Mechanical properties of metallic glasses

Current Status of Structural Materials

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안혜상
Introduction of Metallic glass

Atomic structure of crystalline and 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**

  ![Graph showing mechanical properties](image)

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

  *High strength of metallic glasses*

- **Corrosion resistance**

  ![Graph showing corrosion resistance](image)

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

- **Wear resistance**


  ![Wear resistance images](image)

  *BMG shows better wear resistance than GCr15 steel as a bearing roller*
Characteristic temperature of Metallic glasses

- **Representative DSC curve of metallic glasses**

![DSC curve diagram](image)

- **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*

- **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

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_

2. Free volume model _F.Spaepen_

- **Modified Spaepen model** _Steif_ by including additional free volume change due to pressure

- **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 \((T/T_g) \frac{2}{3}\) temperature dependence

*Spaepen’s and Argon’s models remain most popular for describing deformation of metallic glasses*
Deformation mechanism of metallic glasses

- 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


FIG. 1. (a) SEM micrograph showing shear bands in a 0.5 mm thick melt-spin 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 further 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-spin 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 nonsymmetric bending for two different values of the critical shear displacement, $\Delta u_*$, 3 $\mu$m, and 10 $\mu$m. A fracture toughness of $K_{IC} = 20$ 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.
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).
Localized plastic flow around a Berkovich indent on the surface of bulk amorphous Pd40Cu30Ni10P20.

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

\[ P(> S) = AS^{-\beta} \exp\left(-\left(\frac{S}{S_c}\right)^2\right) \]

- \( A \): Normalization constant
- \( \beta \): Scaling exponent
- \( S_c \): Cut-off of strain burst size
Analysis of shear band Nano-indentation Example 1

Co-based metallic glass

Mg-based metallic glass

Small pop-in event

Large pop-in event

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

<table>
<thead>
<tr>
<th>Metallic glasses</th>
<th>$\rho_m$ (g/cm$^3$)</th>
<th>$E$ (GPa)</th>
<th>$G$ (GPa)</th>
<th>$H$ (GPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Co-based</td>
<td>9.285</td>
<td>293</td>
<td>111.53</td>
<td>16.4</td>
</tr>
<tr>
<td>Fe-based</td>
<td>7.904</td>
<td>256</td>
<td>97.78</td>
<td>13.8</td>
</tr>
<tr>
<td>Zr-based</td>
<td>6.125</td>
<td>90</td>
<td>32.81</td>
<td>5.6</td>
</tr>
<tr>
<td>Mg-based</td>
<td>3.794</td>
<td>60</td>
<td>22.85</td>
<td>2.9</td>
</tr>
<tr>
<td>Ce-based</td>
<td>6.752</td>
<td>45</td>
<td>16.94</td>
<td>2.8</td>
</tr>
</tbody>
</table>

“Hard” metallic glass

“Soft” metallic glass
Analysis of shear band_Nano-indentation_Example 1

Co-based metallic glass

"Hard" metallic glass

Mg-based metallic glass

"Soft" metallic glass

Concordant regions are smaller in size
Mechanical response of local region from Statistical analysis by nano-indentation

$Ta \rightarrow Nb \rightarrow Ti \rightarrow Zr$ decrease larger strain burst, increase smaller strain burst
Thank you