Mechanical properties of metallic glasses

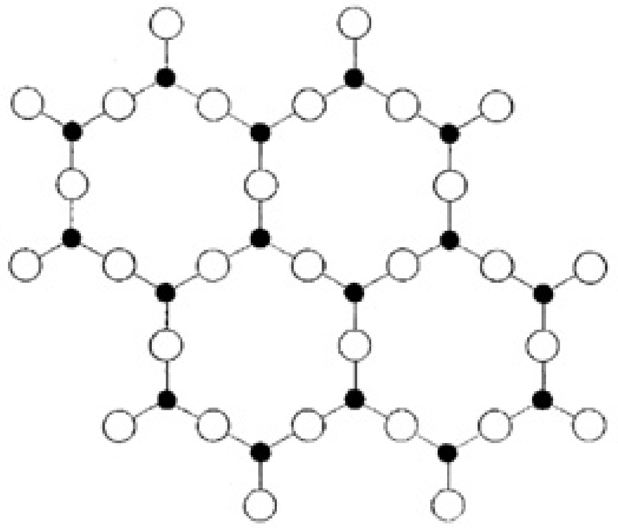
Current Status of Structural Materials

2018. 05. 02

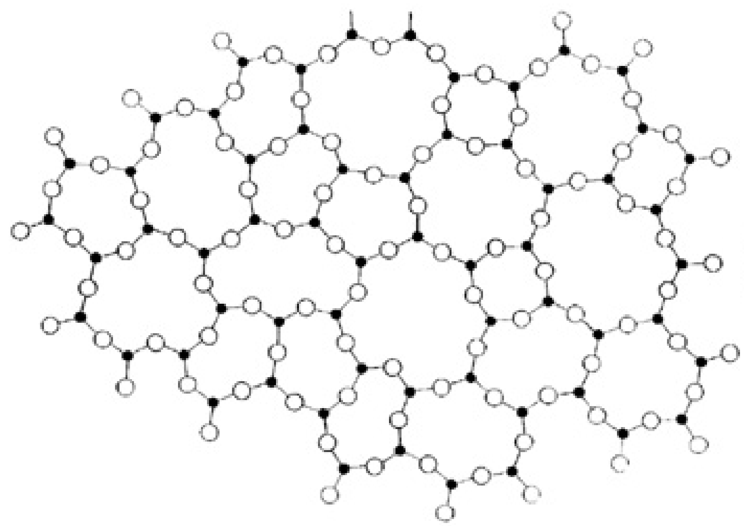
안혜상

Introduction of Metallic glass

Atomic structure of crystalline and amorphous materials



Crystalline materials



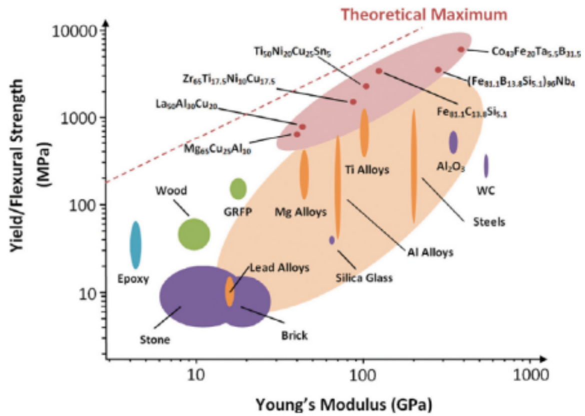
Amorphous materials

Unlike crystalline materials, absence of long-range order

→ Unique mechanical properties, corrosion resistance induced by no defect, homogeneous distribution

Properties of metallic glasses

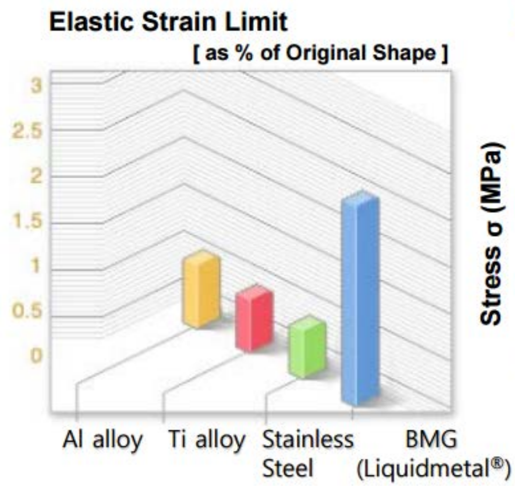
- ## Mechanical properties of Metallic glass

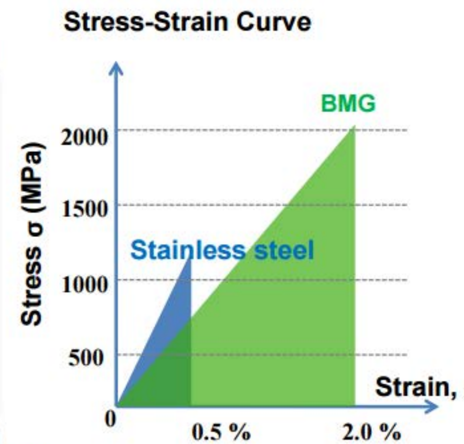


High fracture strength over 5 GPa in Fe-based BMGs

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

High strength of metallic glasses

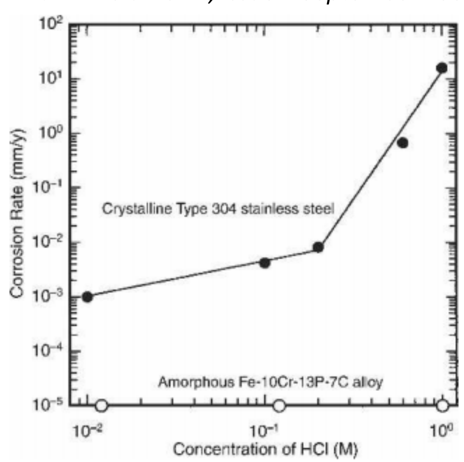




Large elastic limit of metallic glasses

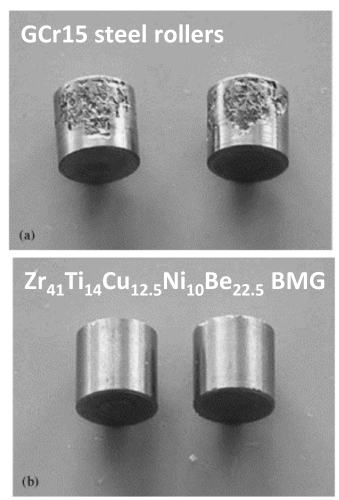
- ## Corrosion resistance

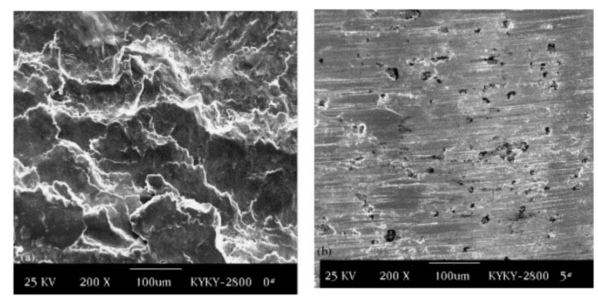
JMR Volume 22, Issue 2 September 2006 , pp. 302-313



- ## Wear resistance

Materials Science and Engineering A 386 (2004) 326–330



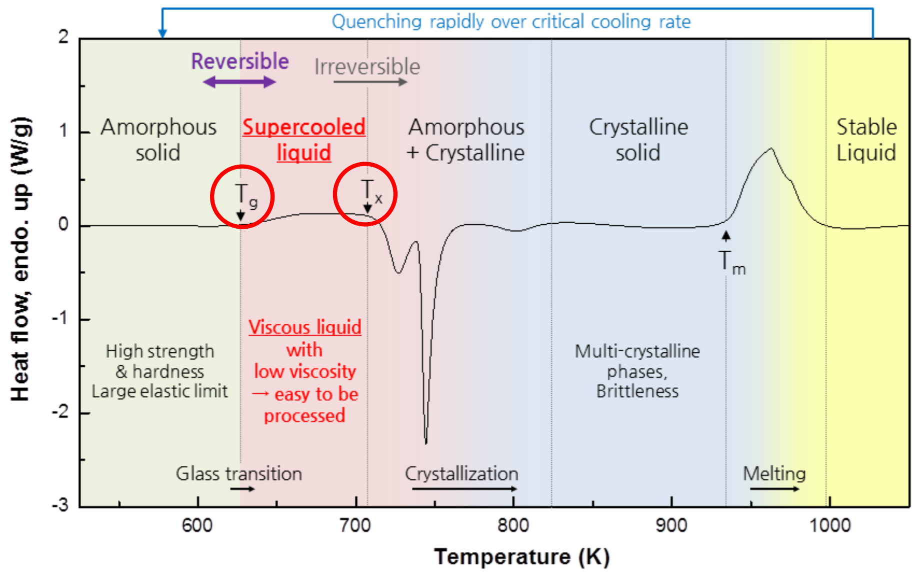


GCr15 steel rollers **$Zr_{41}Ti_{14}Cu_{12.5}Ni_{10}Be_{22.5}$ BMG**

- BMG shows better wear resistance than GCr15 steel as a bearing roller

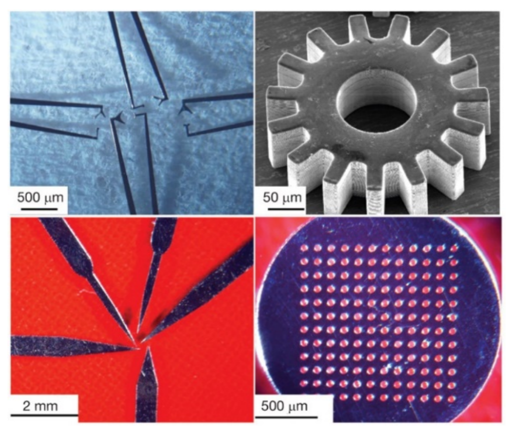
Characteristic temperature of Metallic glasses

- **Representative DSC curve of metallic glasses**

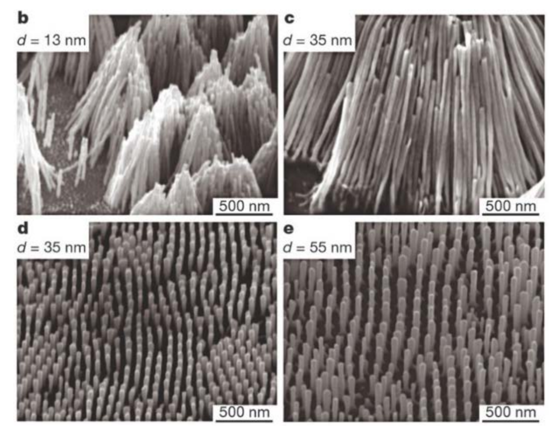


- **Application of metallic glasses**

Thermoplastic forming & Joining technique

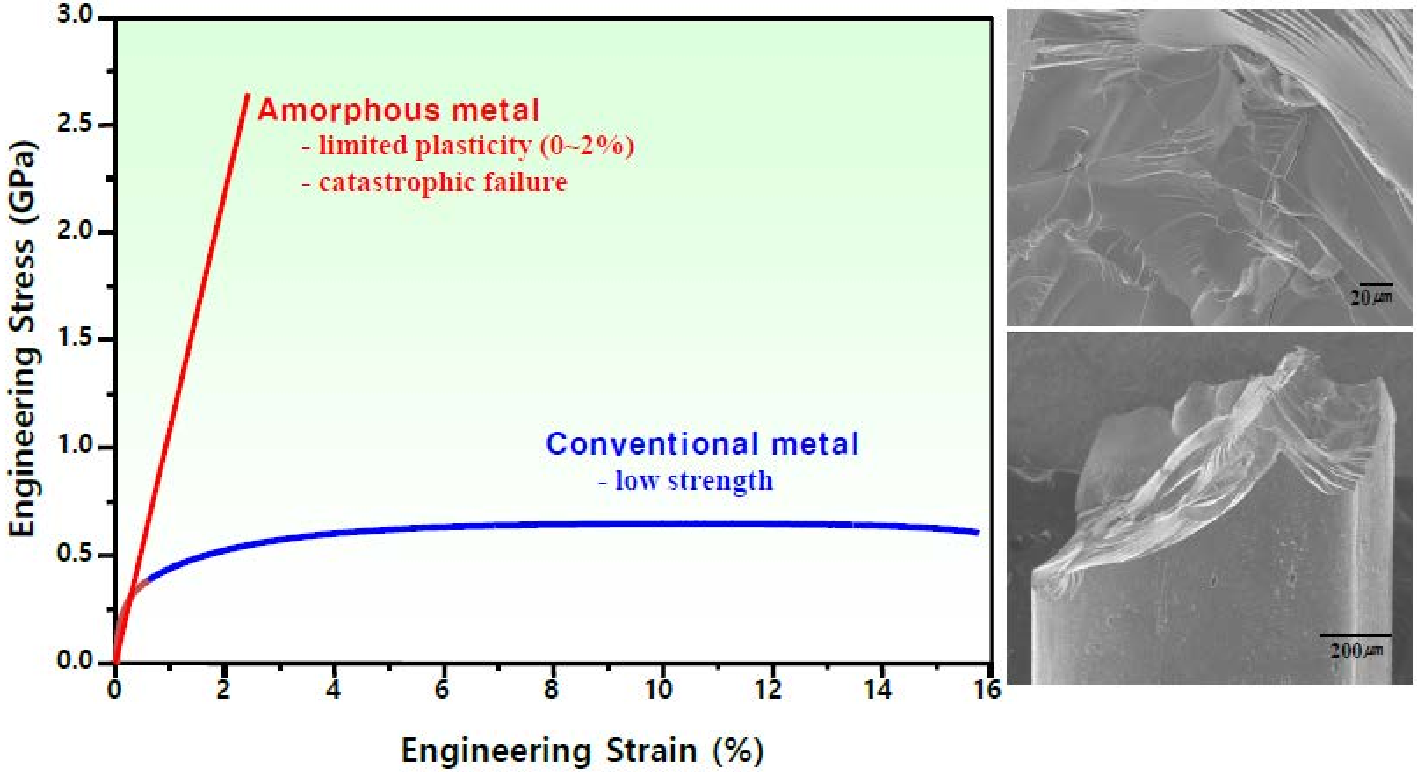


Micro-forming of Pt-BMG fabricated by hot embossing on an etched Si wafer and hot cutting



Nano-rod of Pt-BMG formed by embossing on porous alumina

Drawback of metallic glasses

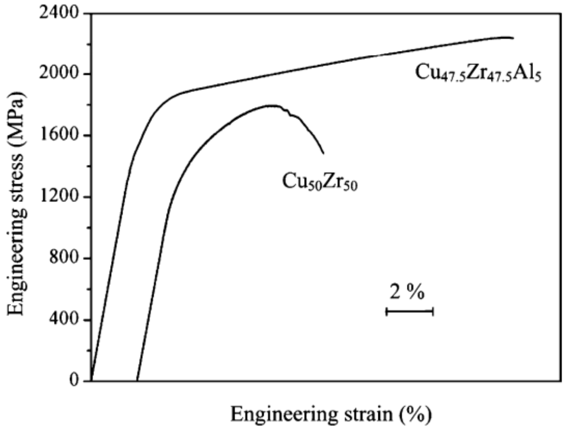


Although BMGs possess very high strength compared to their crystalline counterparts, they generally suffer from low ductility

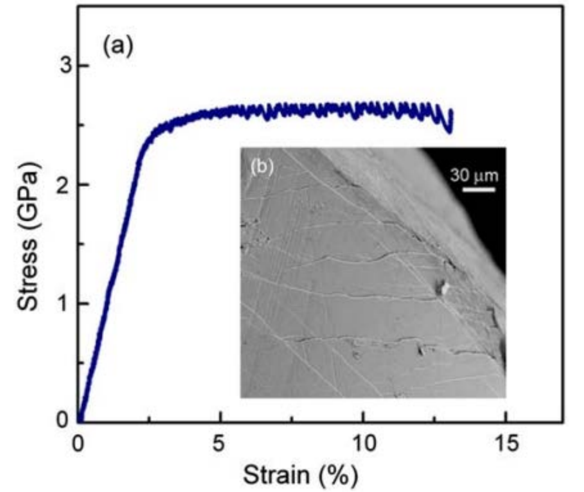
Overcoming the drawback of metallic glasses

- **Improvement of ductility through alloy design**

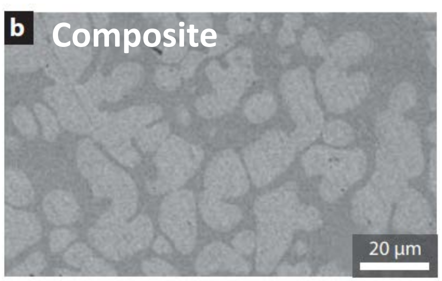
J. Eckert et al. / Intermetallics 14 (2006) 876–881

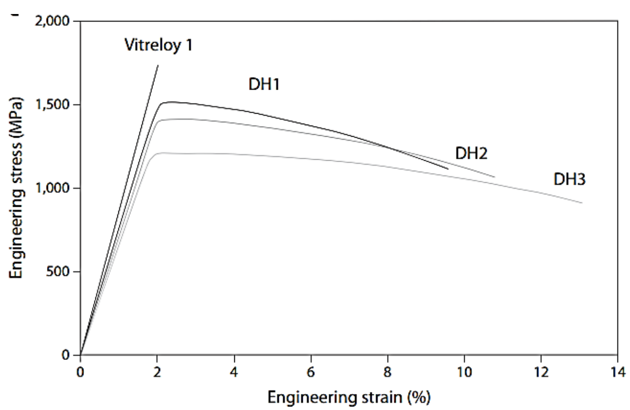


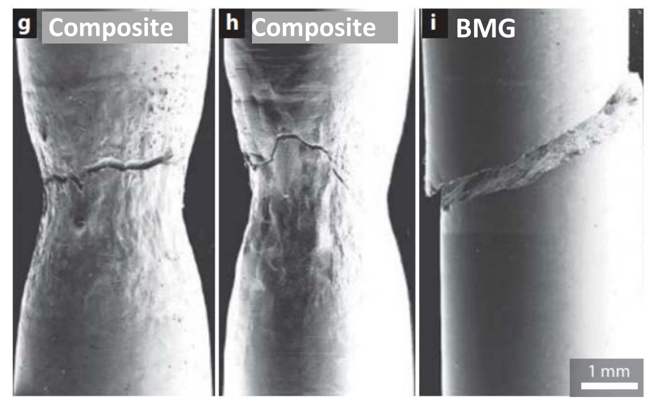
P. Jia et al. / Scripta Materialia 54 (2006) 2165–2168



- **Improvement in the tensile ductility of BMG composites**





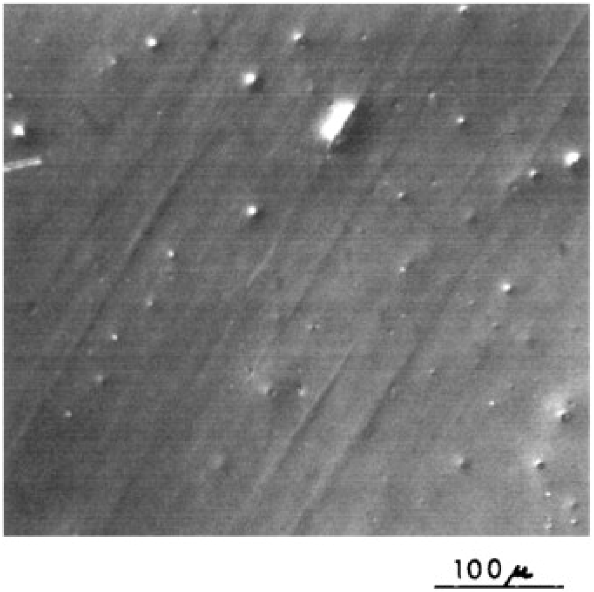


Dramatic improvement in the tensile ductility of titanium–zirconium-based BMG composites containing a ~50 vol% dendritic phase

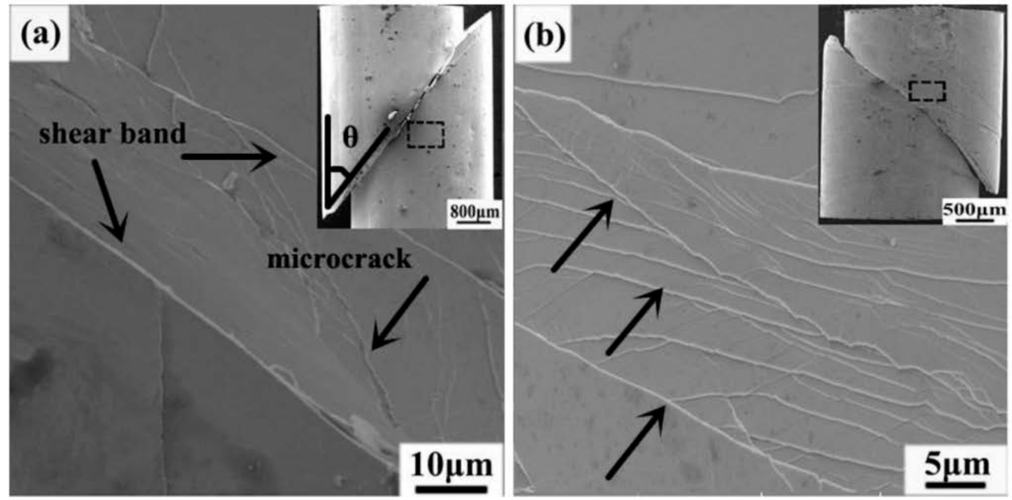
Atomistic models for plastic deformation in metallic glasses

Formation of shear band in metallic glass

Materials Science and Engineering: R: Reports
Volume 74, Issue 4, April 2013, Pages 71-132



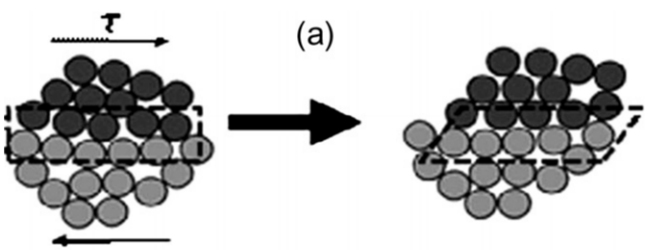
Preferential etching of shear bands on a polished cross-section of deformed $Pd_{77.5}Cu_6Si_{16.5}$glass.



Fracture in glassy metals proceeds by highly localized shear deformations which contrasts with the brittle fracture commonly observed in non-metallic glasses.

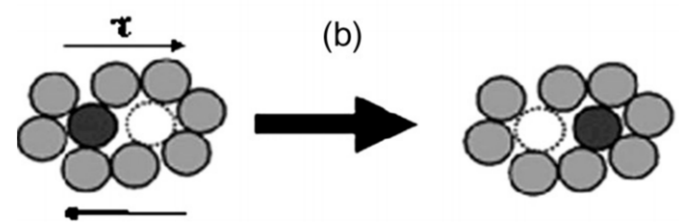
Deformation mechanism of metallic glasses

1. Shear transformation zones (STZs)_A.S.Argon



Diffuse and rearrangement

2. Free volume model_F.Spaepen



"atomic jumps" into free volume spaces

Ect

- Modified Spaepen model_Steif

by including additional free volume change due to <u>pressure</u>

- Directional structural relaxation model_Khonik

suggesting that each rearrangement event can be interpreted as a thermally-activated shear due to local atomic structures and subsequently nearly athermal viscous flow by external stress

- Cooperative shear model_Johnson and Samwer

yielding of metallic glasses displays a (T/Tg) 2/3 temperature dependence

Spaepen's and Argon's models remain most popular for describing deformation of metallic glasses

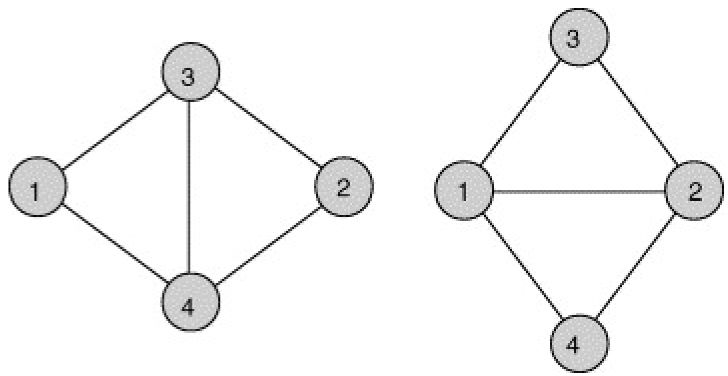
Deformation mechanism of metallic glasses

T. Egami / Intermetallics 14 (2006) 882–887

- Local topological fluctuation_T.Egami

propose an alternative approach based upon the exchange and fluctuation of atomic bonds, described in terms of the atomic level stresses.

Free-volume theory ➡ However, volume **responds only to pressure**, not to shear stress.



A **more realistic approach** is to consider deformation from the point of view of atomic bond rearrangement.

If the structure is defined by the topology of **atomic connectivity**, deformation should involve **changes in the bond arrangement**.

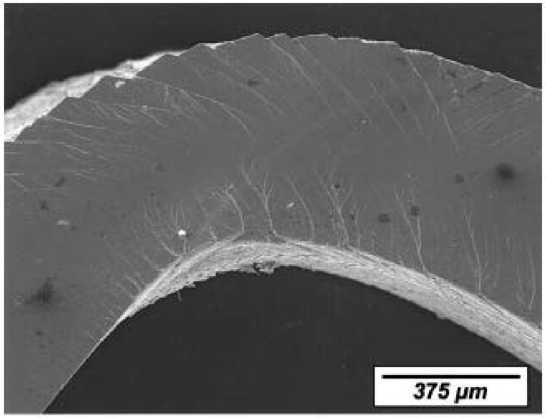
total number of bonds ➡ conserved during the rearrangement

deformation ➡ by bond-exchange

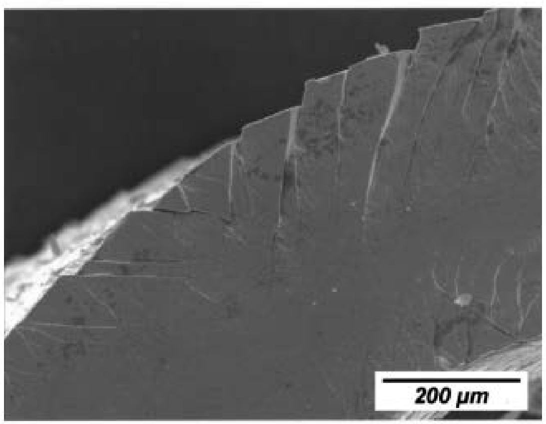
well describe glass transition, structural relaxation, glass formation and mechanical deformation

Analysis of shear band_bending test

J. Appl. Phys., Vol. 94, No. 2, 15 July 2003



(a)



(b)

FIG. 1. (a) SEM micrograph showing shear bands in a 0.5 mm thick melt-spun ribbon of Vitreloy 106, bent over a mandrel with a radius of 1 mm. The shear displacements associated with the shear bands are easily visible and secondary shear bands are also observed. The shear bands on the tension side of the sample extend farther into the sample than do those on the compression side. Conner *et al.*[11] (b) SEM micrograph showing shear bands in a 0.58 mm thick melt-spun ribbon of Vitreloy 106, bent over a mandrel with a radius of 1 mm. Some of the shear bands on the tension side of the sample appear to have developed as cracks. Conner *et al.*[11]

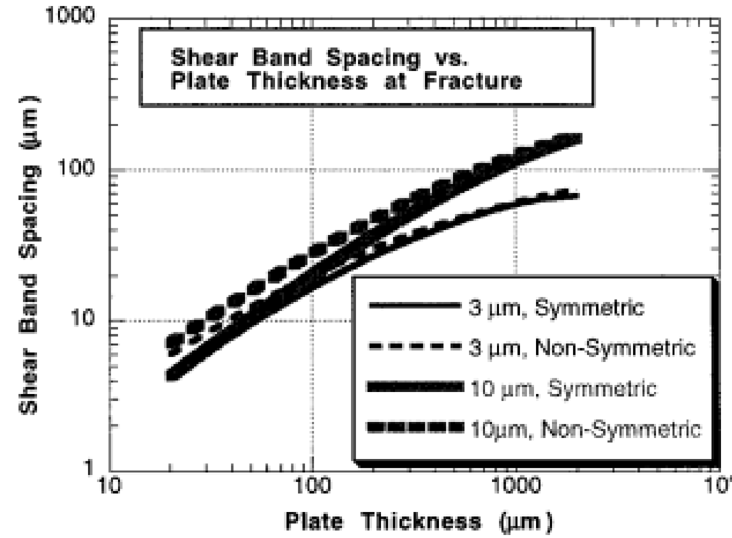


FIG. 10. Calculated shear band spacing vs plate thickness at the point of fracture for Vitreloy 1 for both *symmetric* and *nonsymmetic bending* for two different values of the critical shear displacement, Δu^*, 3 μm, and 10 μm. A fracture toughness of $K_{I_c} = 20$ MPa$\sqrt{m}$ was used for these calculations. The shear band spacing at the point of fracture is observed to increase with increasing plate thickness; the relationship is similar to the experimental results shown in Fig. 3.

Analysis of shear band_In-situ TEM

PHYSICAL REVIEW B 77, 155419 (2008)

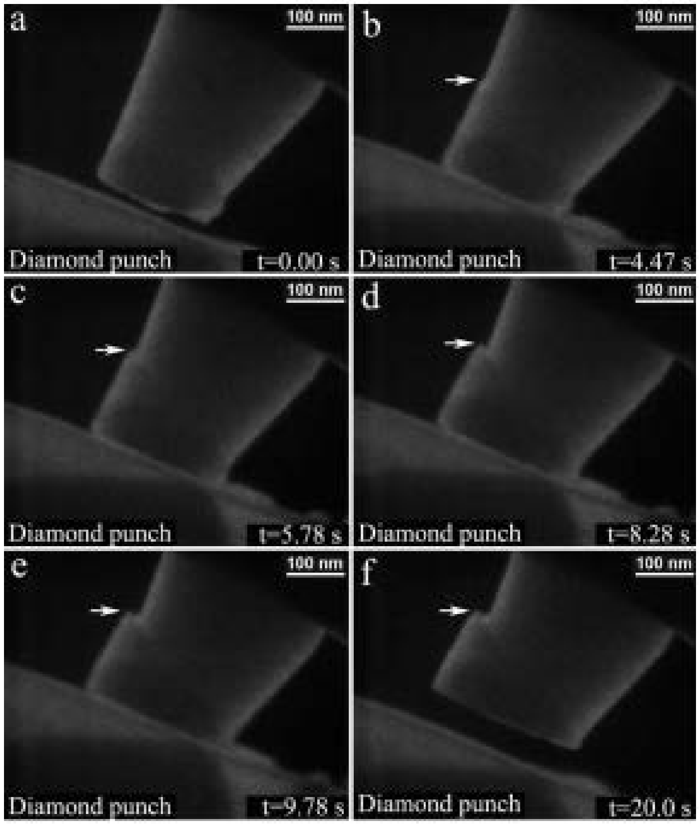


FIG. 3. *In situ* dark-field TEM observation of the formation and evolution of a major shear. The individual still frames [(a)–(f)] are extracted from a dynamic video sequence. The growing shear offset is indicated by the white arrow shown in (b)–(f) (see video in Ref. 25 for the jerky advancement of the shear offset and the flow of the MG outside the shear band region).

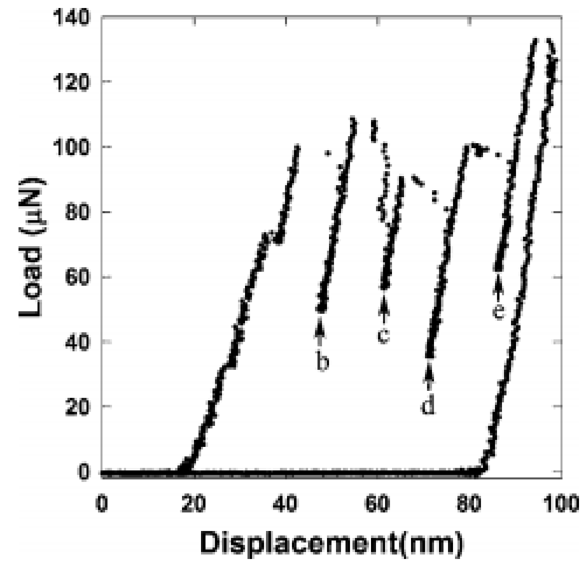
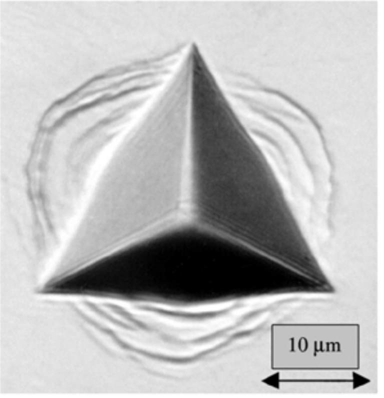


FIG. 4. Load vs displacement curve for the displacement-controlled compression test. The various stages corresponding to those shown in Fig. 3(b)–3(e) are marked with letters. The load drops in the curve are observed to synchronize with the jerky advancement of the shear step seen during the compression test (see Ref. 25).

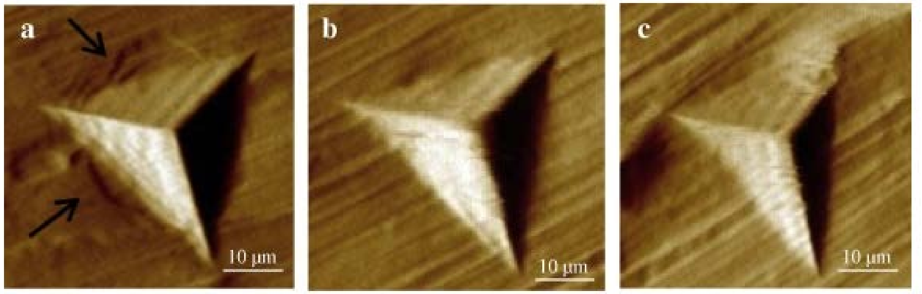
Analysis of shear band_Nano-indentation

Scripta Materialia, Volume 45, Issue 8, 29 October 2001, Pages 947-952



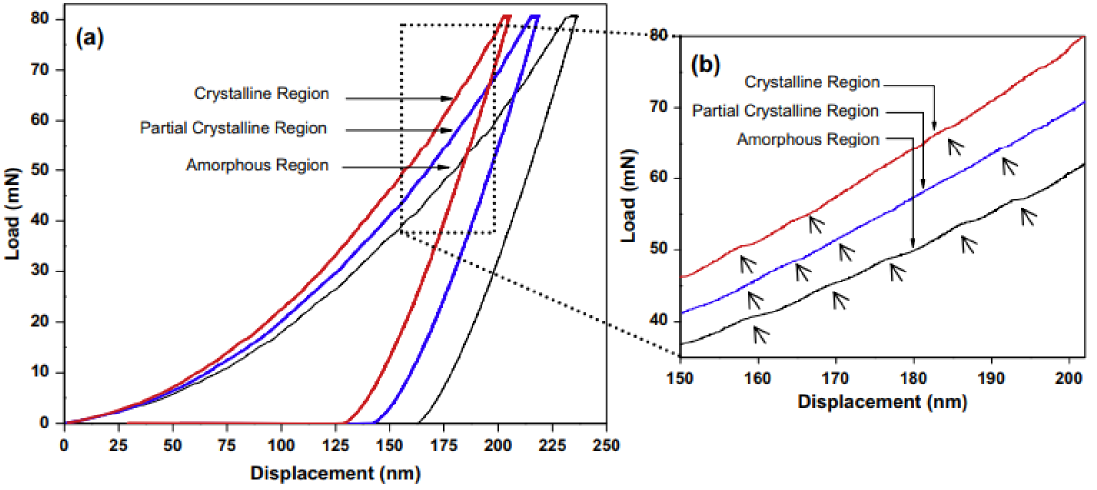
Localized plastic flow around a Berkovich indent on the surface of bulk amorphous Pd40Cu30Ni10P20.

S. Vincent et al. / Materials and Design 65 (2015) 98–103



amorphous partially crystalline crystalline

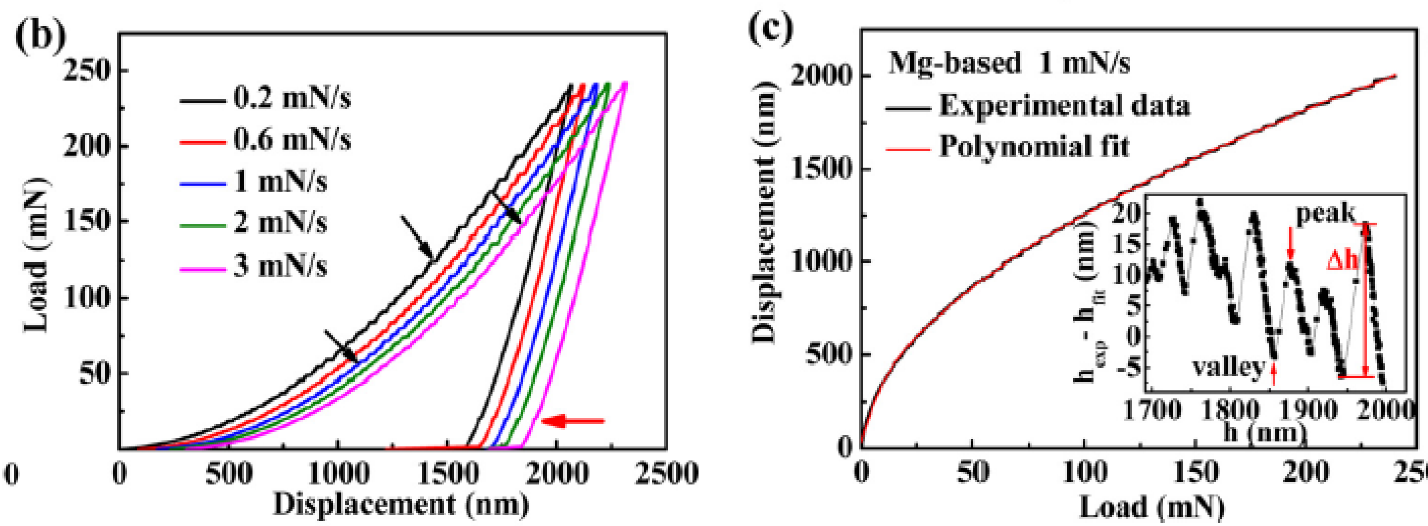
Distinct shear band can clearly be observed in the amorphous region of the sample.

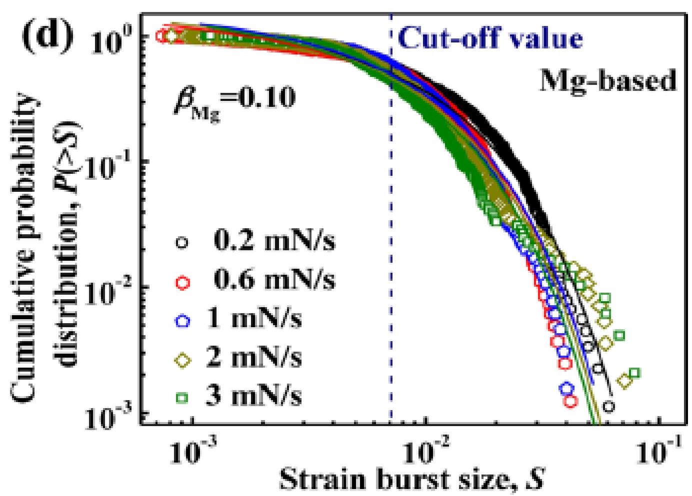


pop-ins can lead to nucleation and propagation of shear bands inside of the material as well

Analysis of shear band_Nano-indentation

APPLIED PHYSICS LETTERS 103, 101907 (2013)



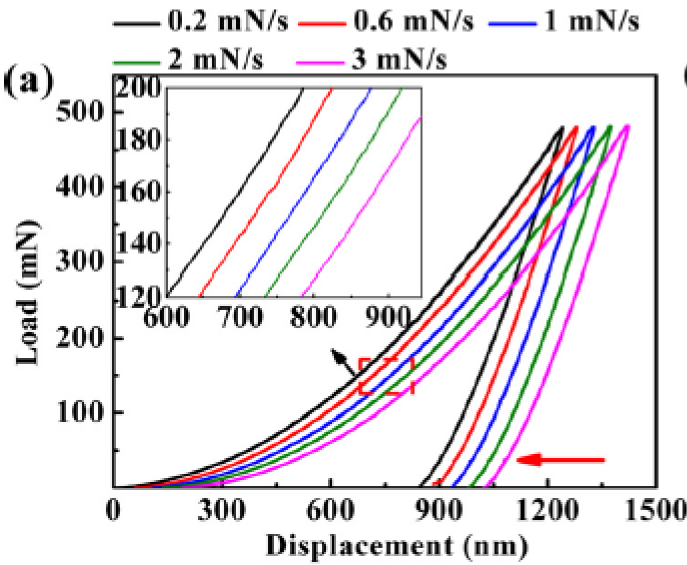


$$P(>S) = AS^{-\beta}exp(-(\frac{S}{Sc})^2)$$

- A : Normalization constant
- β : Scaling exponent
- S_c : Cut-off of strain burst size

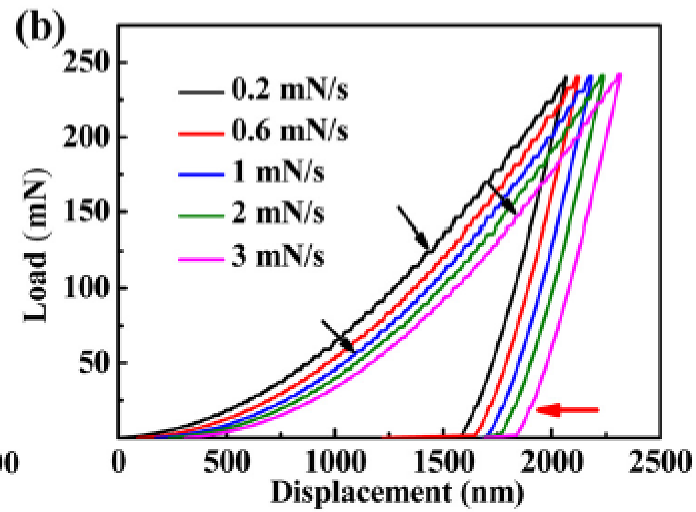
Analysis of shear band_Nano-indentation_Example 1

Co-based metallic glass



Small pop-in event

Mg-based metallic glass



Large pop-in event

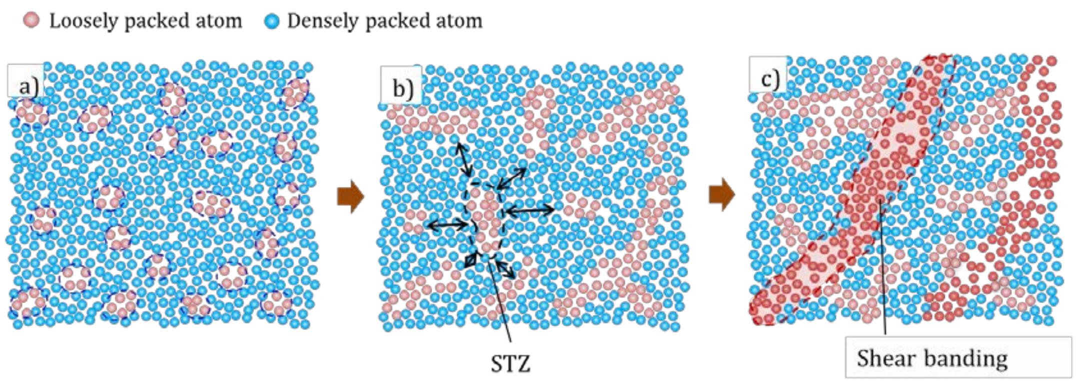
TABLE I. Parameters for the five metallic glasses. ρ_m is mass density; E is elastic modulus; G is shear modulus; H is hardness.

Metallic glasses	ρ_m (g/cm^3)	E (GPa)	G (GPa)	H (GPa)
Co-based	9.285	293	111.53	16.4
Fe-based	7.904	256	97.78	13.8
Zr-based	6.125	90	32.81	5.6
Mg-based	3.794	60	22.85	2.9
Ce-based	6.752	45	16.94	2.8

"Hard" metallic glass

"Soft" metallic glass

Analysis of shear band_Nano-indentation_Example 1

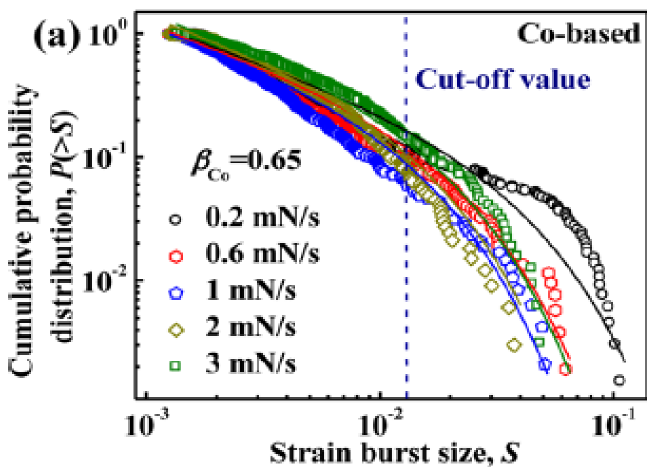


(1) Local atom rearrangements upon loading

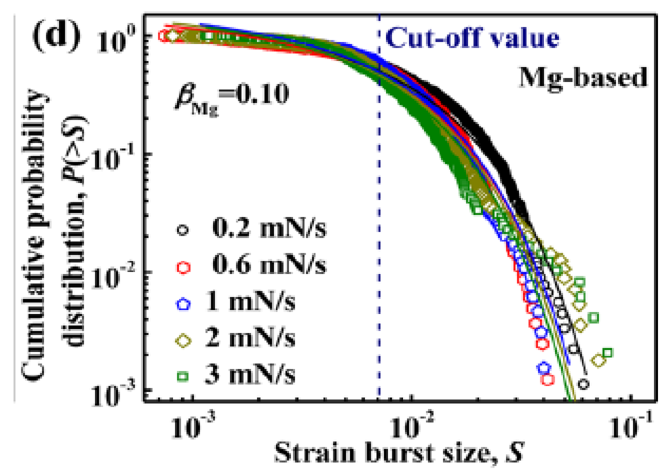
(2) Expansion and coalescence of individual regions
(Self-organized deformation events confined by elastic matrix)

(3) Formation of an apparent shear band
(Chaotic deformation events cutting through the elastic matrix)

Co-based metallic glass
"Hard" metallic glass

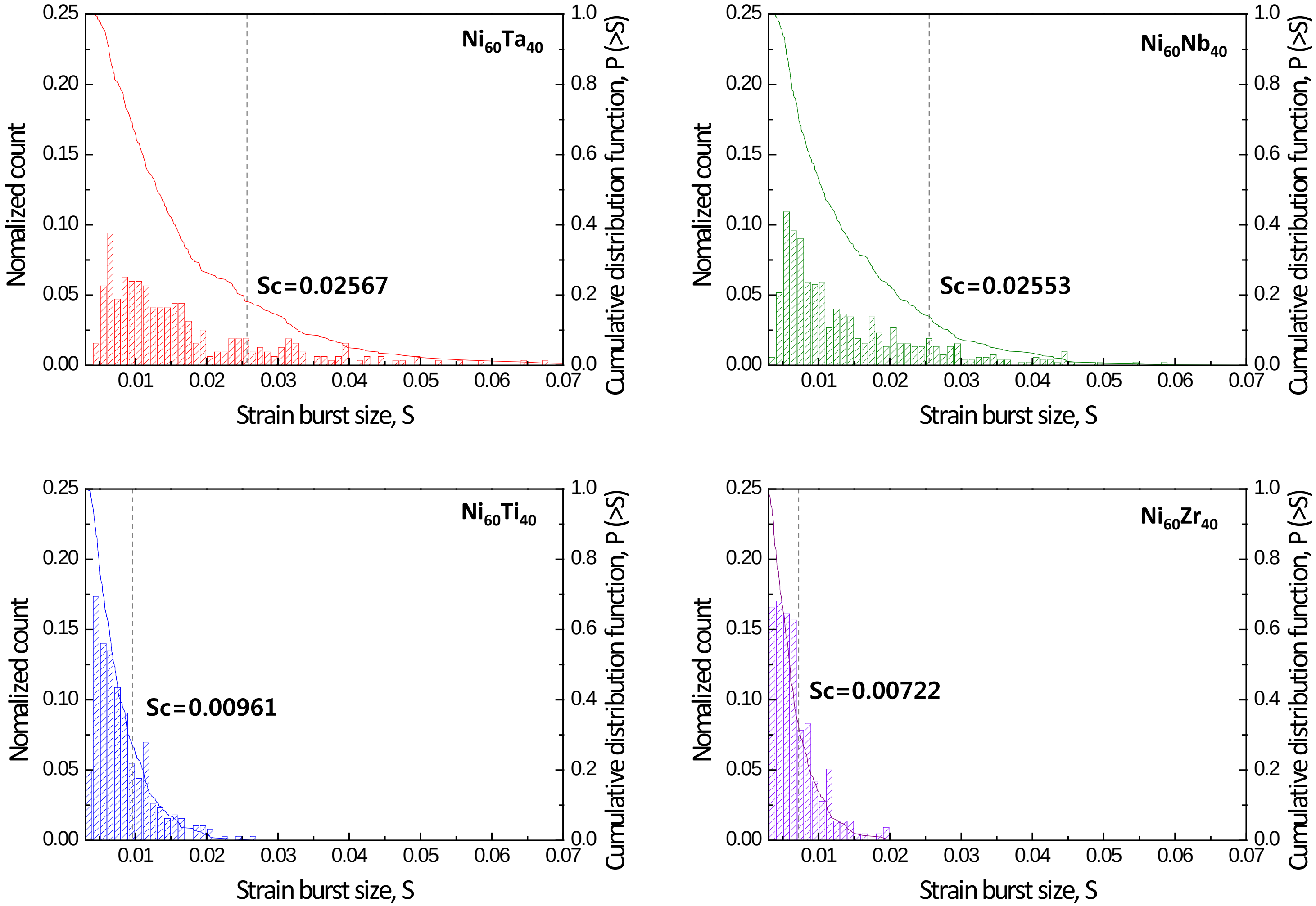


Mg-based metallic glass
"Soft" metallic glass



Concordant regions are smaller in size

Analysis of shear band_Nano-indentation_Example 2



Mechanical response of local region from Statistical analysis by nano-indentation

Ta → Nb → Ti → Zr decrease larger strain burst, increase smaller strain burst

Thank you