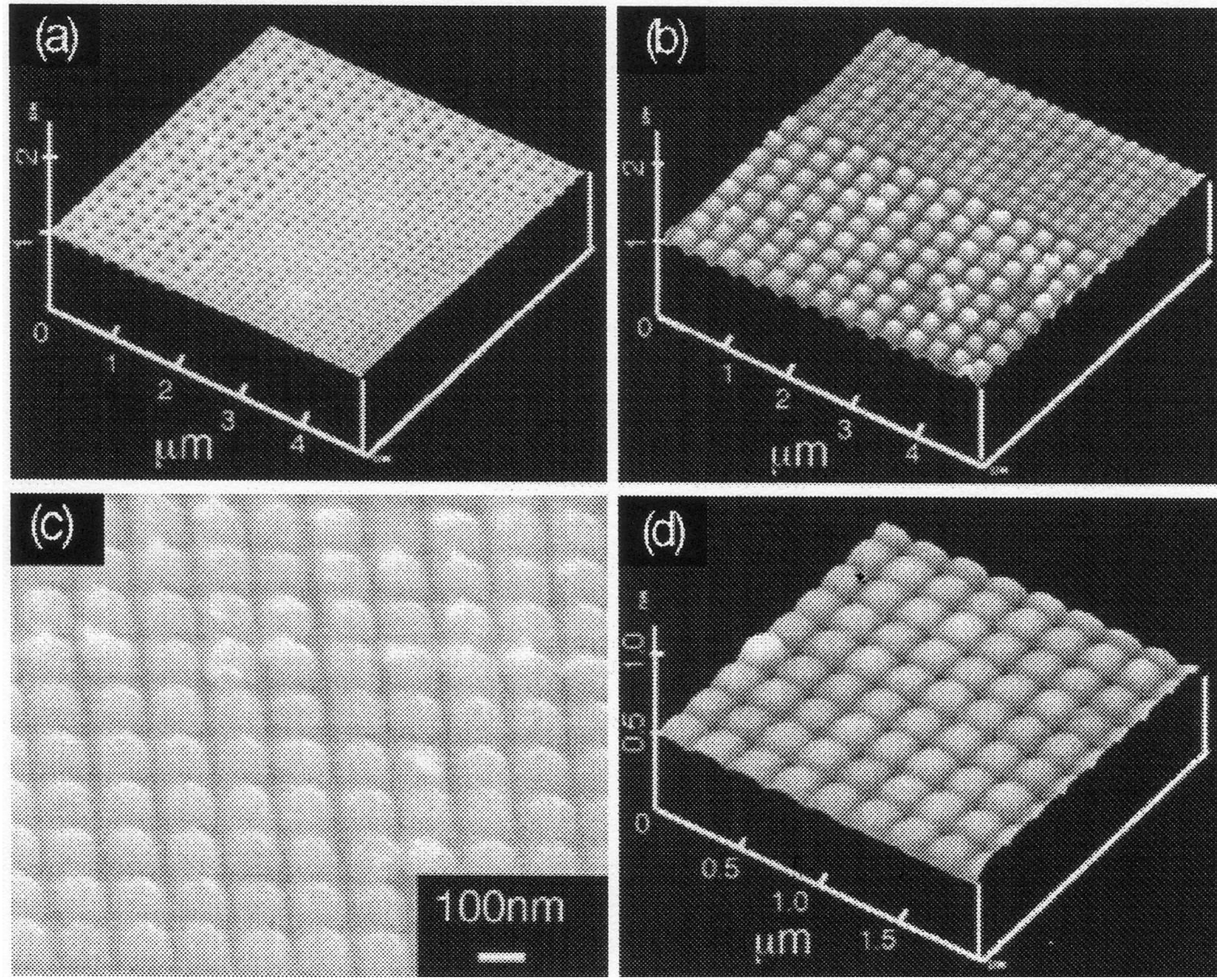
G Kumar, HX Tang & J. Schroers, *Nature* **457**, 868-872 (2009)

nature

Microformability of BMGs

• of interest for micro- & nano-imprinting of surfaces

AFM and SEM images of a patterned (100) Si die and a Pt-based BMG imprinted with the die (10 MPa, 550 K, 300 s)



Y. Saotome et al. “The micro-nanoformability of Pt-based metallic glass and the nanoforming of three-dimensional structures”, *Intermetallics* **10** (2005) 1241.

J. Schroers: "The superplastic forming of bulk metallic glasses", *JOM* **57**(5) (2005) 35.

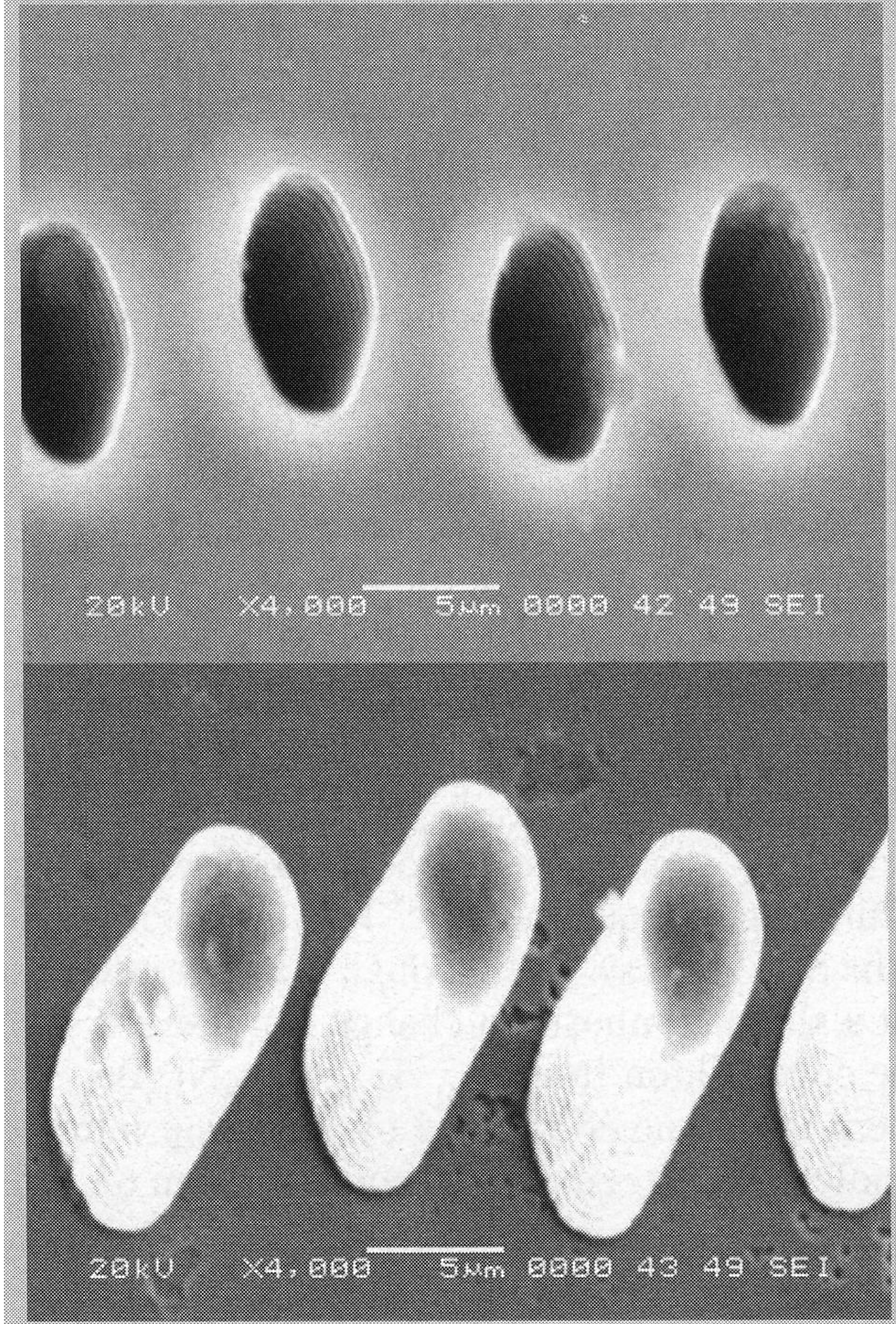
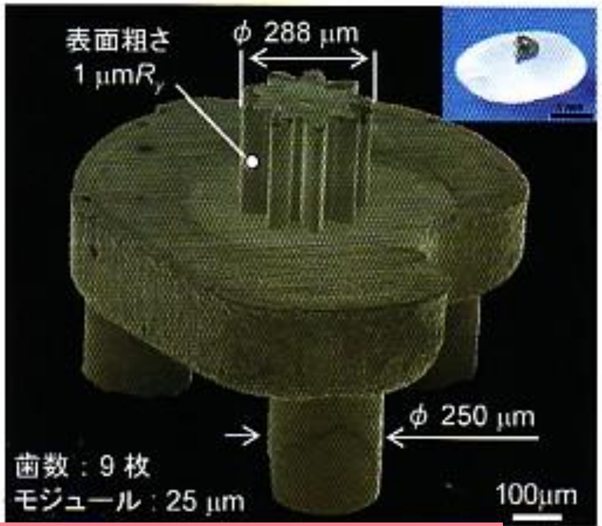
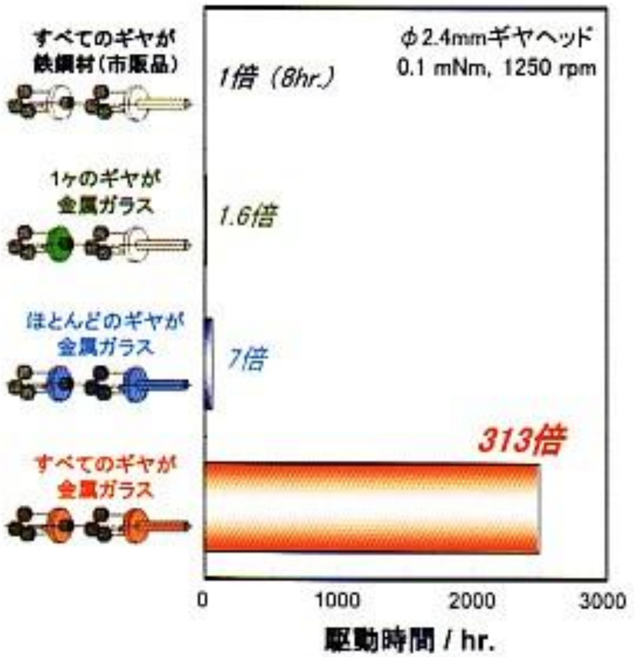


Figure 5. A micro-replication of protrusions from a silicon mold (top) by SPF of $Pt_{57.5}Cu_{14.7}Ni_{5.3}P_{22.5}$ at 270°C for 300 s at a pressure of 30 MPa. These processing parameters enable the replication of features in the 100 nm range.

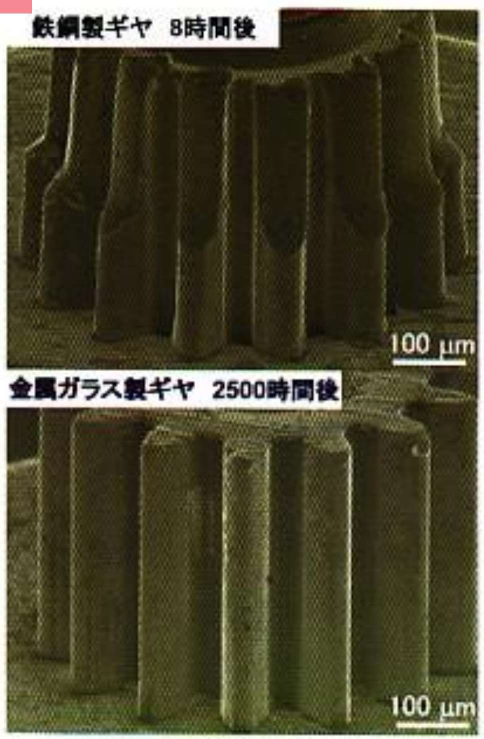


金属ガラス製超精密歯車を組み込んだ世界最小マイクロギヤードモータ

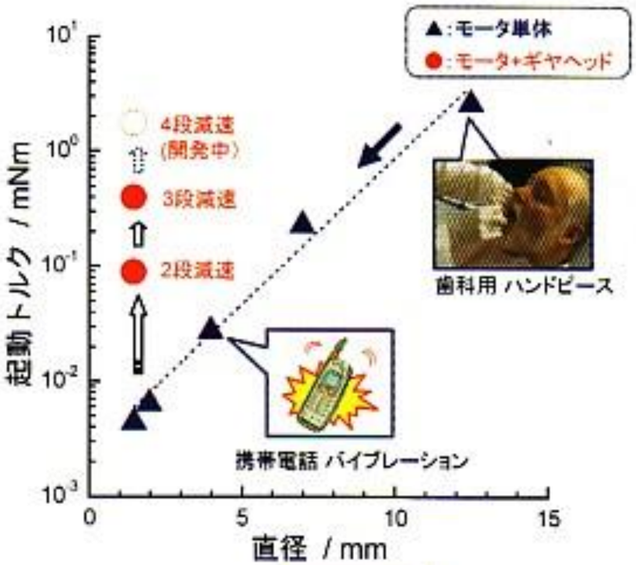
The world's smallest motor



直径2.4 mmギヤヘッド(従来品)を用いた駆動時間比較

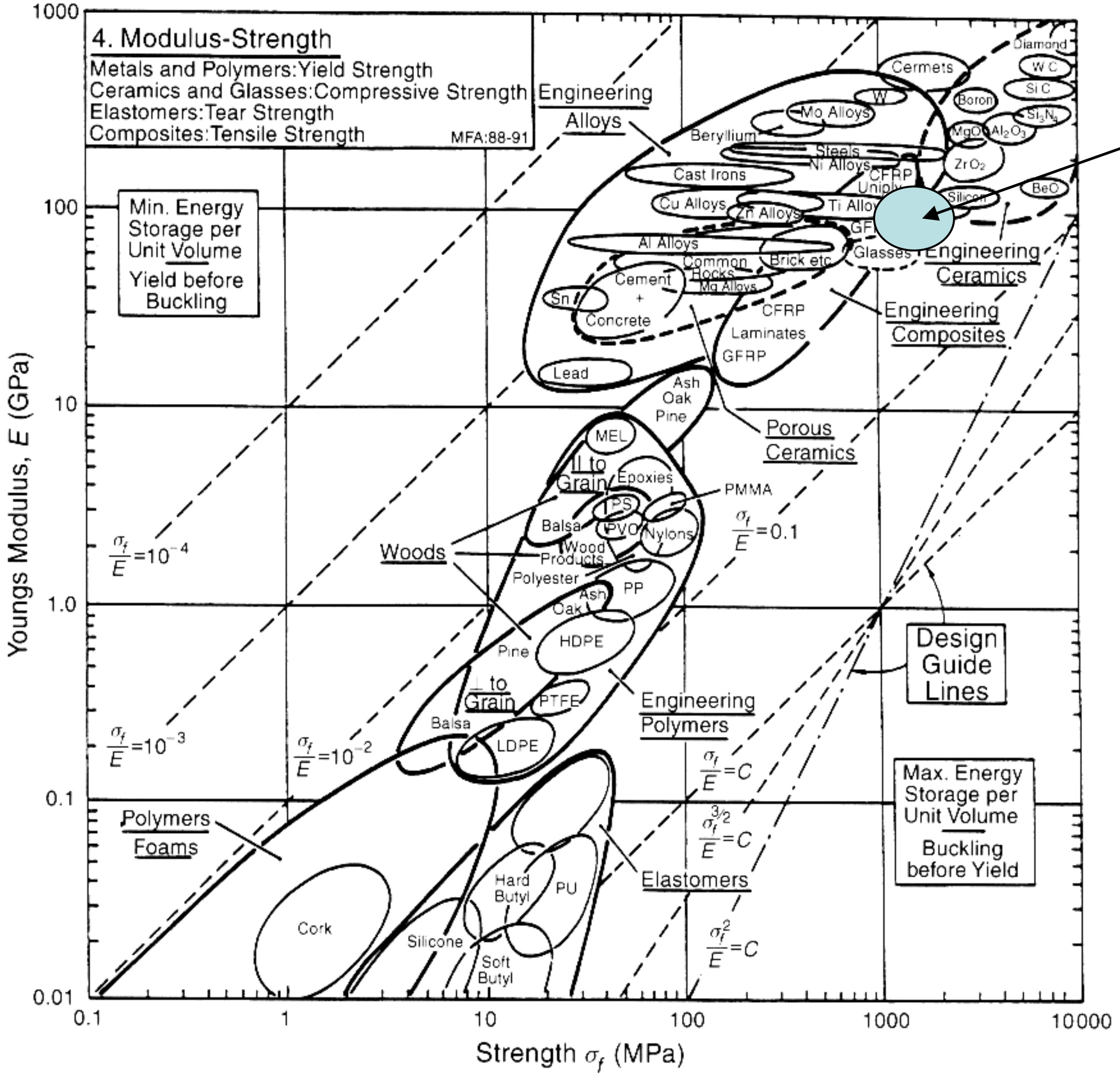


駆動試験後の歯車摩耗状況



小型&高出力

医療機器、ロボット等に適用可能



metallic glasses

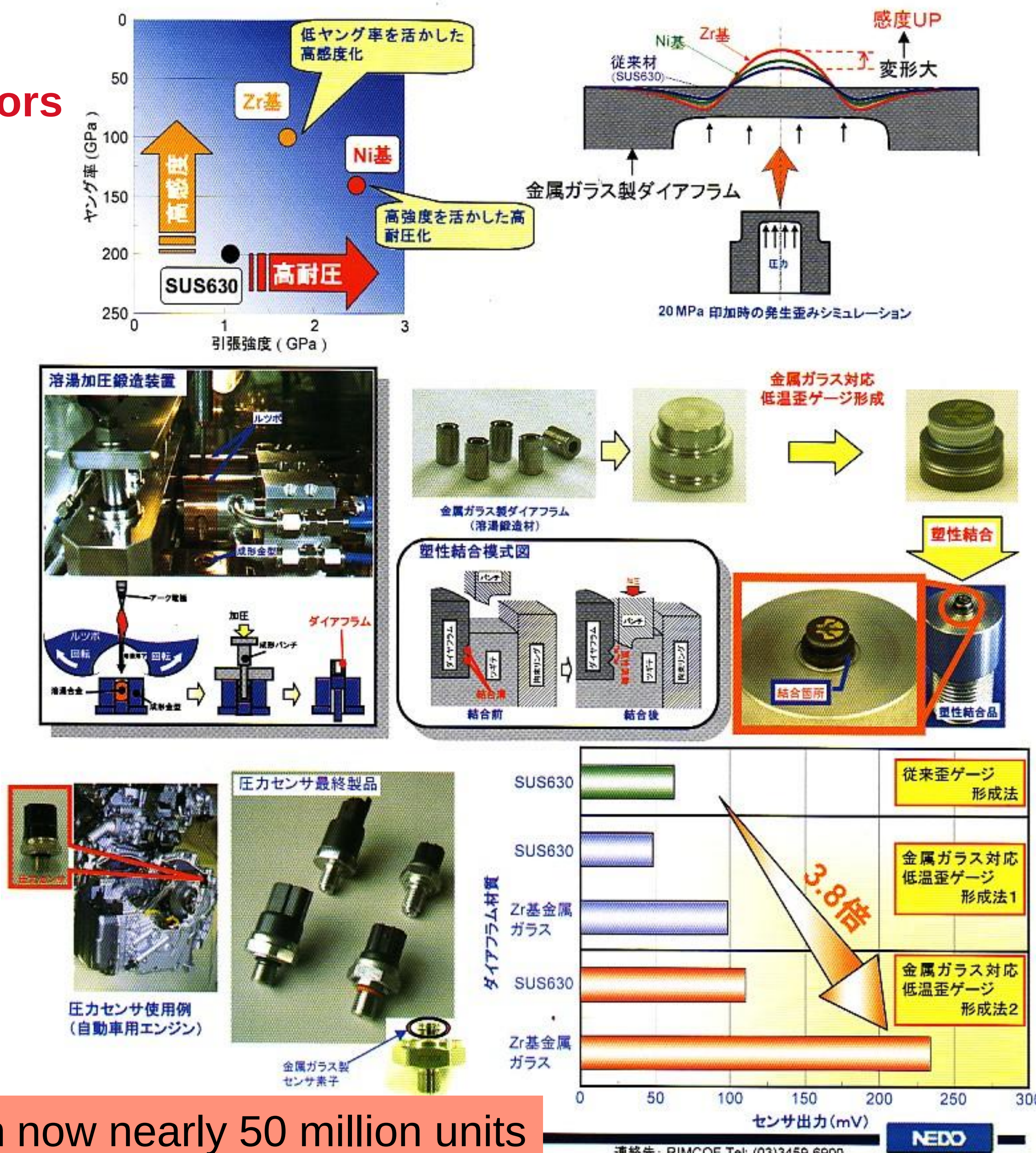
— compared to metals and alloys in general, the glasses have high strength σ and low stiffness *E*, that is, **unusually high elastic strain —**

σ/E

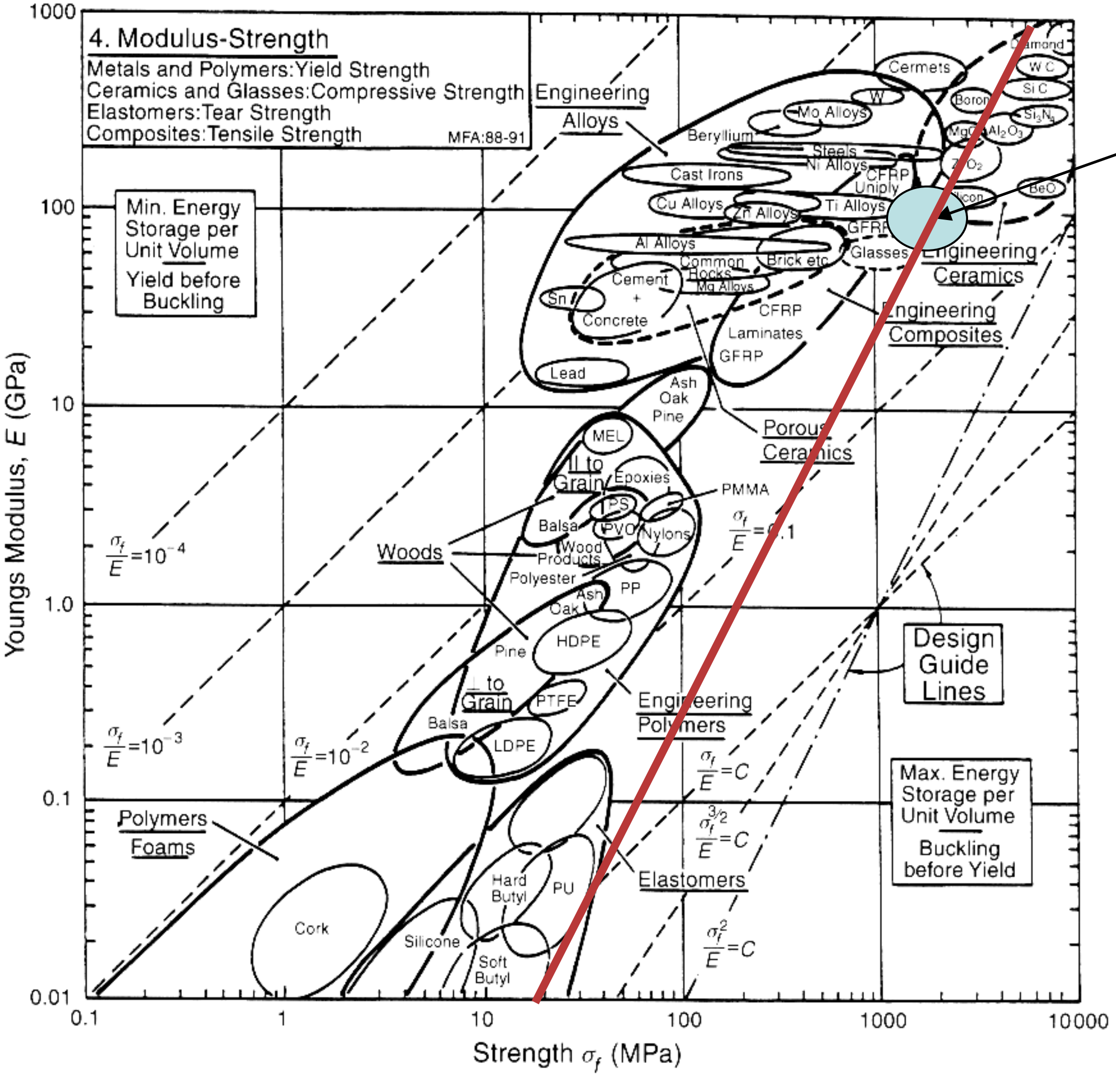
from *Materials Selection in Mechanical Design* (2nd ed.)
M. F. Ashby, Butterworth-Heinemann, 1999

Pressure Sensors

Diaphragms



Annual production now nearly 50 million units



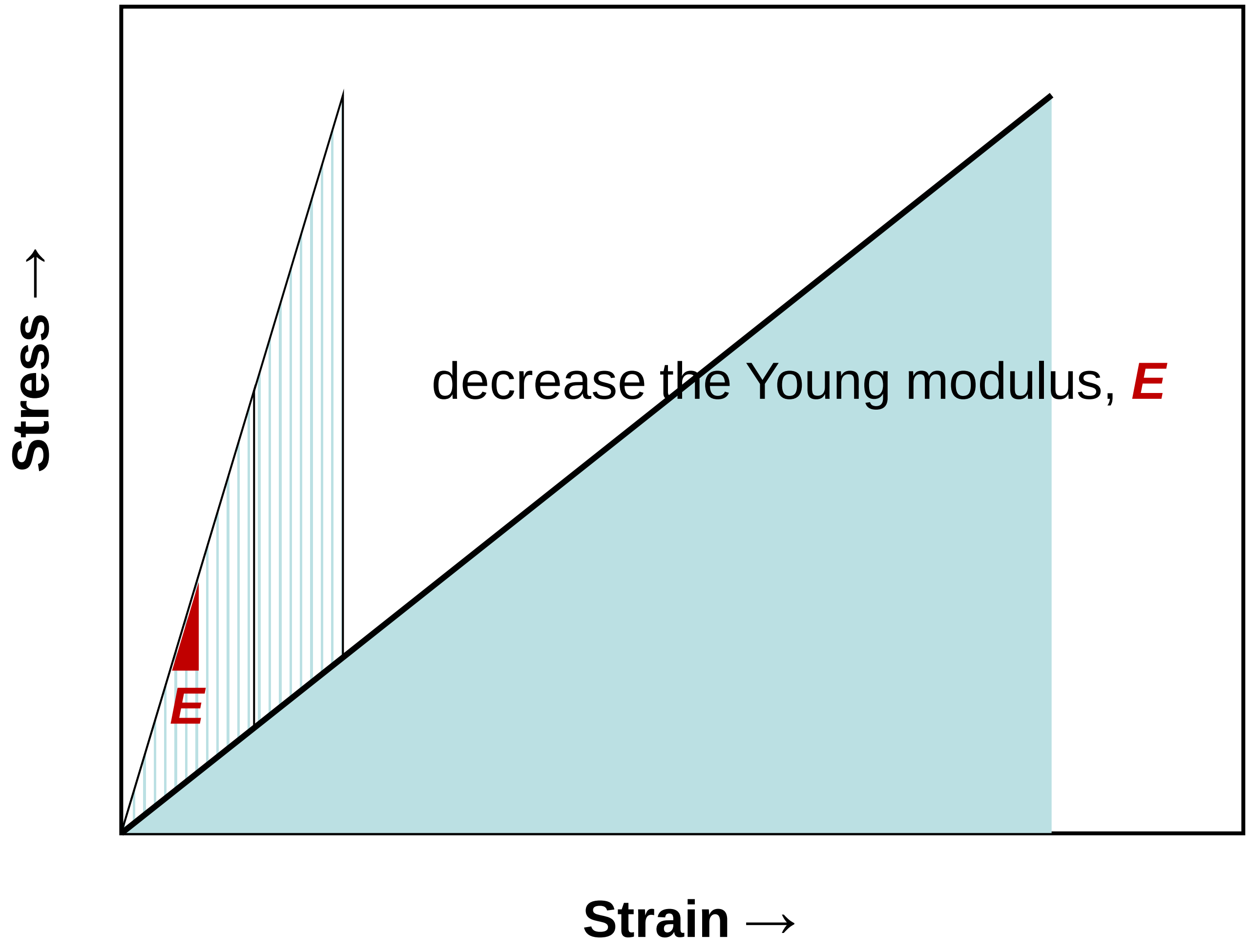
metallic glasses

materials for **elastic energy storage** —

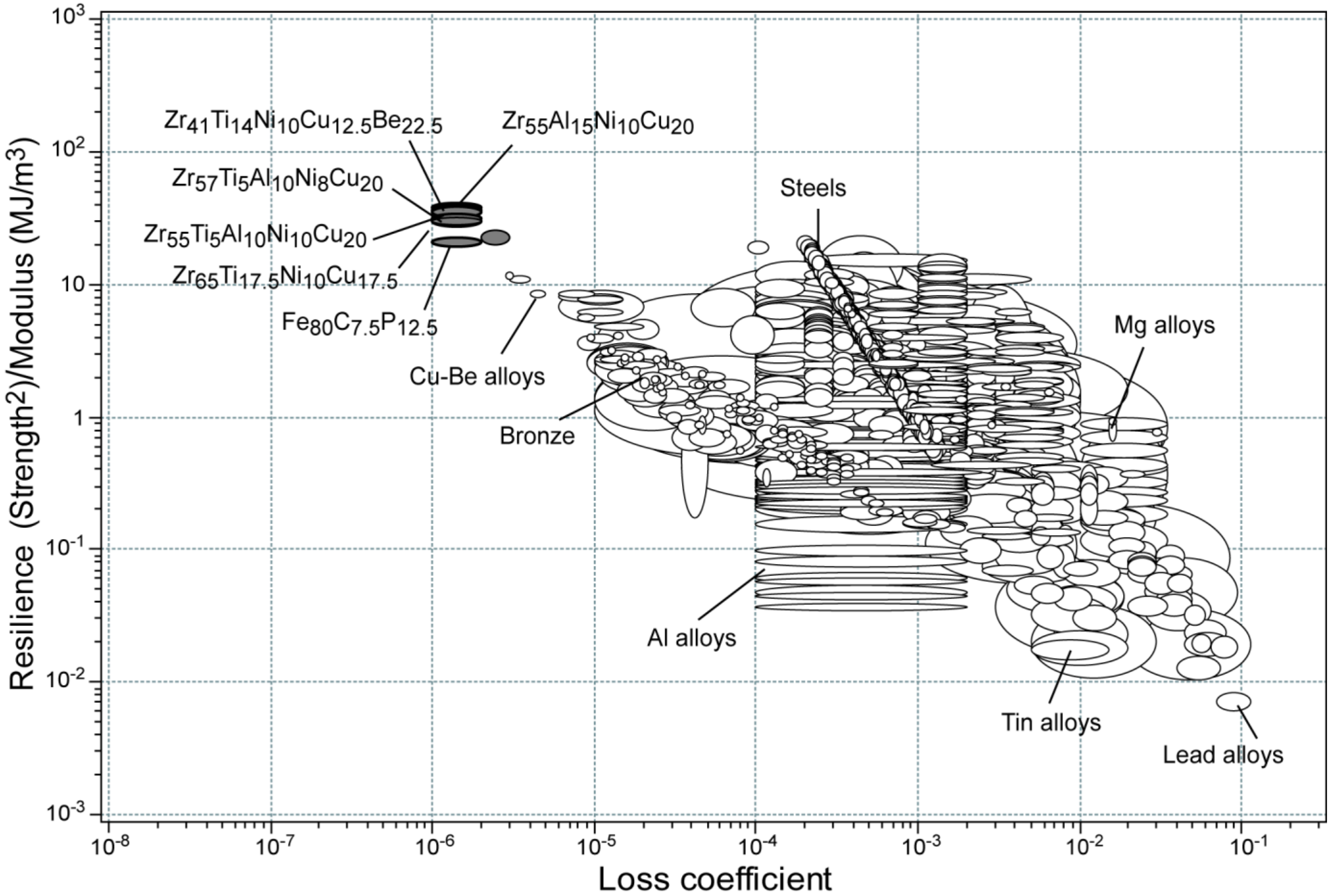
want to maximize
σ^2/E

from *Materials Selection in Mechanical Design* (2nd ed.)
M. F. Ashby, Butterworth-Heinemann, 1999

to increase the elastic stored energy —



Golf clubs …. and tennis-racket frames, baseball bats, skis …

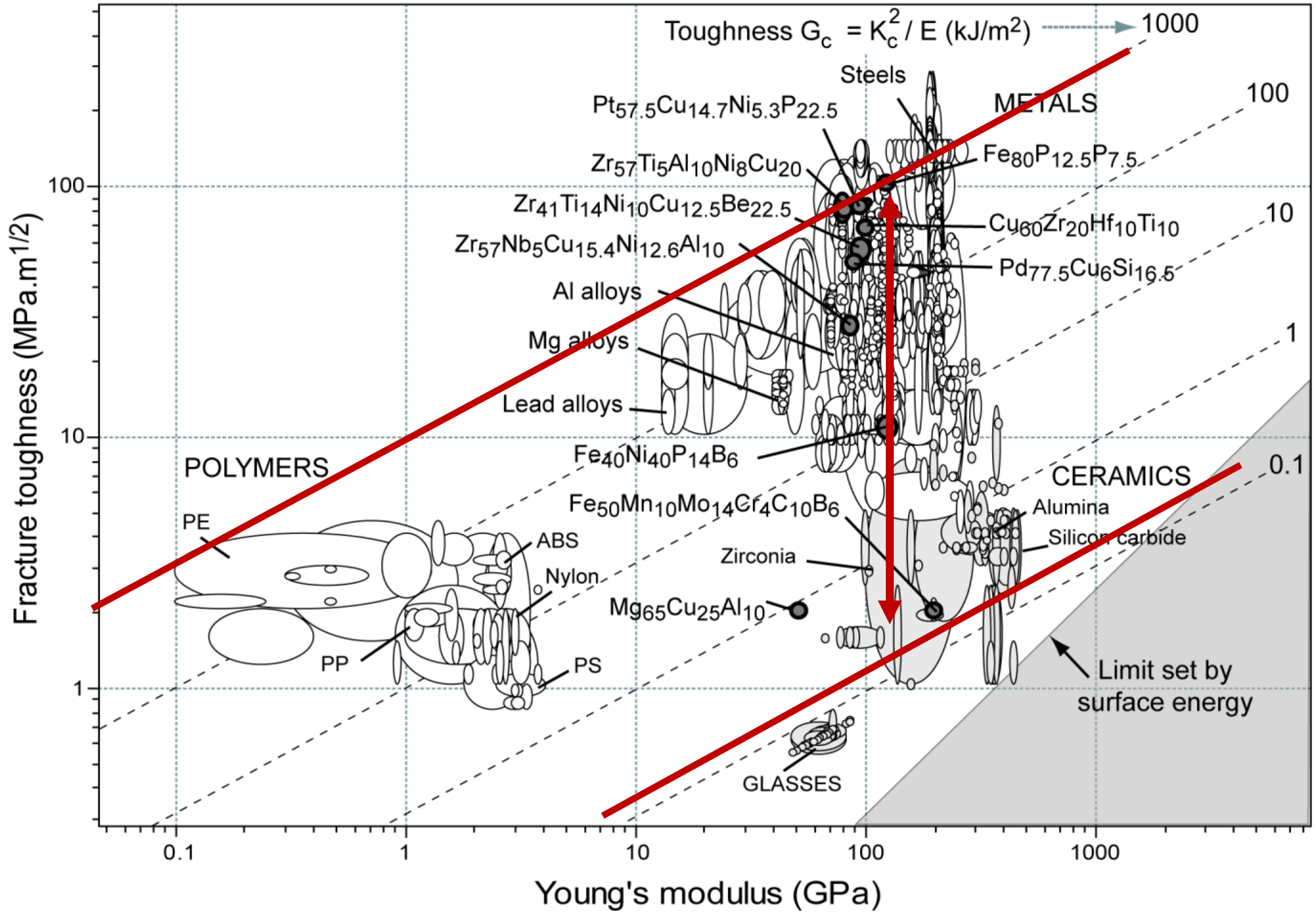


Resilience σ_y^2/E and **loss coefficient** η for 1507 metals, alloys, metal-matrix composites and metallic glasses.

M.F. Ashby & A.L. Greer: *Scripta Materialia* **54** (2006) 321.
(in Viewpoint Set on *Mechanical Behavior of Metallic Glasses*, edited by T.C. Hufnagel)

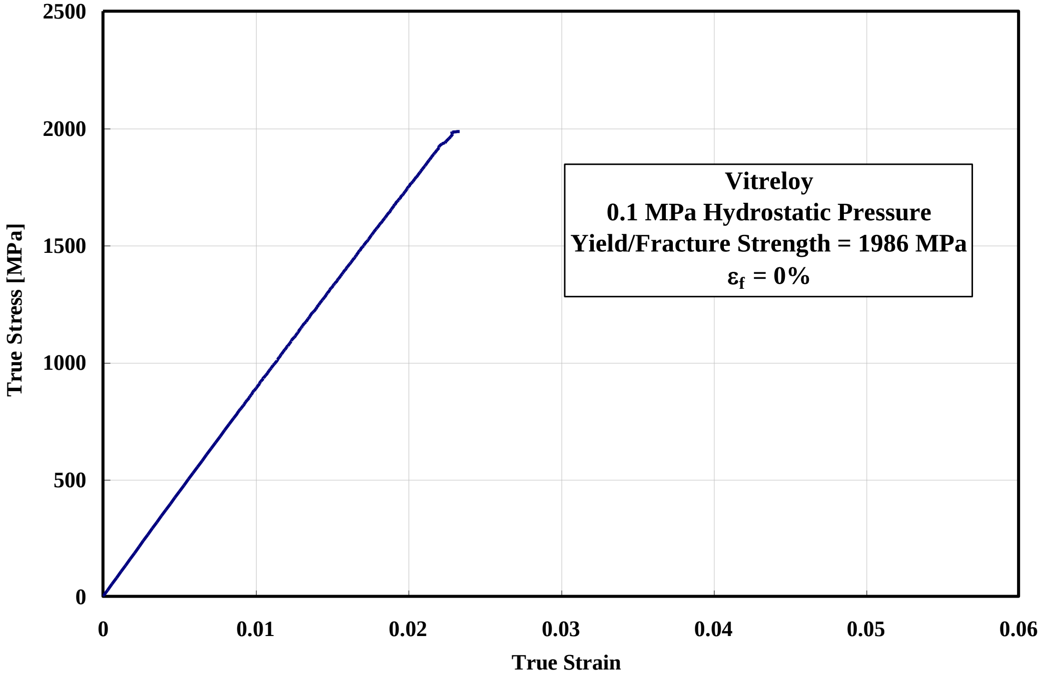
Conventional glasses are brittle —

What about metallic glasses?

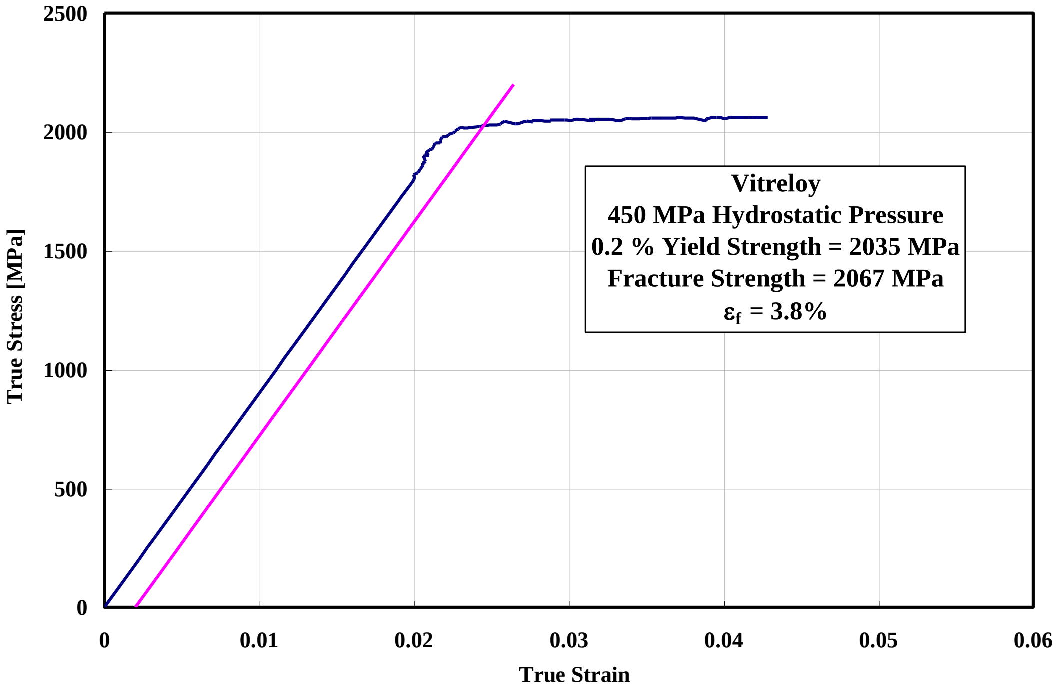


Fracture toughness and **Young's modulus** for metals, alloys, ceramic, glasses, polymers and metallic glasses. The contours show the **toughness** G_c in kJ m^{-2}.

M.F. Ashby & A.L. Greer: *Scripta Materialia* **54** (2006) 321.
(in Viewpoint Set on *Mechanical Behavior of Metallic Glasses*, edited by T.C. Hufnagel)

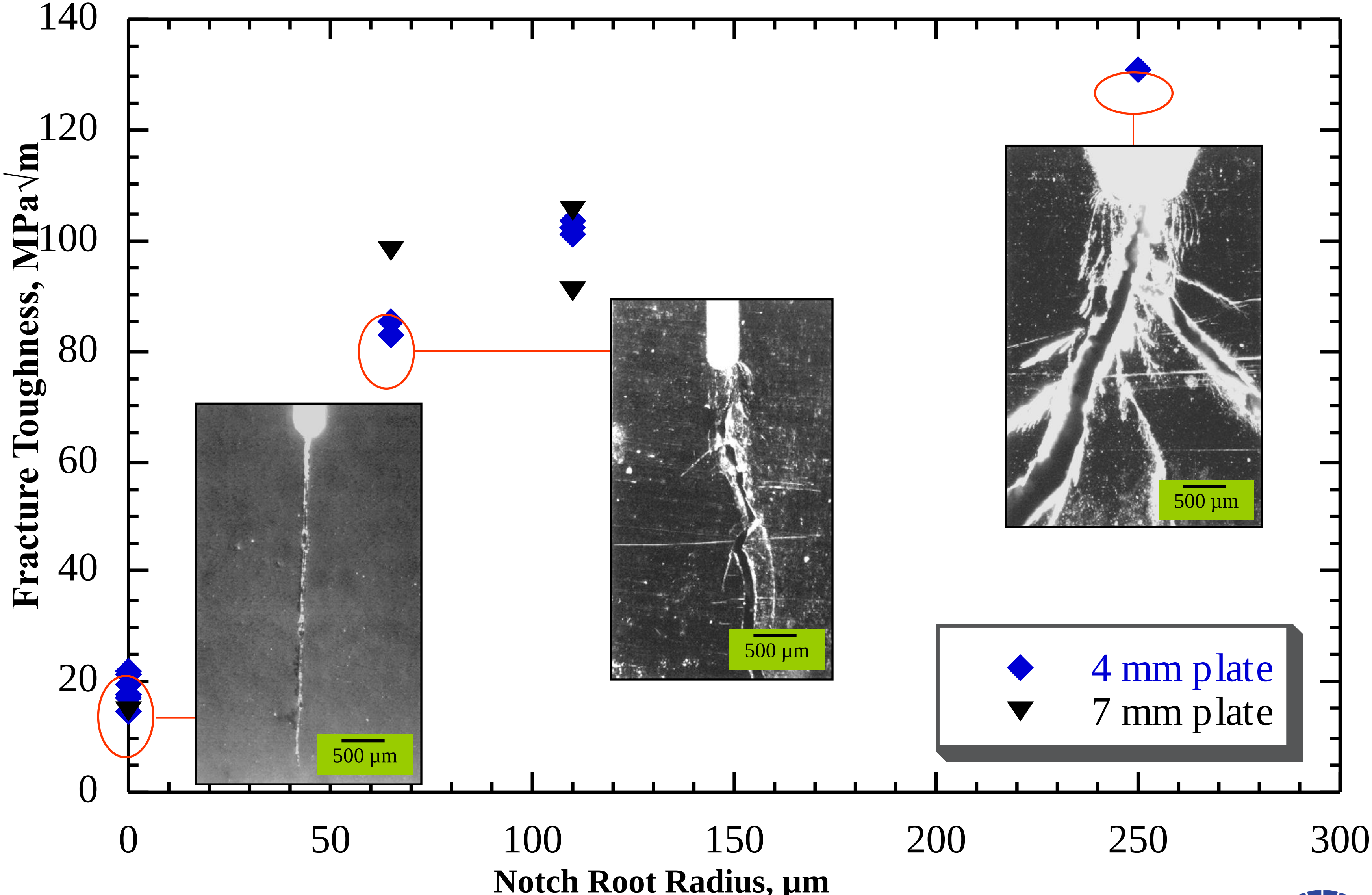


At ambient temperature metallic glasses **in tension** **appear macroscopically brittle**. There is plastic flow, but it is localized into **shear bands**, a sign of **work softening**.



J. J. Lewandowski

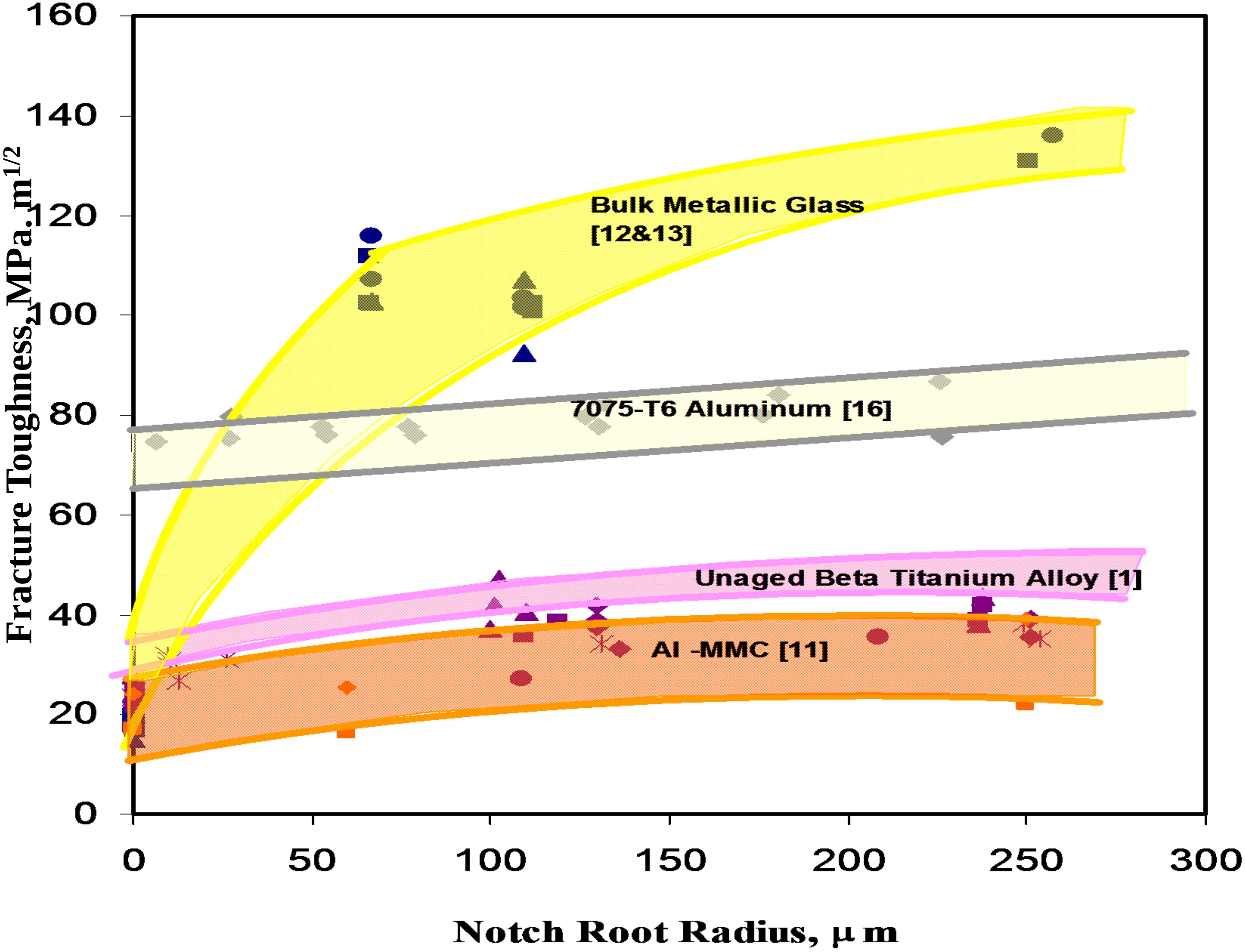
Effects of Notch Root Radius on Fracture Profile and Toughness of Zr-Ti-Ni-Cu-Be Bulk Metallic Glass



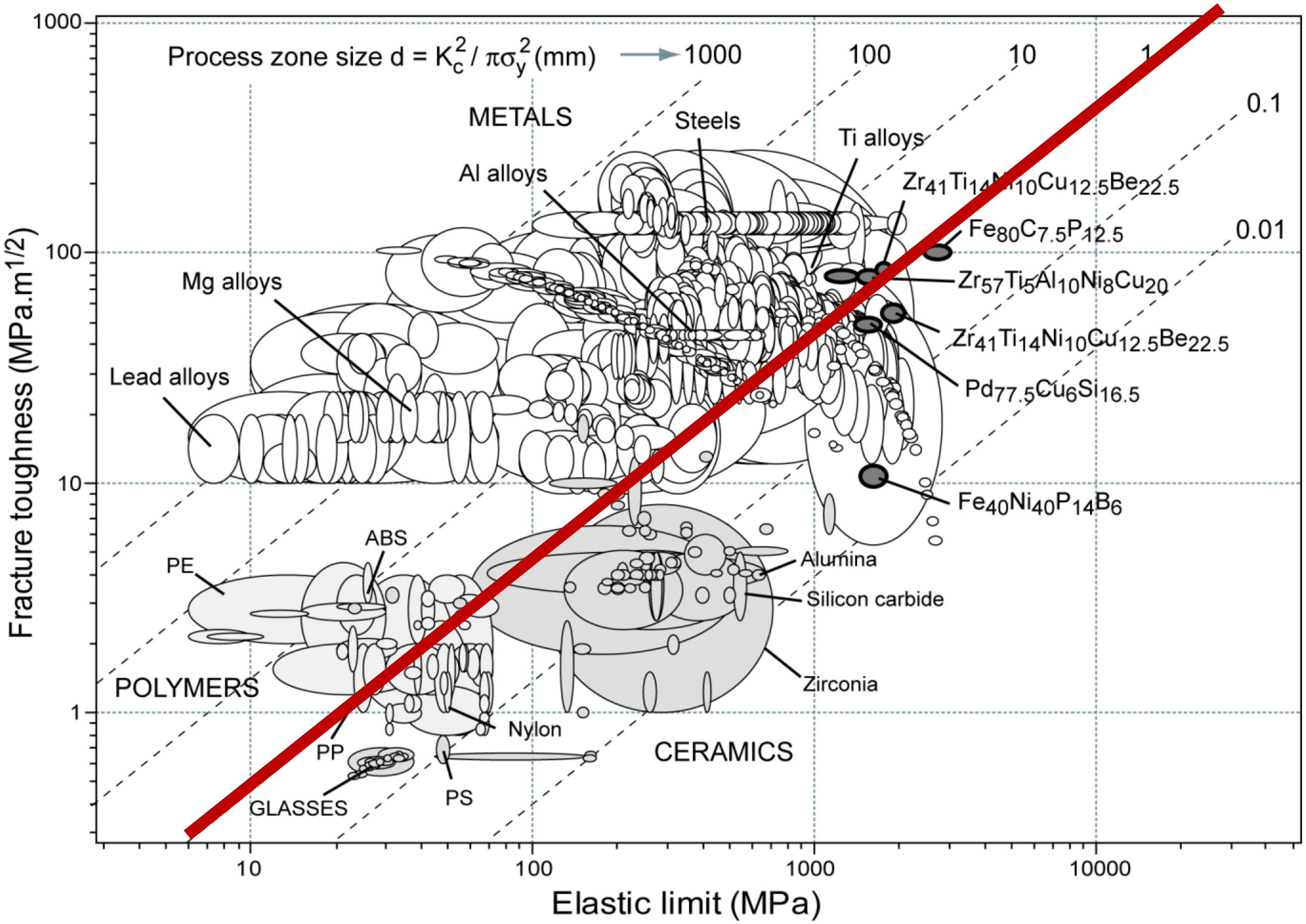
P. Lowhaphandu & J.J. Lewandowski, *Scripta Mater*. **38** (1998) 1811.

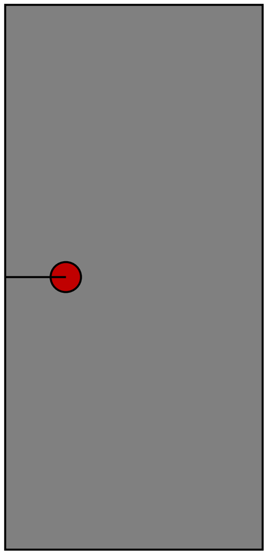
J.J. Lewandowski – DAAD19-01-0525

CWRU



J.J. Lewandowski, *Mater. Trans. JIM*, **42** (2001) 633.



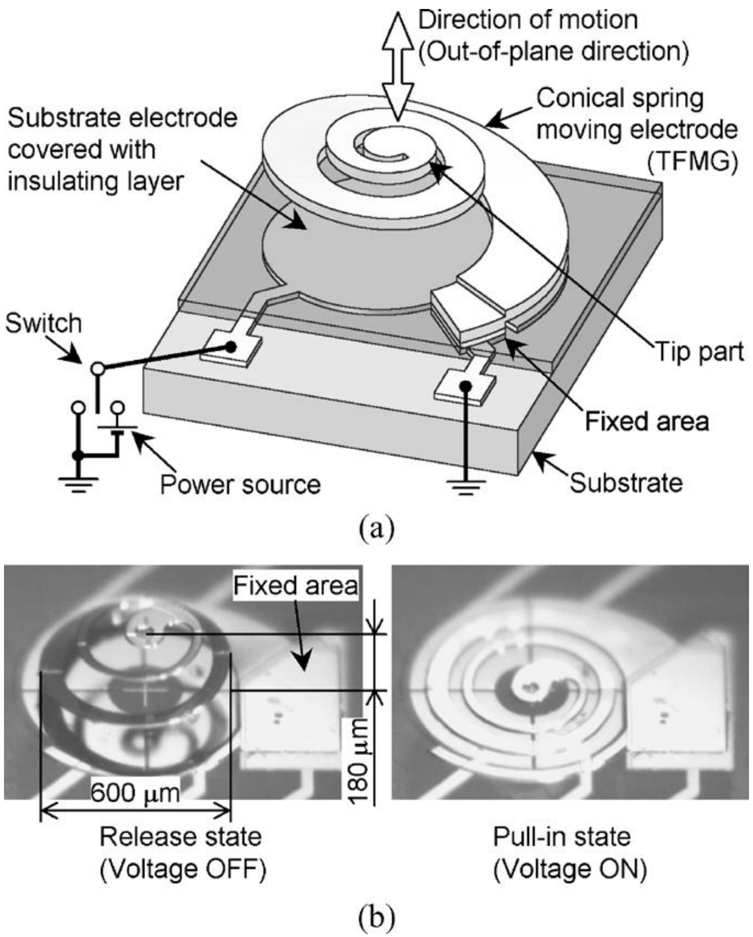


Fracture toughness and **elastic limit** for metals, alloys, ceramic, glasses, polymers and metallic glasses. The contours show the **process-zone size** *d* in mm.

M.F. Ashby & A.L. Greer: *Scripta Materialia* **54** (2006) 321.
(in Viewpoint Set on *Mechanical Behavior of Metallic Glasses*, edited by T.C. Hufnagel)

MEMS Applications

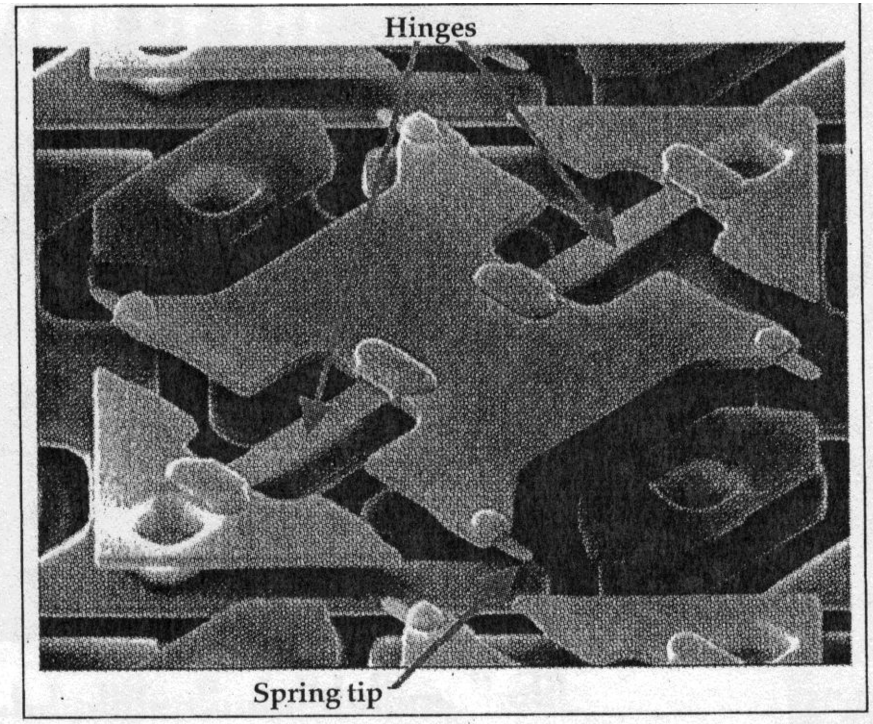
A conical spring microactuator with a long stroke of 200 μm normal to the substrate. The spring is a 7.6 μm thick film of $Pd_{76}Cu_7Si_{17}$ metallic glass.



T Fukushige & S Hata, *J. Microelectro. Syst*. (2005) **14**, 243

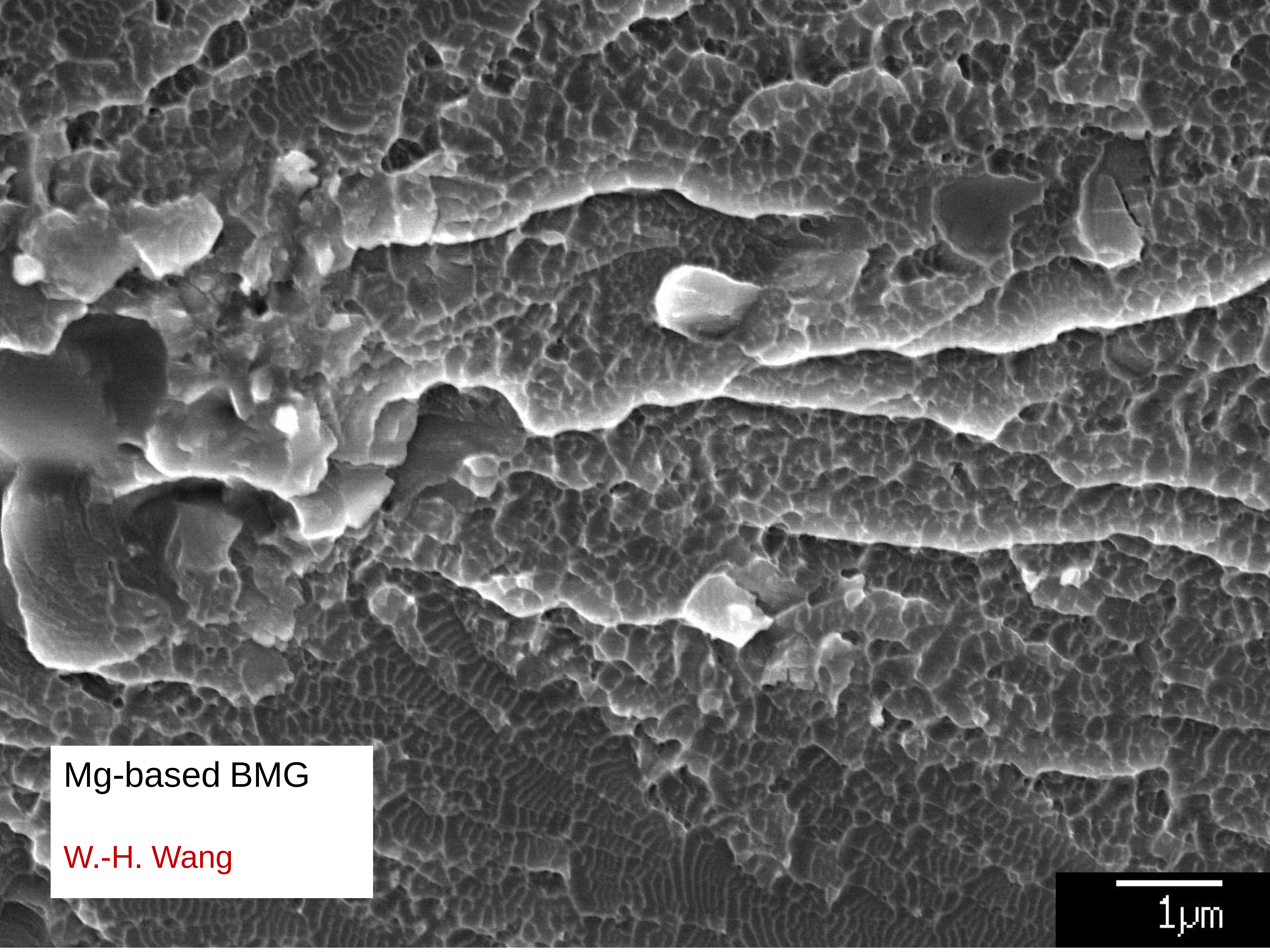
MEMS Applications of Metallic Glasses

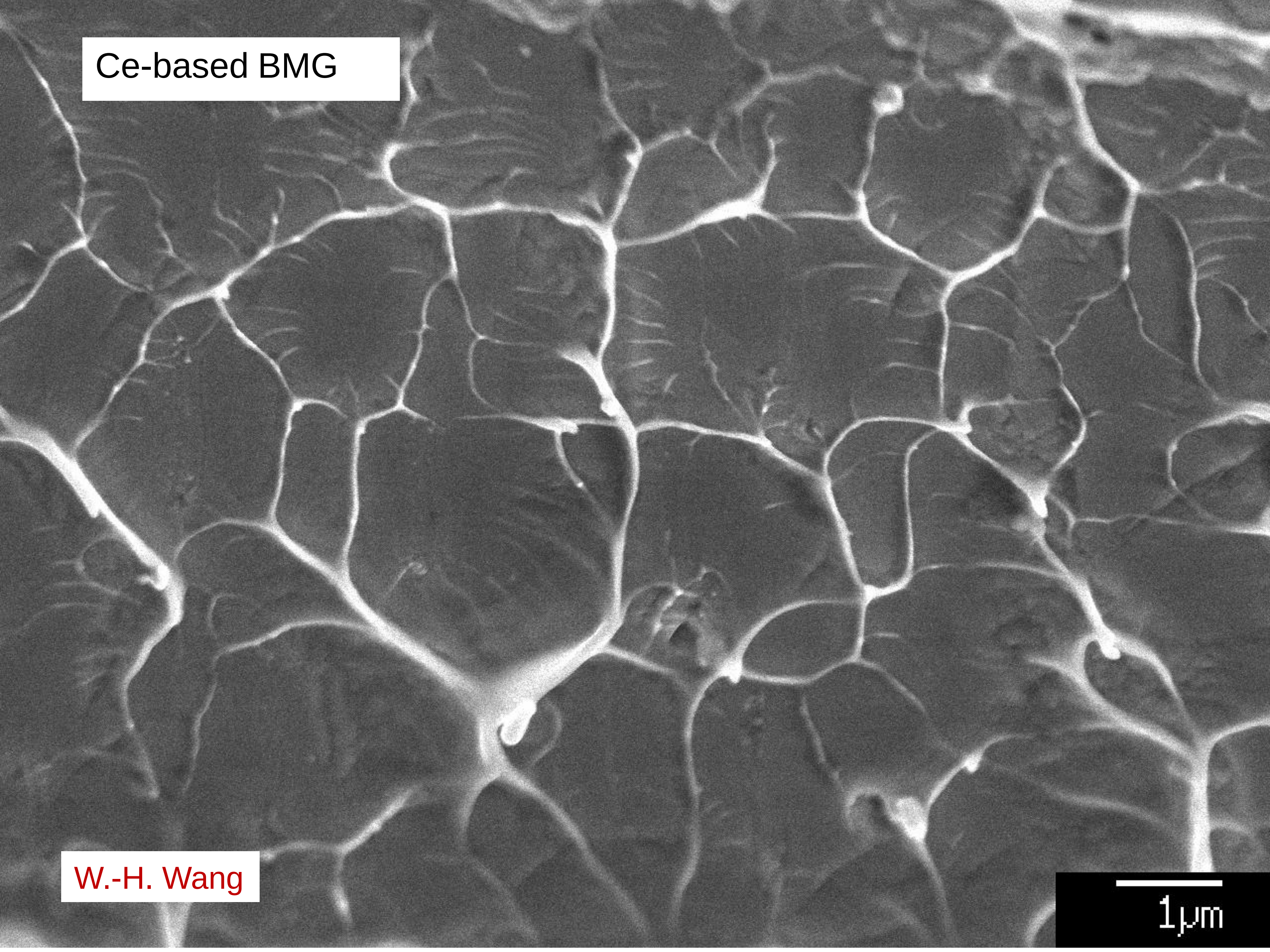
The Texas Instruments Digital Light Processor (DLP) data projector technology is based on mirrors supported by amorphous Ti-Al hinges. DLP devices with >1.3 x 10^6 addressable mirrors are in production, and the hinges still show no fatigue failures after 10^{12} cycles.



This diagram shows a close-up view of the hinges. This is an early digital light processor without the aluminum mirrors, to show the underlying structure with amorphous Ti-Al hinges and spring tips that allow for mirror rotation.

J.H. Tregilgas, "Amorphous titanium aluminide hinge"
Adv. Mater. Proc. **162** (Oct. 2004) 40.


Mg-based BMG
W.-H. Wang
1μm


Ce-based BMG
W.-H. Wang
1μm

Metals: Plasticity or Brittleness?

- the plastic flow stress in shear is proportional to the elastic shear modulus — thus the shear modulus is a measure of the difficulty of plastic flow
- similarly the bulk modulus is a measure of the difficulty of cracking
- thus high values of the shear-to-bulk modulus ratio μ/B should favour brittleness and vice versa
- proposed by Pugh in 1954, and developed by others —

S.F. Pugh, *Philos. Mag*. **45** 823 (1954).

A. Kelly, W.R. Tyson and A.H. Cottrell, *Philos*. *Mag*. **15** 567 (1967).

J.R. Rice and R. Thomson, *Philos. Mag*. **29** 73 (1974).

A.H. Cottrell, in *Advances in Physical Metallurgy*, edited by J.A. Charles and G.C. Smith (Institute of Metals, London, 1990), pp. 181–187.

- For polycrystalline metals there is a scale from ductile, low μ/B (Ag, Au, Cd, Cu) to brittle, high μ/B (Be, Ir)

- for fcc metals $(\mu/B)_{crit}$ = 0.43-0.56 or 0.32-0.57

- for hcp metals $(\mu/B)_{crit}$ = 0.60-0.63

- for bcc metals $(\mu/B)_{crit}$ = 0.35-0.68

- thus critical modulus ratio $(\mu/B)_{crit}$ is **not** very well defined even for one structure type

- $(\mu/B)_{crit}$ is affected by anisotropy

- most detailed theory for $(\mu/B)_{crit}$ concerns dislocation emission from a crack tip

What will happen for metallic glasses?

— no anisotropy

— no dislocations

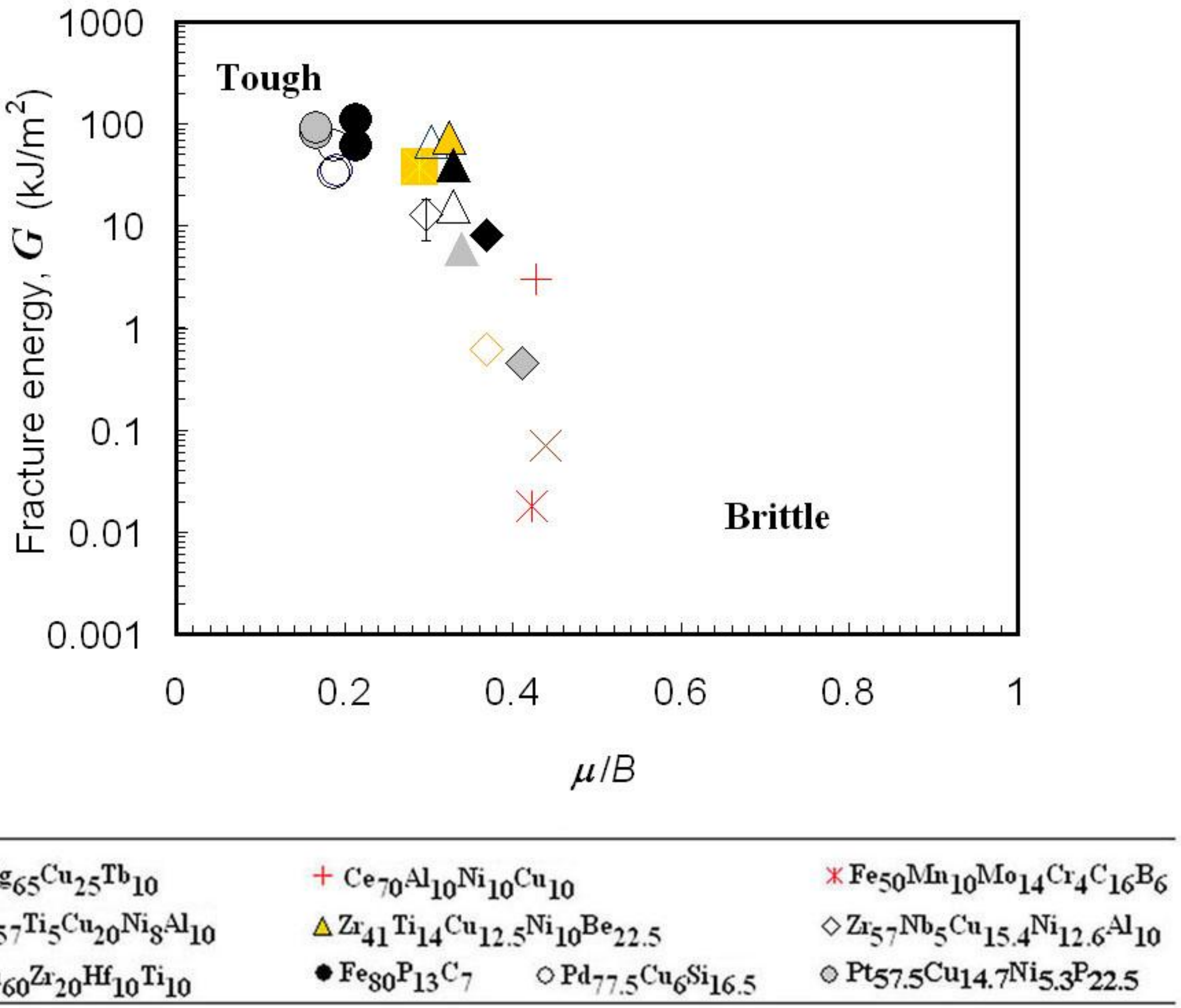
— no clearly different structures

With BMGs, good data are now available

Fracture data are presented in terms of the energy of fracture

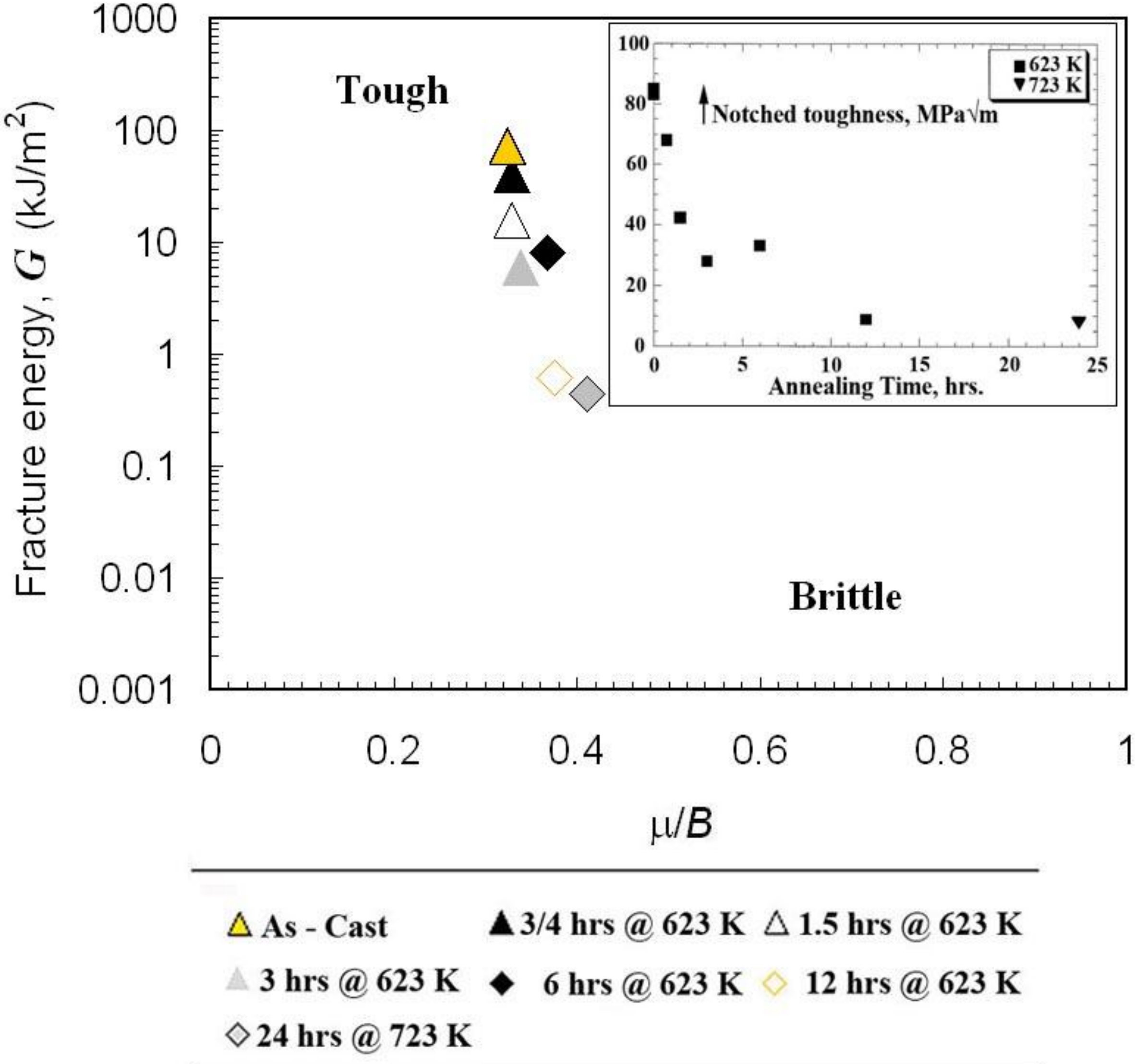
$$G = K^2/E(1 - \nu^2)$$

where K is the toughness (stress intensity at fracture) and ν is Poisson's ratio



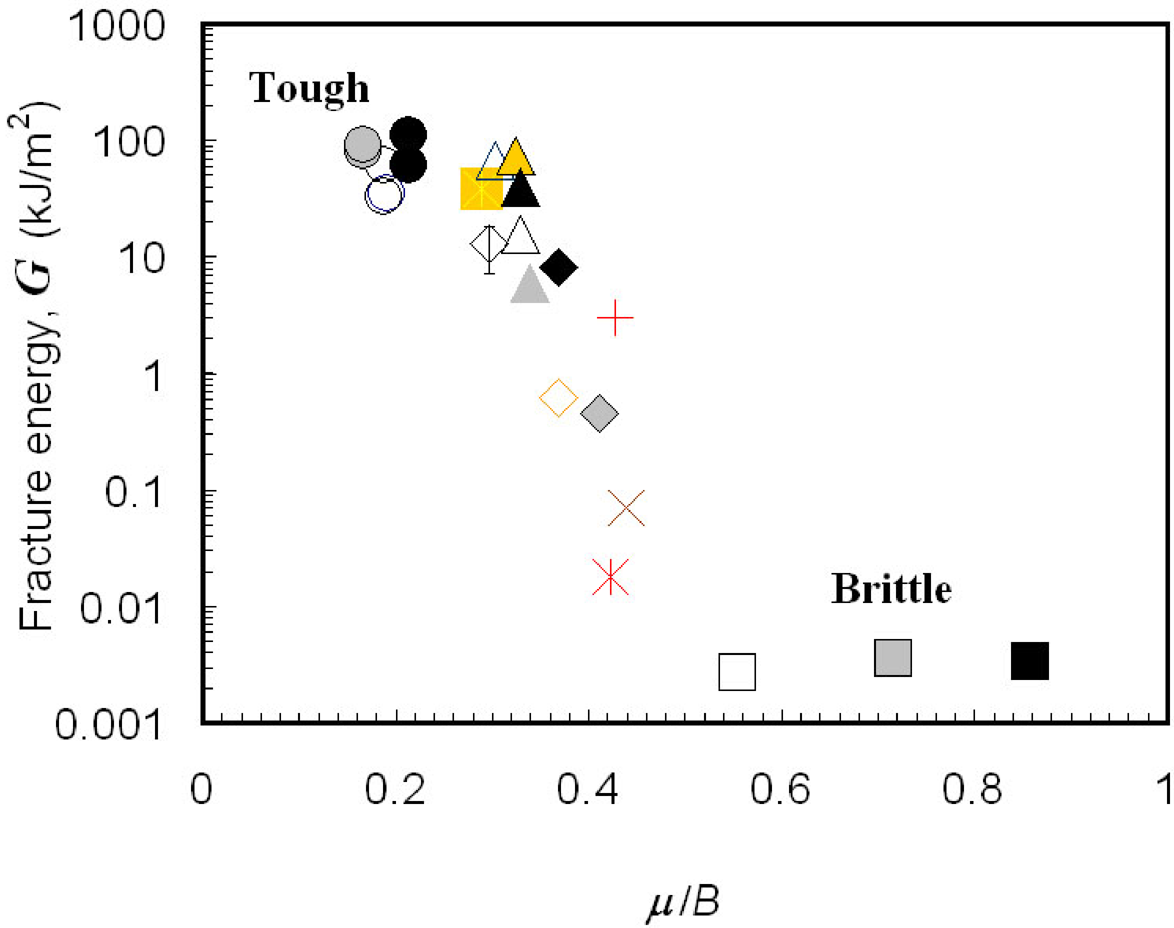
Compilation of **all** relevant and available data on as-cast (unannealed) metallic glasses (mostly, but not all BMGs)

J.J. Lewandowski, W.H. Wang & A.L. Greer, "Intrinsic plasticity or brittleness of metallic glasses", *Philos. Mag. Lett.* **85** (2005) 77.



The inset shows the decrease in toughness as a function of annealing time for Vitreloy 1. The main figure shows a good correlation of embrittlement with the changing *μ/B.*

J.J. Lewandowski, W.H. Wang & A.L. Greer, "Intrinsic plasticity or brittleness of metallic glasses", *Philos. Mag. Lett.* **85** (2005) 77.



□ Toughened (partially crystallized) glass ▩ Window glass ■ Fused silica

All the data superposed, together with data on oxide glasses for comparison. Overall, **$(\mu/B)_{crit}$ = 0.41-0.43**

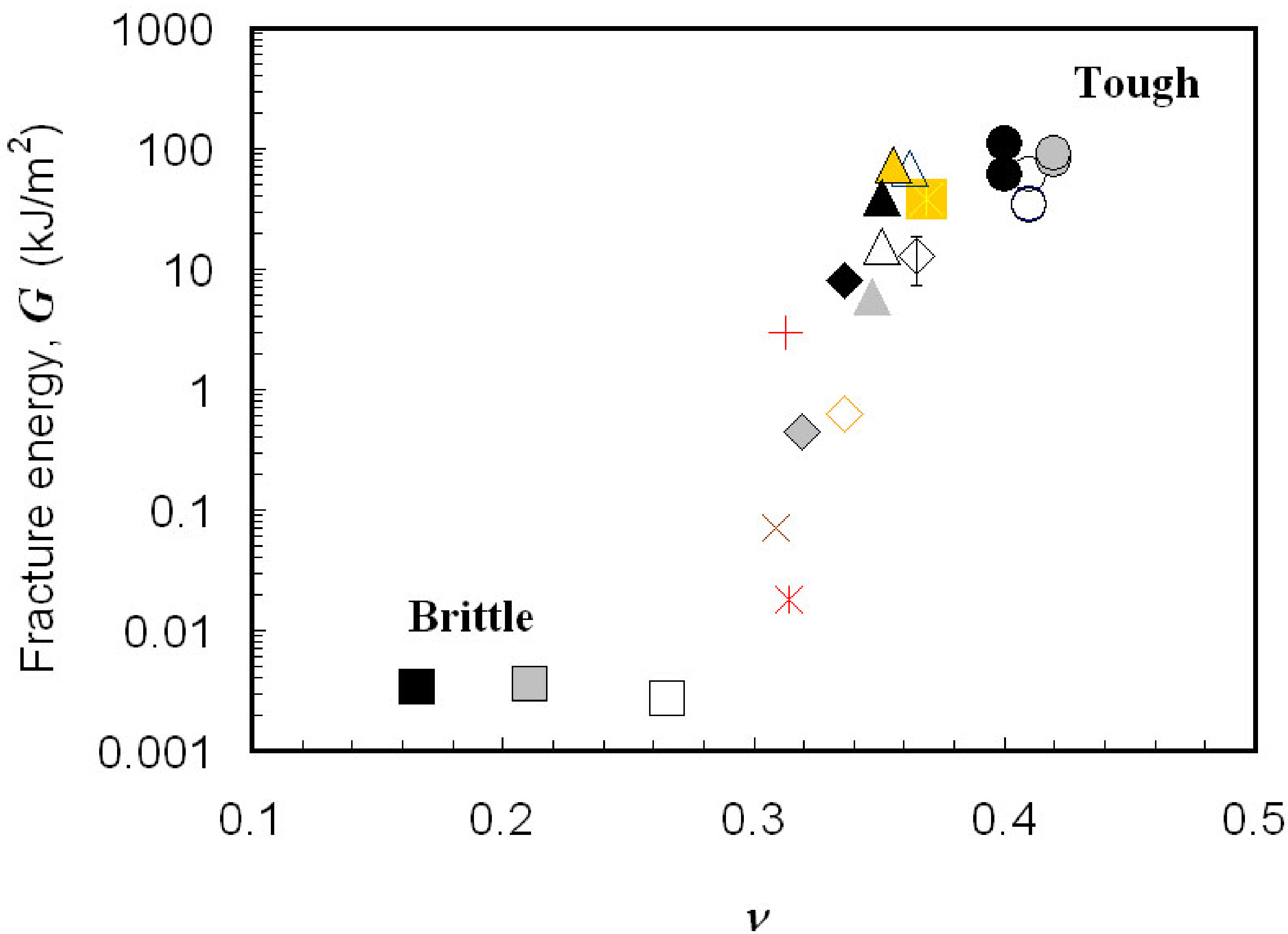
J.J. Lewandowski, W.H. Wang & A.L. Greer, "Intrinsic plasticity or brittleness of metallic glasses", *Philos. Mag. Lett.* **85** (2005) 77.

Poisson's ratio

J. Schroers & W. L. Johnson, [*Phys. Rev. Lett*. **93** (2004) 255506] show that —

• a Pt-rich glass ($Pt_{57.5}Cu_{14.7}Ni_{5.3}P_{22.5}$) has exceptionally good plasticity and exceptionally high Poisson's ratio ν. This is the same correlation because μ/B and ν are related by

$$\frac{\mu}{B} = \frac{3(1-2\nu)}{2(1+\nu)}$$



The same data presented in terms of Poisson's ratio. The critical value corresponding to $(\mu/B)_{crit}$ = 0.41-0.43 is ν_{crit} = 0.31-0.32.

J.J. Lewandowski, W.H. Wang & A.L. Greer, "Intrinsic plasticity or brittleness of metallic glasses", *Philos. Mag. Lett.* **85** (2005) 77.

Alloy design

To avoid intrinsic brittleness and to have greater resistance to annealing-induced embrittlement —

- we need to choose component elements with small μ/B or, equivalently, high ν (ideally ν should tend towards 0.5, which is the value for liquids)

plastic **brittle**

	Au	Nb	Pd	Pt	Hf	Al	Cu	Zr	Ti	Ni	Ca	Co	Fe	Mg	Nd	La	Pr	Y	Tb	Gd	Ce	Be
μ/B	0.12	0.22	0.24	0.27	0.27	0.35	0.35	0.39	0.42	0.43	0.44	0.45	0.48	0.49	0.50	0.52	0.52	0.54	0.57	0.58	0.61	1.02
ν	0.44	0.40	0.39	0.38	0.37	0.34	0.34	0.33	0.32	0.31	0.31	0.30	0.29	0.29	0.28	0.28	0.28	0.26	0.26	0.26	0.25	0.03

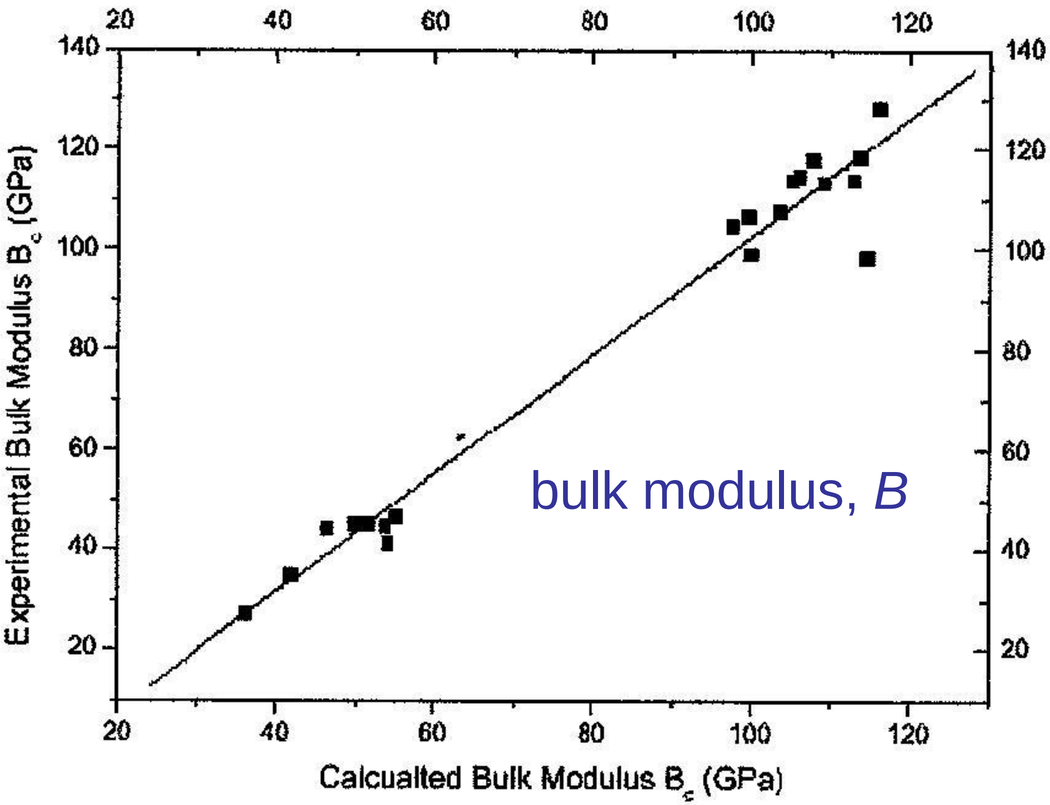
$\mu/B \longrightarrow$

$\longleftarrow \nu$

For metallic glasses containing only metals, elastic moduli can be predicted surprisingly well by simply taking a weighted average of the moduli of the constituent elements. The weighting here is by volume fraction —

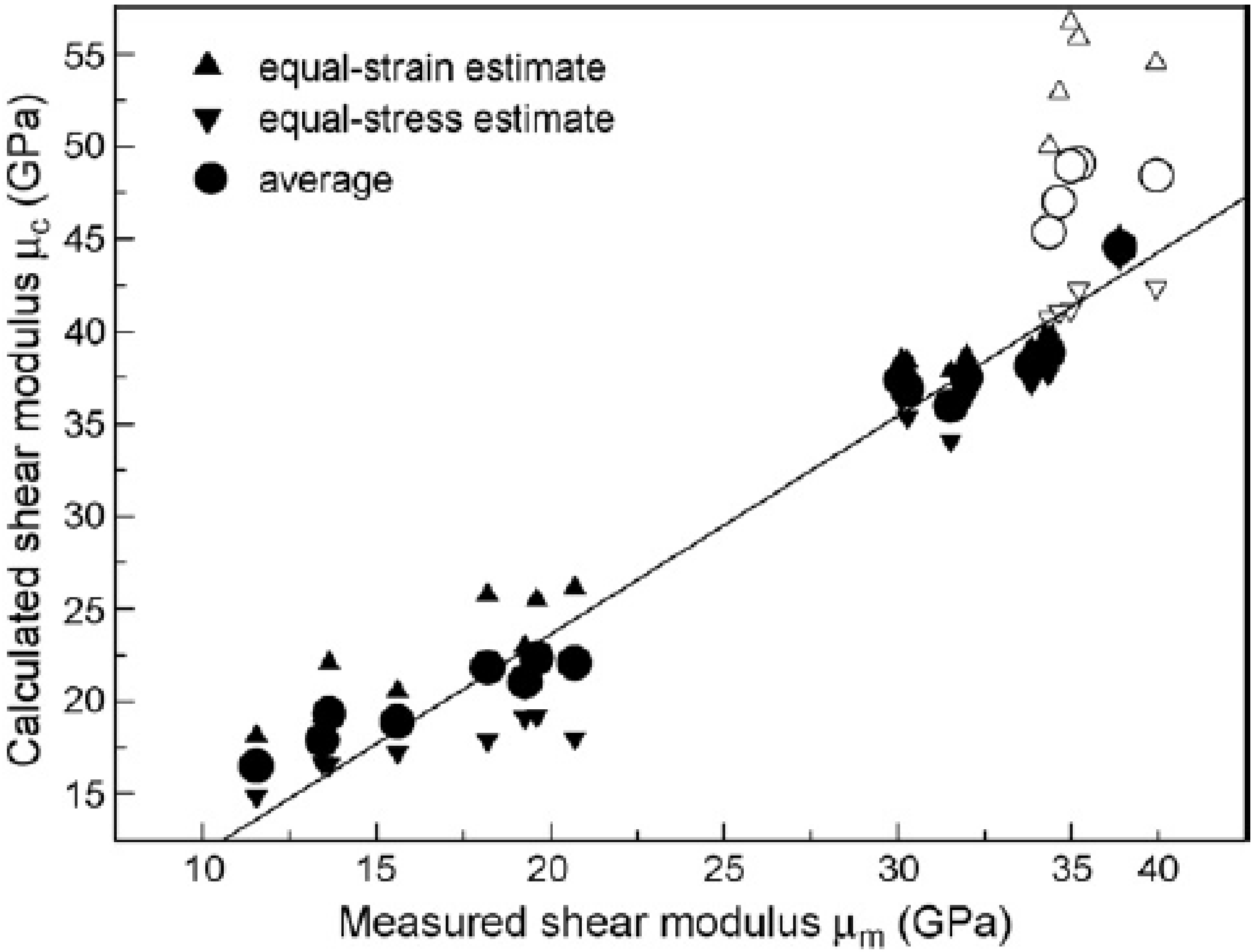
B scales with the number of valence electrons per unit volume

[J.J. Gilman: *Electronic Basis of the Strength of Materials*, CUP, Cambridge, 2003]



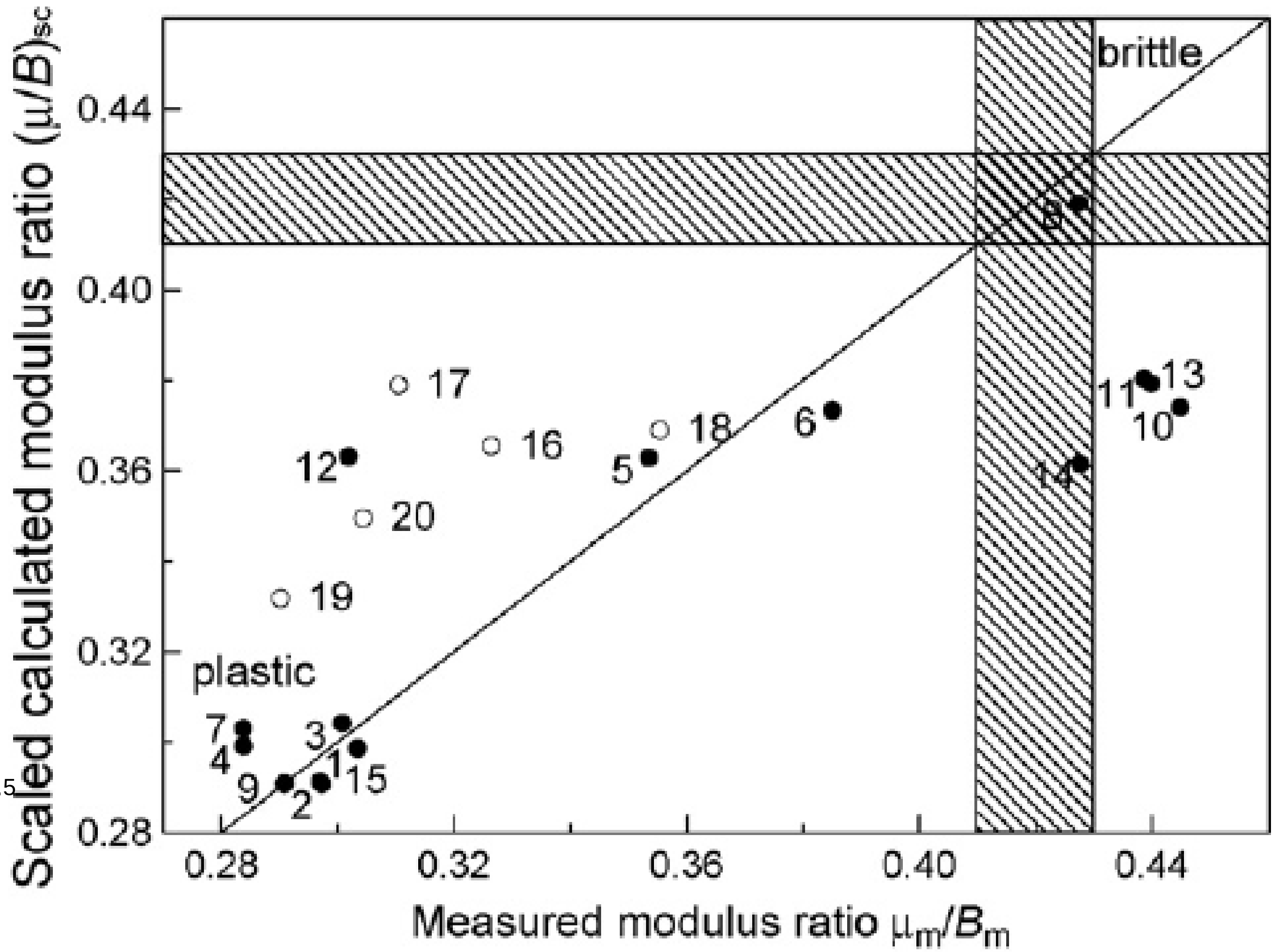
Since both μ and *B* can be predicted moderately well, we should be able to choose compositions to maximize plasticity.

ISMANAM 2005: (proceedings to be published in *J. Alloys Compounds*)
Y. Zhang & A.L. Greer, “Correlations for predicting plasticity or brittleness of metallic glasses”



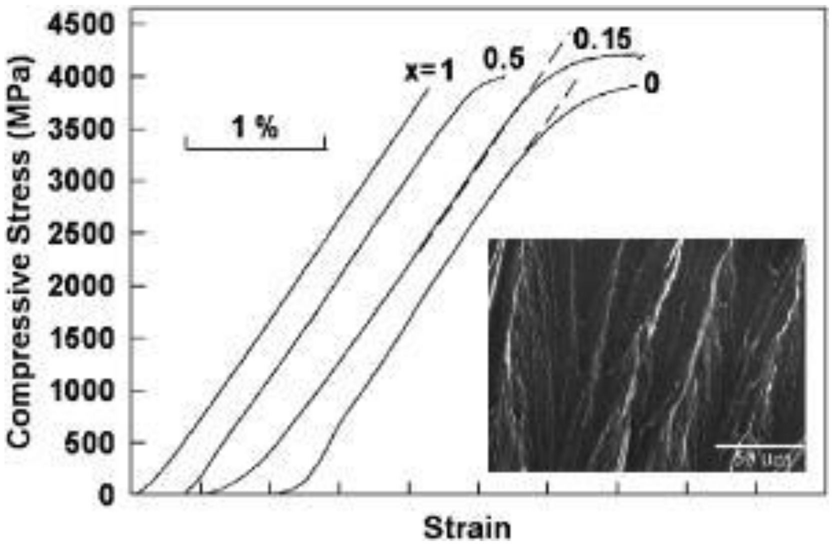
Y. Zhang & A.L. Greer: "Correlations for predicting plasticity or brittleness of metallic glasses", *J. Alloys Comp.* **434-435** (2007) 2.

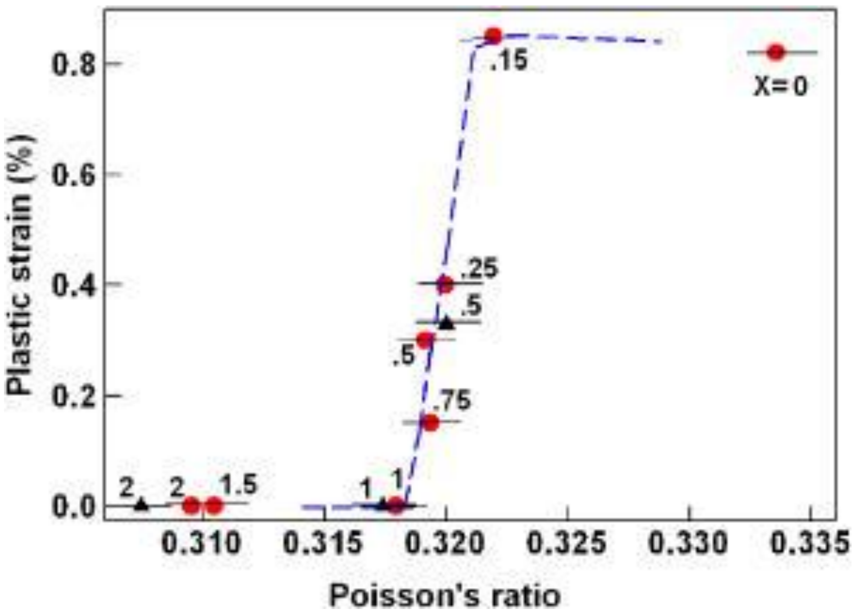
1. $Zr_{57}Ti_5Cu_{20}Ni_8Al_{10}$
2. $Zr_{57}Nb_5Cu_{15}.4Ni_{12.6}Al_{10}$
3. $(Zr_{55}Al_{15}Ni_{10}Cu_{20})_{96}Y_4$
4. $Zr_{65}Al_{10}Ni_{10}Cu_{15}$
5. $La_{55}Al_{25}Cu_{10}Ni_5Co_5$
6. $La_{66}Al_{14}Cu_{10}Ni_{10}$
7. $Cu_{60}Zr_{20}Hf_{10}Ti_{10}$
8. $Cu_{50}Zr_{42.5}Ti_{2.5}Al_5$
9. $Cu_{47}Zr_{47}Al_6$
10. $Mg_{65}Cu_{25}Tb_{10}$
11. $Mg_{65}Cu_{25}Gd_{10}$
12. $Pr_{55}Al_{12}Fe_{30}Cu_3$
13. $Pr_{60}Al_{10}Ni_{10}Cu_{20}$
14. $Ce_{70}Al_{10}Ni_{10}Cu_{10}$
15. $Nd_{60}Al_{10}Fe_{20}Co_{10}$
16. $Zr_{41}Ti_{14}Cu_{12.5}Ni_{10}Be_{22.5}$
17. $Zr_{46.75}Ti_{8.25}Cu_{7.5}Ni_{10}Be_{27.5}$
18. $Zr_{41}Ti_{14}Cu_{12.5}Ni_2Be_{22.5}$
19. $Zr_{48}Nb_8Cu_{14}Ni_{12}Be_{18}$
20. $Zr_{48}Nb_8Cu_{12}Fe_8Be_{24}$



Y. Zhang & A.L. Greer: “Correlations for predicting plasticity or brittleness of metallic glasses”, *J. Alloys Comp.* **434-435** (2007) 2.

Use of doping to improve plasticity





Compression tests on $Fe_{65}Mo_{14}C_{15}B_6$ show improved plasticity on doping with Er or Dy.

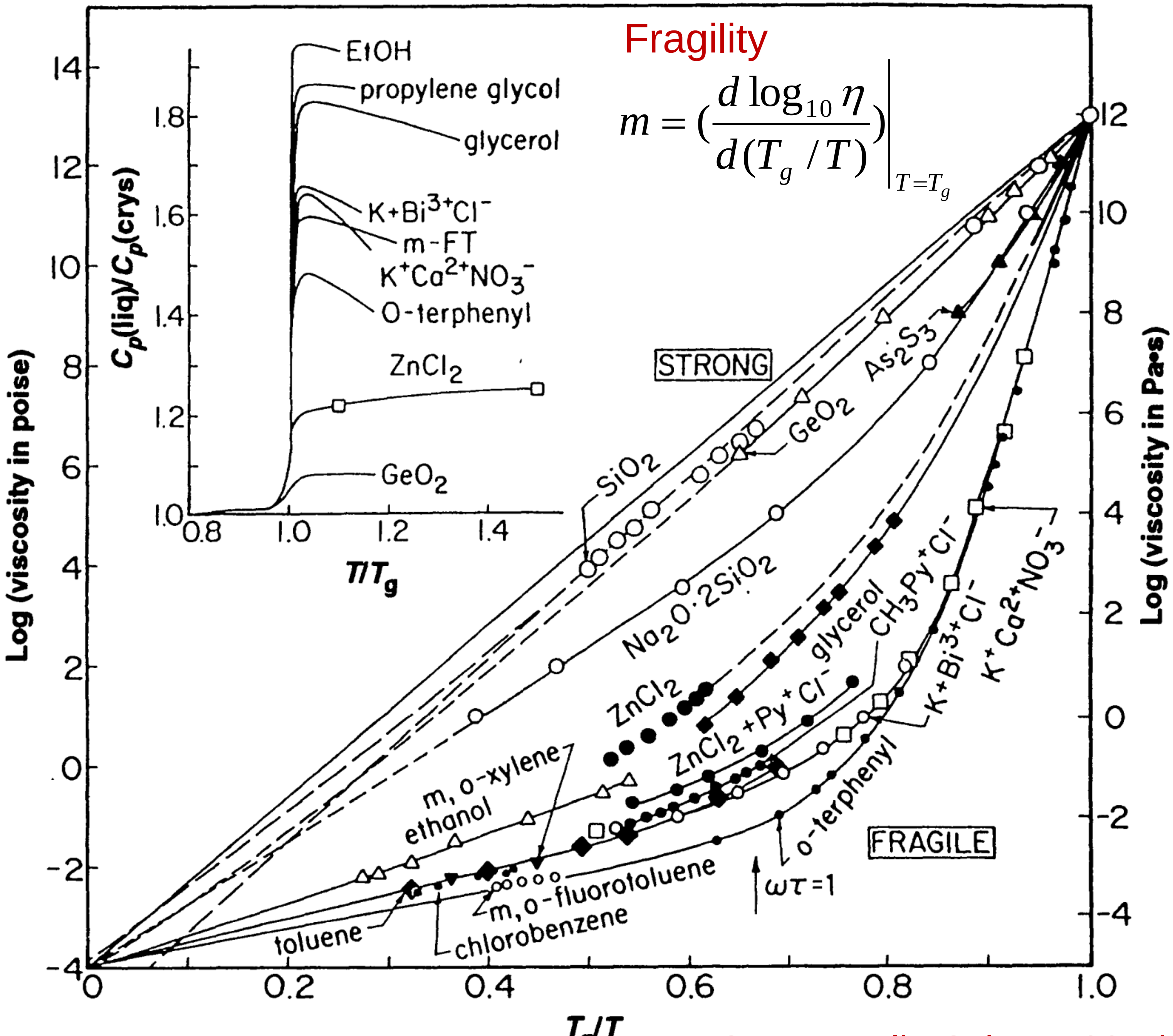
$Fe_{65-x}Mo_{14}C_{15}B_6Er_x$ (circles)
$Fe_{65-x}Mo_{14}C_{15}B_6Dy_x$ (triangles)

The critical ν is again ~0.32

X.J. Guo, A.G. McDermott, S.J. Poon & G.J. Shiflet, *Appl. Phys. Lett.* **88** (2006) 211905.

Fragility

$$m = \left(\frac{d \log_{10} \eta}{d(T_g / T)}\right)\Bigg|_{T=T_g}$$

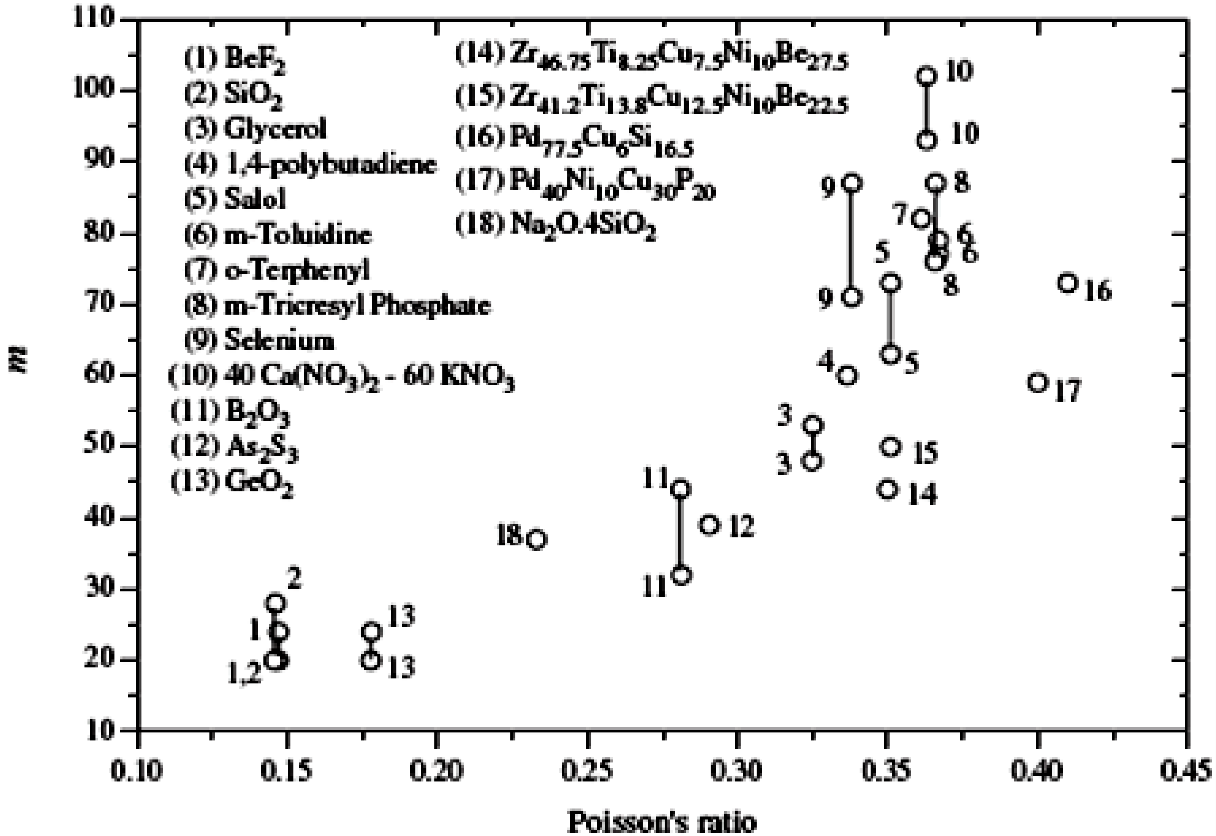


C. A. Angell: *Science* **267** (1995) 1924.

Angell's "fragility" of liquid: $m = (\frac{d \log_{10} \eta}{d(T_g / T)})\Big|_{T=T_g}$

"fragility"

"strength"



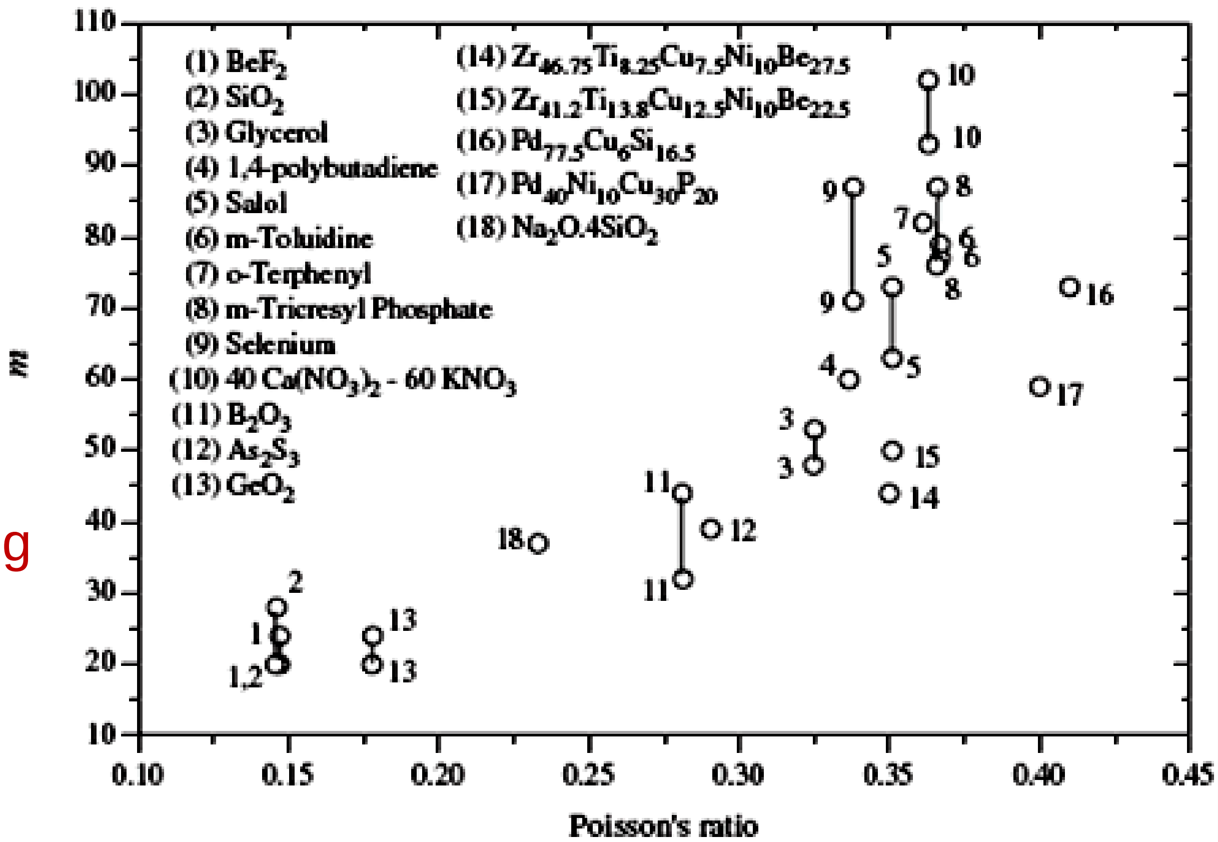
brittleness
"fragility"

plasticity
"strength"

G. P. Johari: *Philos. Mag*. **86** (2006) 1567.

The better the glass-forming ability, the more likely to be brittle!

better glass-forming ability



brittleness ⟷ plasticity

Deformation of Metallic Glasses

Ambient temperature / high stress
-- flow localization in shear bands

High temperature / low stress
-- homogeneous viscous flow

F. Spaepen: "A microscopic mechanism for steady state inhomogeneous flow in metallic glasses", *Acta Metall*. **25** (1977) 407.

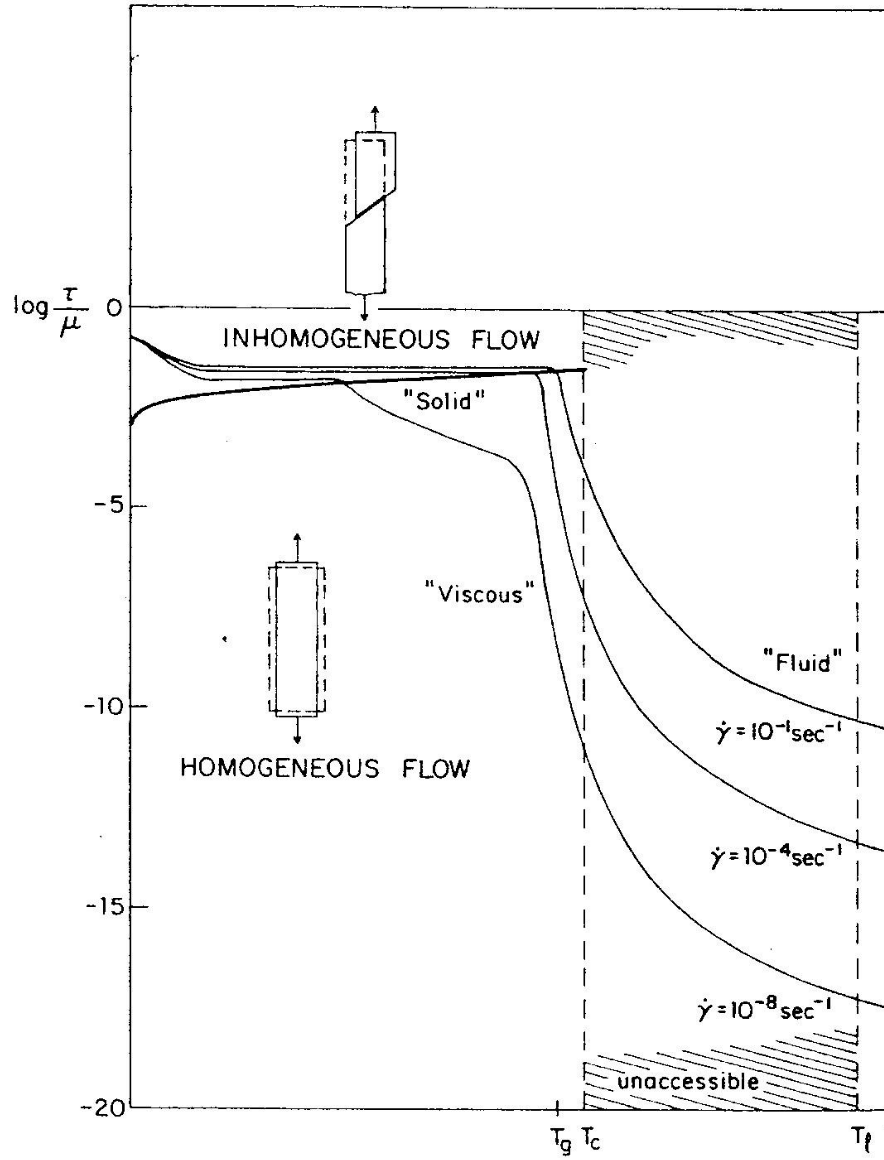
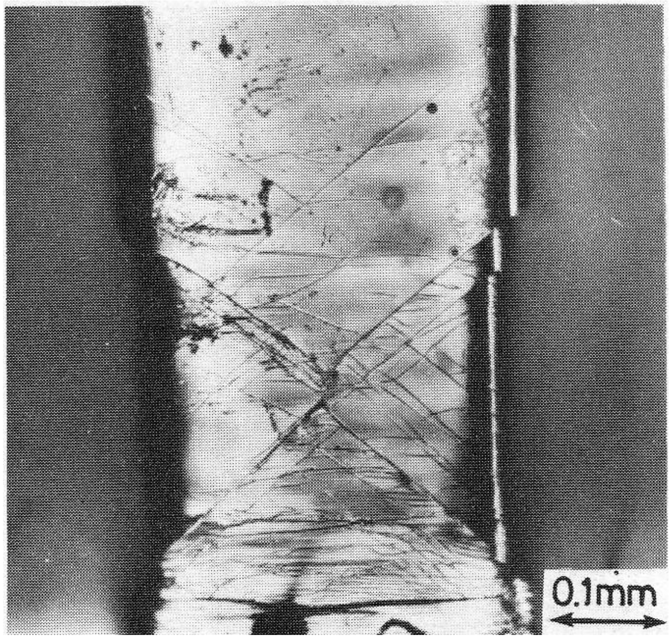


Fig. 2. Schematic deformation map of a metallic glass. The various modes of deformation are indicated.

The flow in shear bands does change the structure

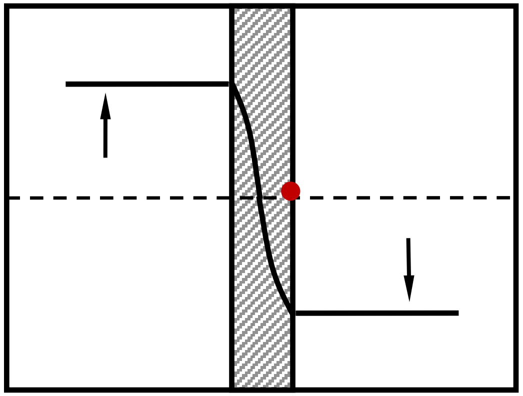
—and the structural change can be erased by annealing



- **preferential etching at shear bands:**
  C.A. Pampillo, Scripta Metall. 6 (1972) 915

- **preferential shear on existing bands:**
  K.D. Krishnanand & R.W. Cahn, Scripta Metall. 9 (1975) 1259

Quench rate associated with shear bands?



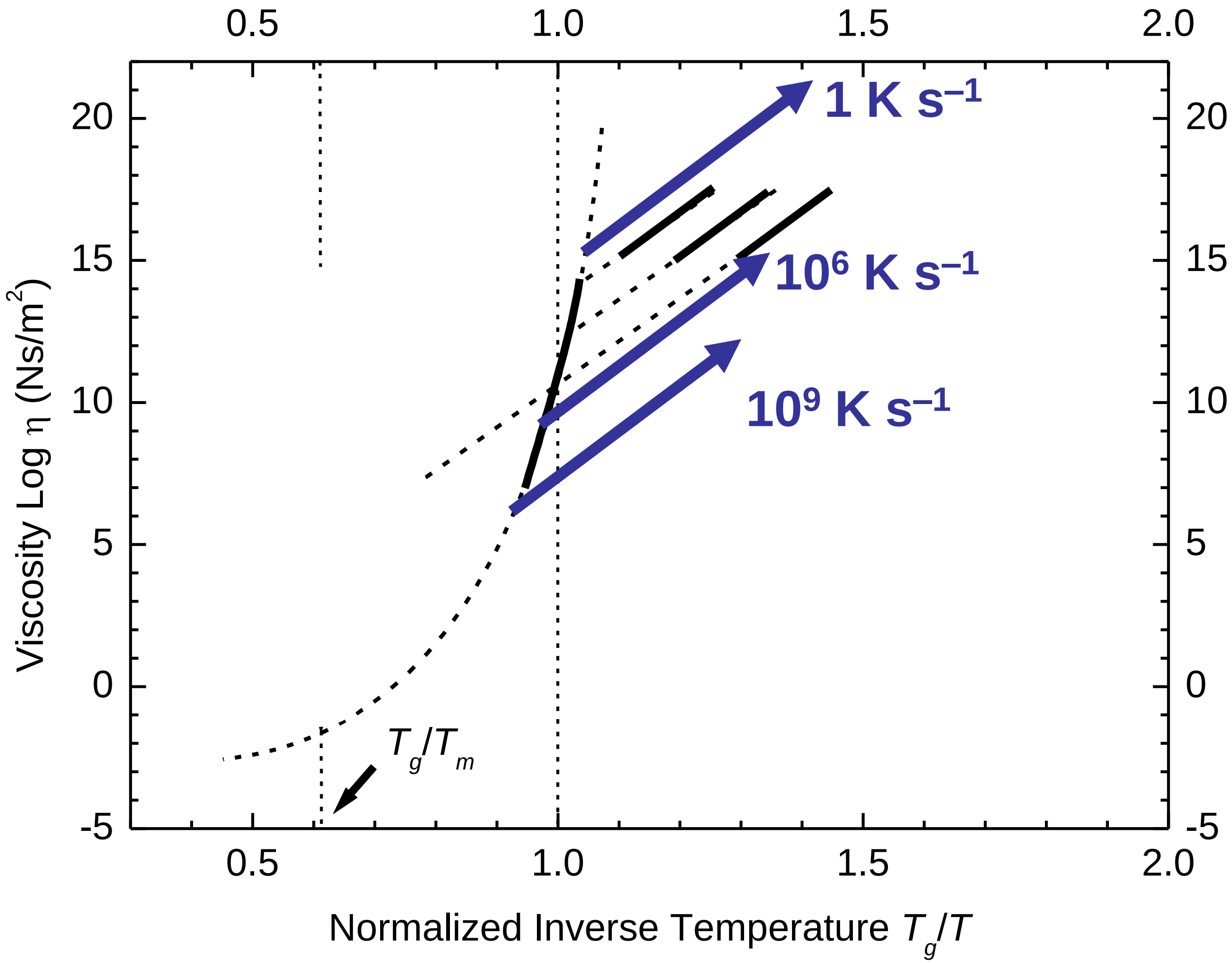
For a typical shear band in Vitreloy 1:

10 nm from centre plane

at T_g (= 613 K) (occurs at ~190 ns)

→ the cooling rate is **~10^9 K s^{-1}**

Variability in the metallic glassy state



Data on Pd-Cu-Si and Pd-Si glasses from A.I. Taub & F. Spaepen, *Acta Metall.* **28** (1980) 1781. Isoconfigurational heating shown by C.A. Volkert & F. Spaepen, *Acta Metall.* **37** (1989) 1355.

L. Battezzati et al. *J. Non-Cryst. Solids* **61-62** (1984) 877.

— heat of relaxation is affected by quenching rate

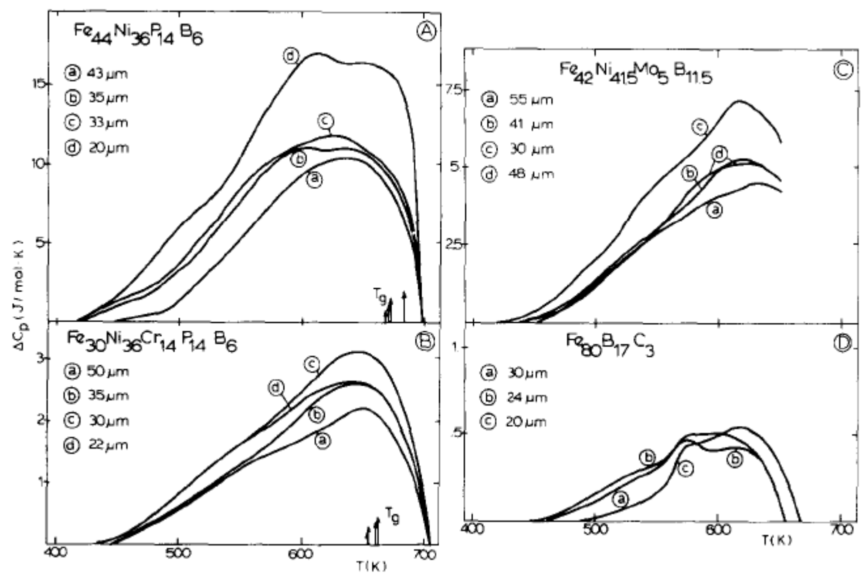


TABLE 1

Enthalpy of relaxation of metallic glasses prepared with different quenching rates. Ribbon thickness is given in brackets (μm).

Alloy	Enthalpy of crystallization (kJ/mol)	Enthalpy of relaxation (kJ/mol) at wheel velocity (m/s)				
		20	25	30	40	50
$Fe_{44}Ni_{36}P_{14}B_6$	7.9	2.6 (43)	3.5 (35)	3.6 (33)		5.5 (20)
$Fe_{30}Ni_{36}Cr_{14}P_{14}B_6$	4.3	1.0 (50)		1.3 (35)	1.6 (30)	1.5 (22)
$Fe_{42}Ni_{41.5}Mo_5B_{11.5}$	4.4		1.1 (55)	1.2 (41)	1.8 (30)	1.2 (48)
$Fe_{80}B_{17}C_3$	3.0			0.7 (30)	0.6 (24)	0.6 (20)

The Stored Energy of Cold Work

Early work by H.S. Chen

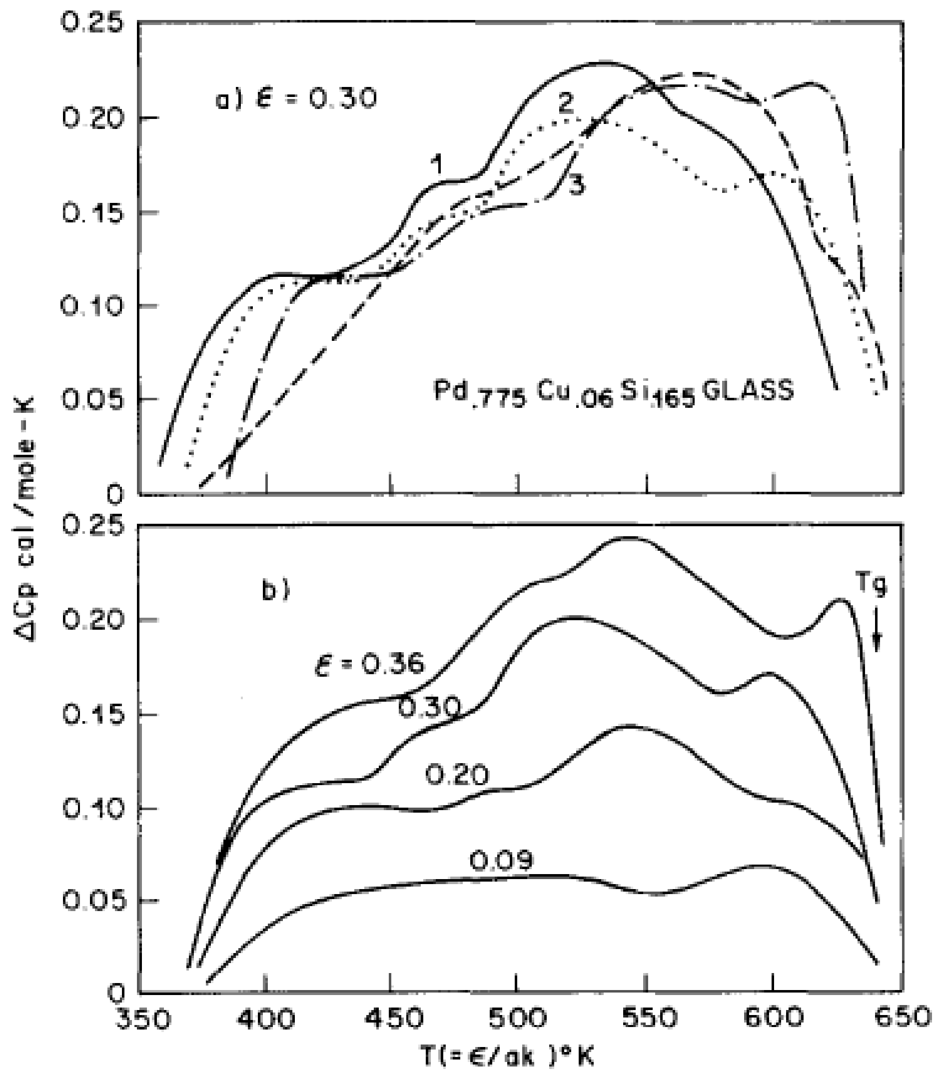
***Appl. Phys. Lett*. 29 (1976) 328.**

Melt-spun $Pd_{77.5}Cu_6Si_{16.5}$ cold-rolled to a maximum reduction of 36%.

Heat of relaxation measured in DSC —

Maximum stored energy

209 J mol^{-1}



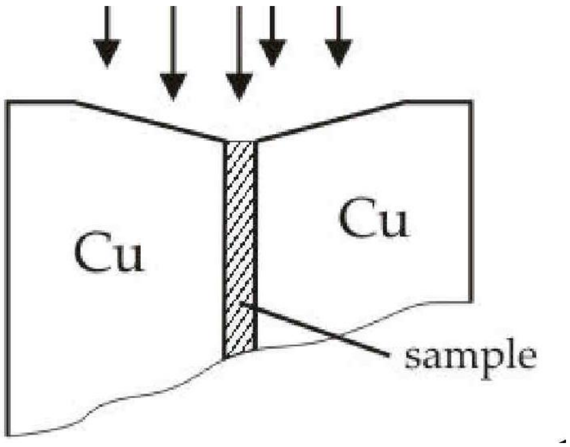
Relaxation spectrum of $Pd_{40}Cu_{30}Ni_{10}P_{20}$

Shot-peening of end-face of the metallic-glass rods

— at liquid-nitrogen temperature

— at dry-ice temperature, or

— at room temperature



— can store up to ~7% of the cold work at RT.

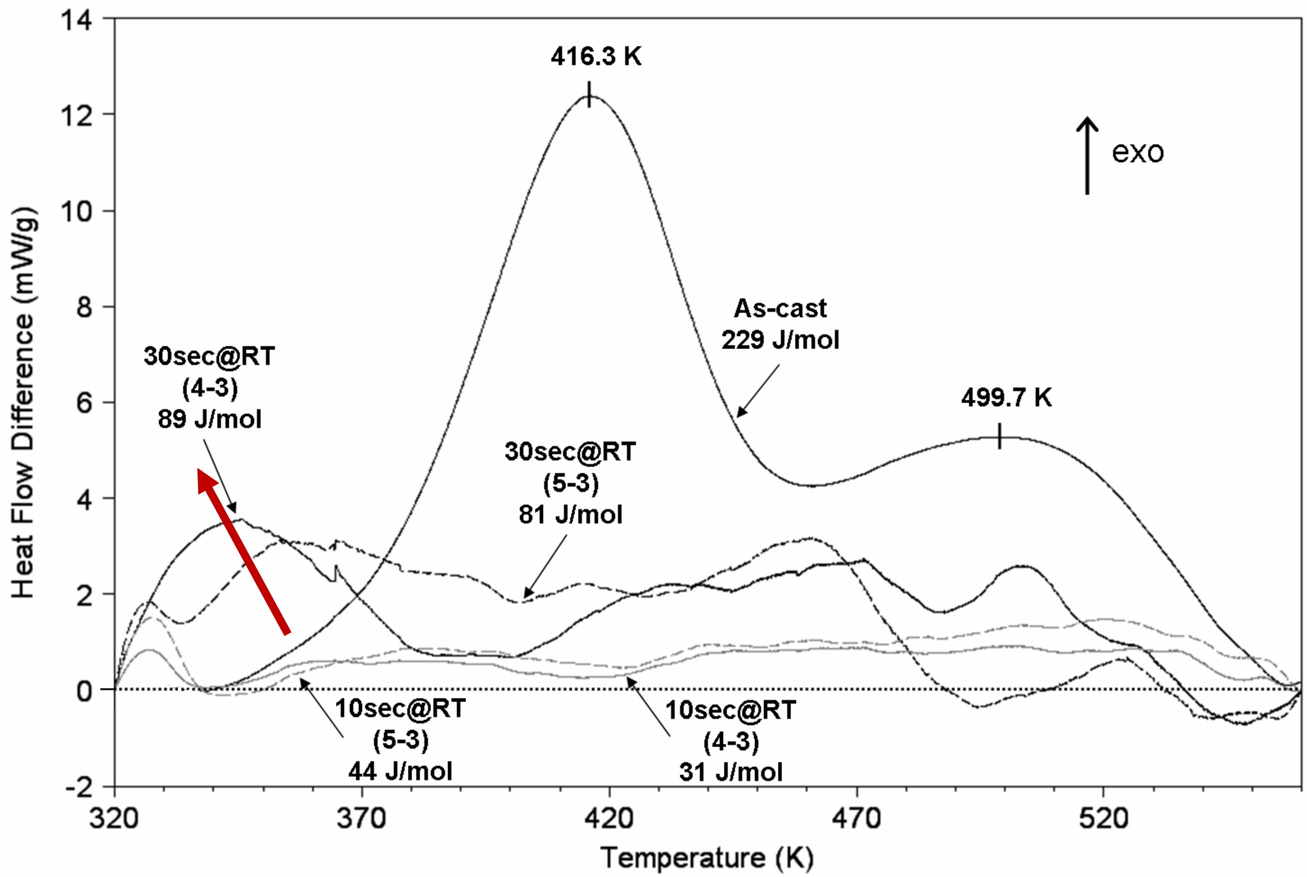
F.O. Méar, B. Lenk, Y. Zhang & A.L. Greer, "Structural relaxation in heavily cold-worked metallic glass" *Scripta Mater.* **59** (2008) 1243-1246.

Shot-peening of annealed glass (30 min at 593 K)

— restores some heat of relaxation

— implies a **less relaxed** state at lower temperature

— does not simply reverse the effect of annealing



F.O. Méar et al., *Scripta Mater.* **59** (2008) 1243.

Phase Changes Induced by Shot Peening

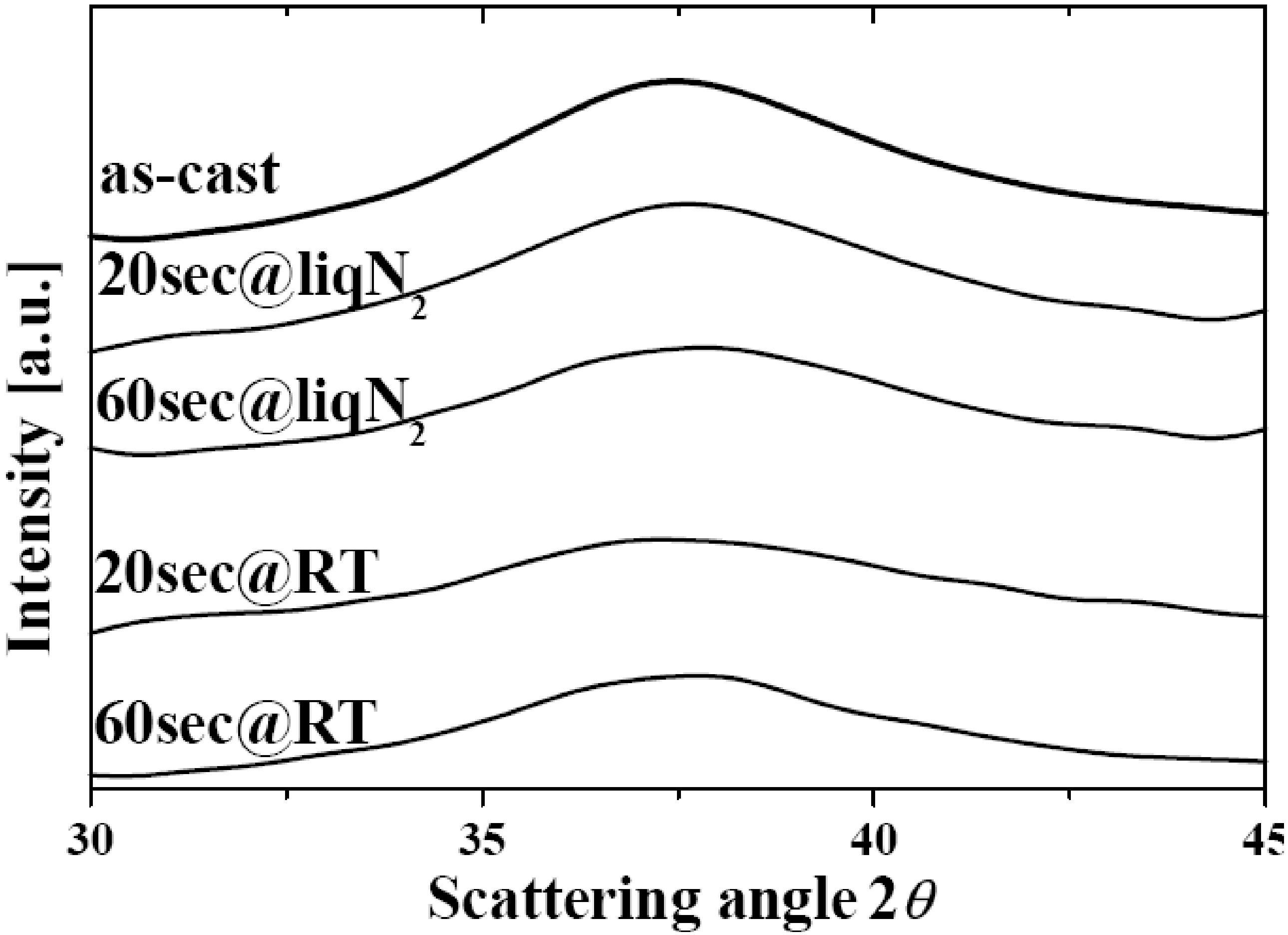
Studies of $Zr_{55}Al_{10}Cu_{30}Ni_5$

2 mm thick plate, as-cast fully glassy
3 mm diam. rod, as-cast partially crystalline

shot-peened at
- room temperature
- liquid nitrogen temperature

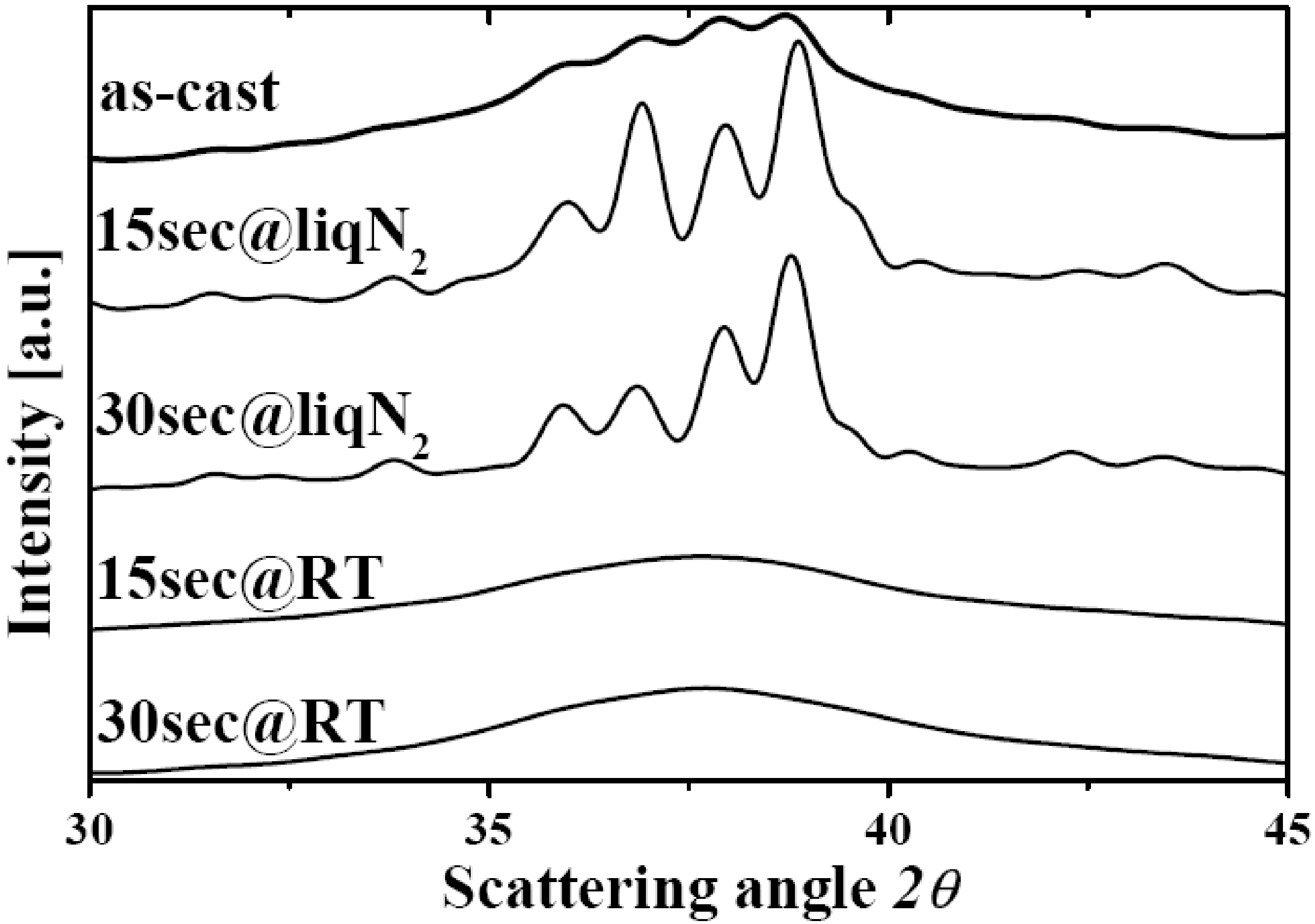
— a system already studied by T. Yamamoto et al. [*J. Alloys Comp*. **430** (2007) 97]

F.O. Méar, B. Doisneau, A.R. Yavari & A.L. Greer: "Structural effects of shot-peening in bulk metallic glasses" *J. Alloys Comp.* **483** (2009) 256–259.



Fully glassy samples stay fully glassy on shot-peening, independent of temperature

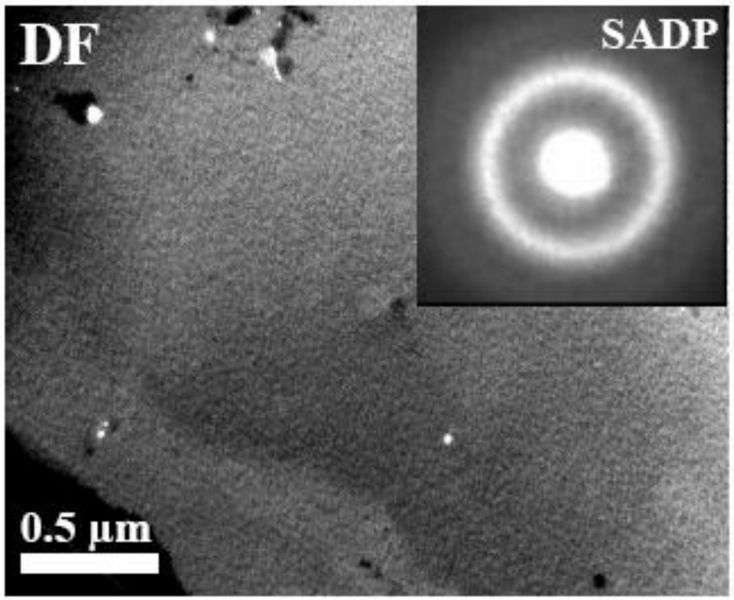
F.O. Méar et al., *J. Alloys Comp.* **483** (2009) 256.



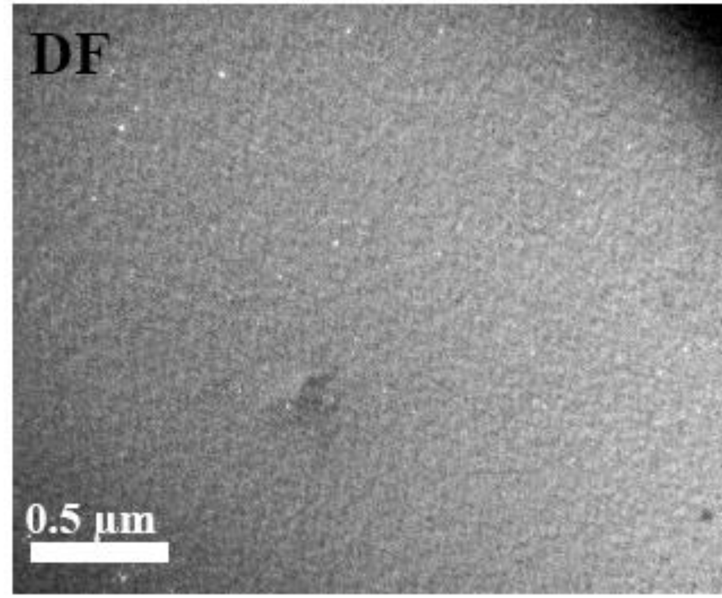
Partially crystalline as-cast samples —

- **amorphized** by peening at **room temperature**
- **crystallized** by peening at **liq. nitrogen temperature**

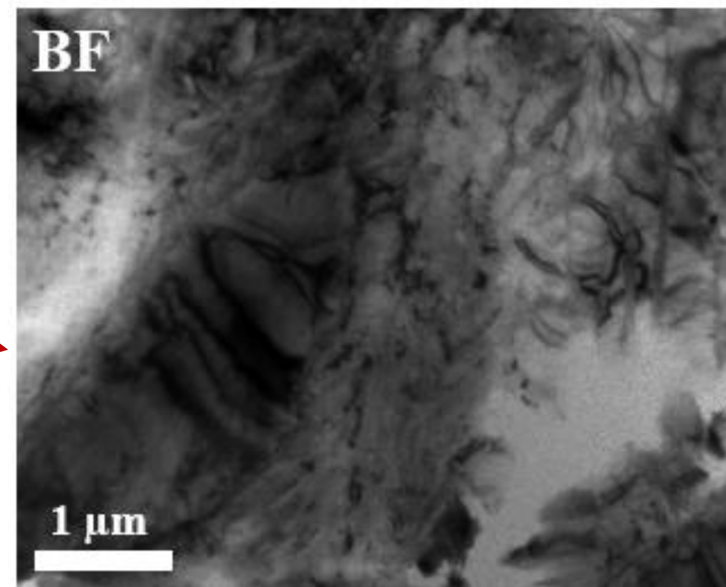
F.O. Méar et al., *J. Alloys Comp.* **483** (2009) 256.



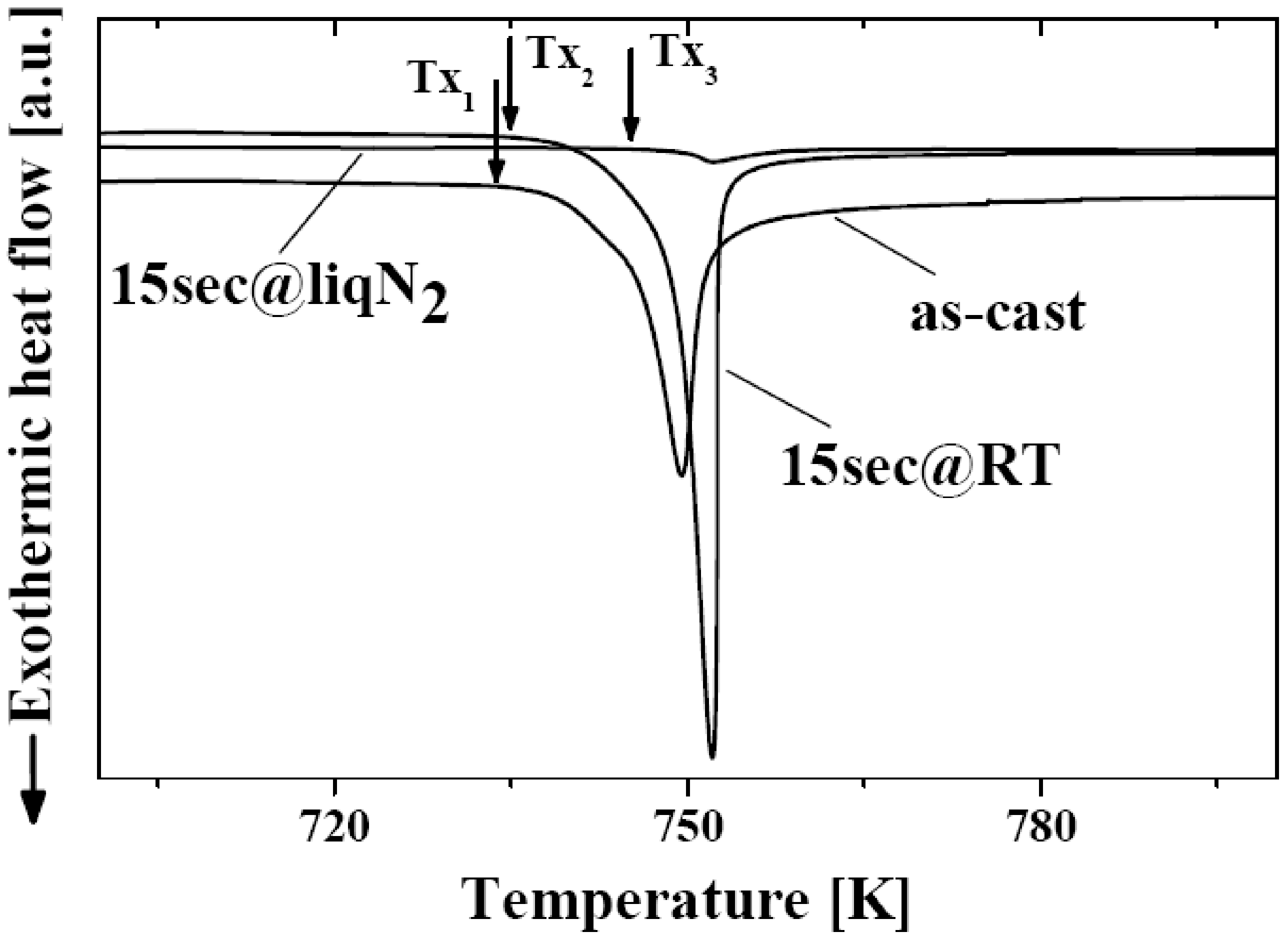
shot-peening at room temp.
→ AMORPHIZATION



shot-peening at 77 K
→ CRYSTALLIZATION

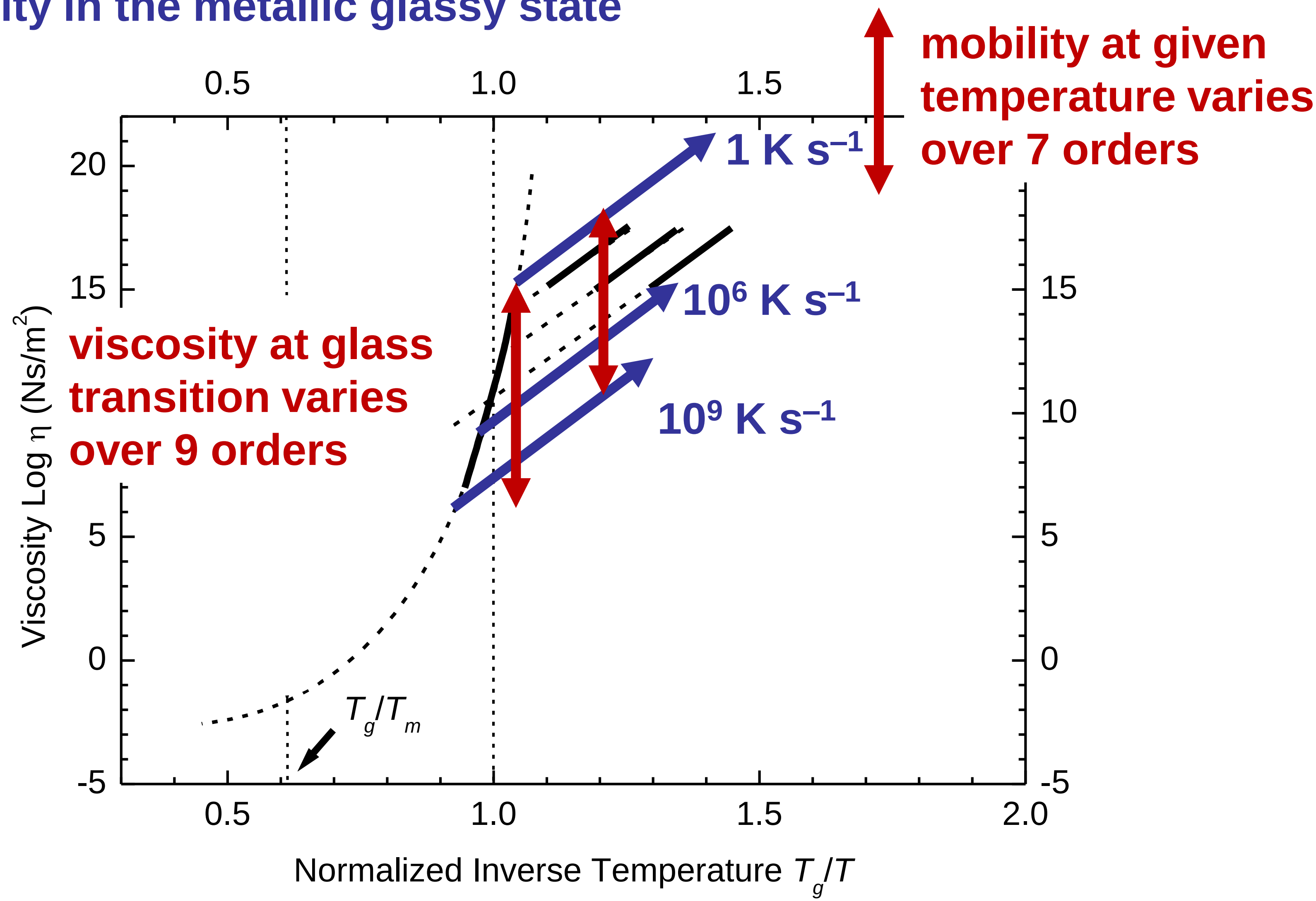


F.O. Méar et al., *J. Alloys Comp.* **483** (2009) 256.



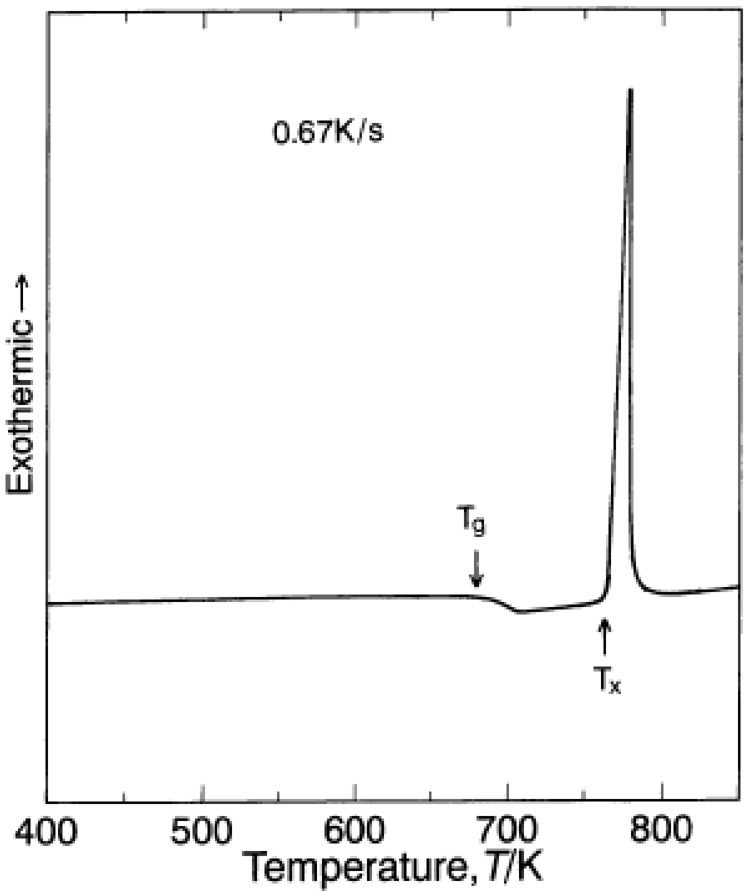
F.O. Méar et al., *J. Alloys Comp.* **483** (2009) 256.

Variability in the metallic glassy state



Data on Pd-Cu-Si and Pd-Si glasses from A.I. Taub & F. Spaepen, *Acta Metall.* **28** (1980) 1781. Isoconfigurational heating shown by C.A. Volkert & F. Spaepen, *Acta Metall.* **37** (1989) 1355.

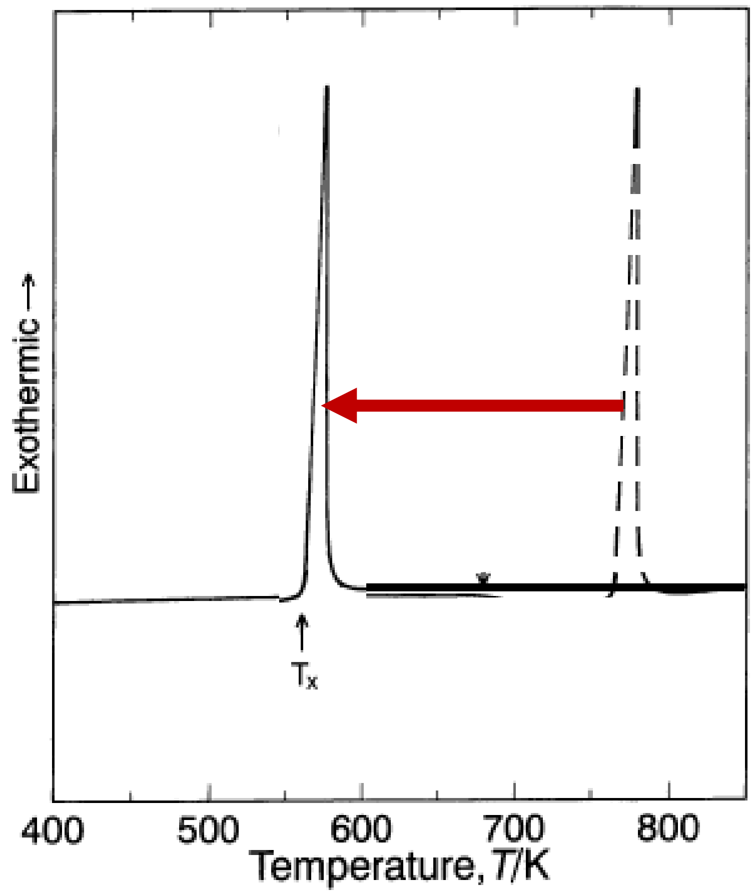
On heating a metallic glass, we expect to see the glass transition before crystallization:
— the crystallization is always of a relaxed sample.



DSC of $Zr_{55}Al_{10}Cu_{30}Ni_5$

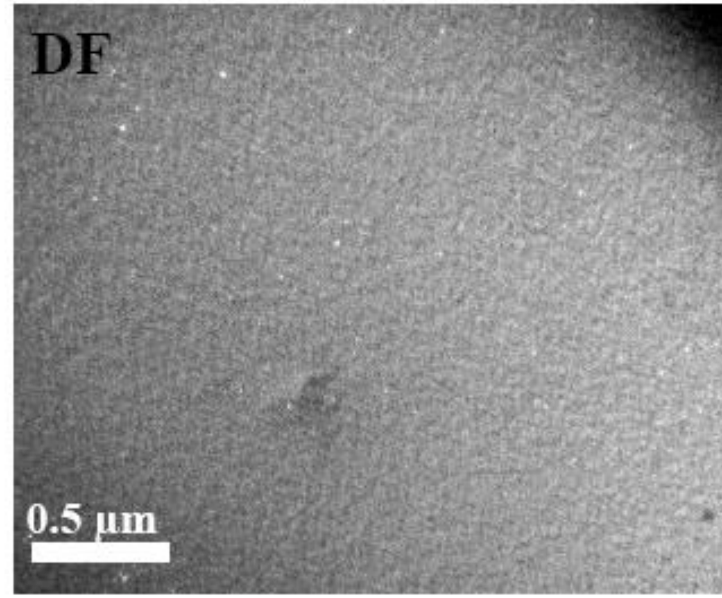
A. Inoue & T. Zhang, *Mater. Trans. JIM* **37** (1996) 185.

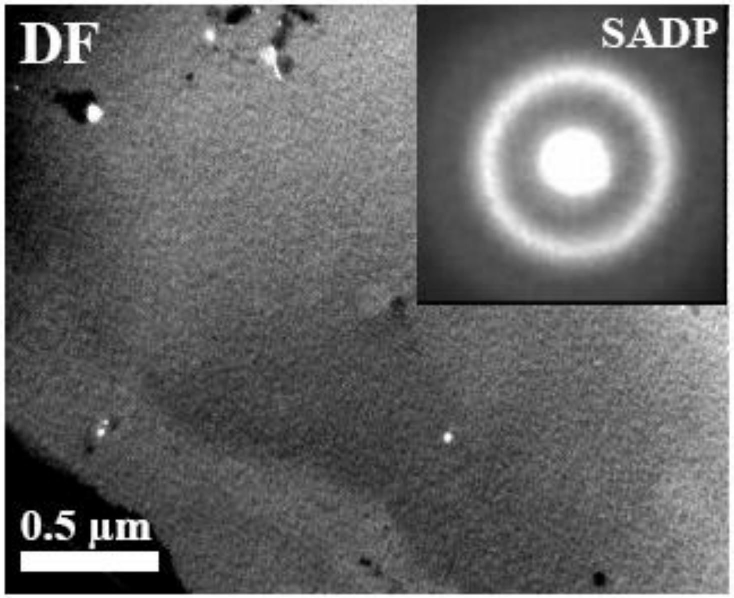
Applying a typical activation energy for crystallization, a change in mobility by a factor of 10^7 is equivalent to a temperature shift of **~200 K**



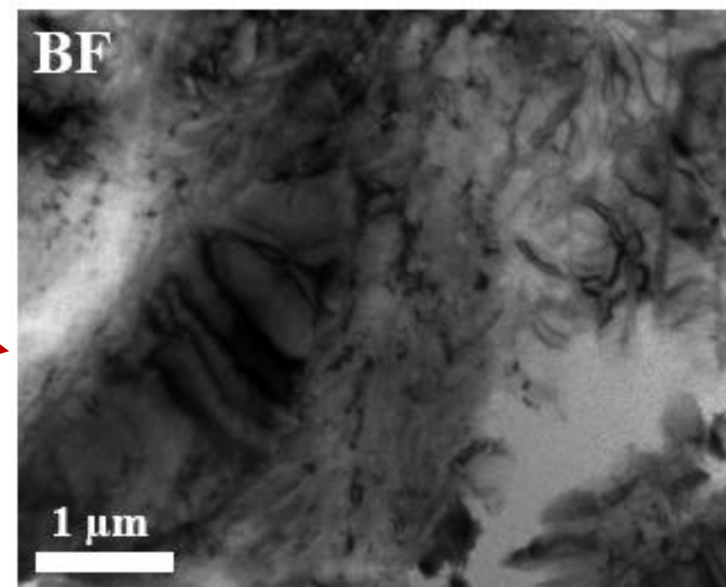
Therefore, on heating a highly unrelaxed sample, we may see crystallization before relaxation.

shot-peening at room temp.
→ AMORPHIZATION





shot-peening at 77 K
→ CRYSTALLIZATION



F.O. Méar et al., *J. Alloys Comp.* **483** (2009) 256.

Summary

- elasticity — moduli low compared to crystalline counterparts
- yield strength — highest known for metallic materials
- formability — excellent, especially at fine scale
- elastic strain limit — exceptionally high
- elastic energy storage — exceptionally high
- losses — exceptionally low
- toughness — extremely variable
- shear bands and work softening — more in Part II
- brittleness and plasticity — can be related to elastic properties
- effects of plastic deformation on structure — stored energy of cold work

— and overall a look at applications — many niche applications

Conclusions

Metallic glasses are difficult to compare with conventional structural materials — their low process-zone size suggests that they are best suited to small components.

Their high elastic limit and structural uniformity suggest a number of applications

A basis has been established for selection of component elements — a low μ/B (or high ν) favours plasticity rather than brittleness, by facilitating shear-band initiation.

The ability to plastically deform at RT permits highly unrelaxed states to be reached.

Work softening and the associated shear-banding are the biggest fundamental obstacle to a wider range of structural applications