Shear bands evolution in an annealed $Zr_{41}Ti_{14}Cu_{12.5}Ni_{10}Be_{22.5}$ bulk metal glass under indenter

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1. Introduction

The plastic deformation in bulk metallic glass (BMG) is dominated by the formation of shear bands and the initiation, propagation and formation of shear bands have been well documented to be associated with the free volume in BMG, which is related to BMG's thermal history. Therefore, an isothermal annealing can reduce the free volume in BMGs, and then lead to different features of shear band formation between the as-cast and annealed BMG. Utilizing the Vickers indentation adopted bonded interface technique and nano-indentation, the plastic deformation behavior was investigated on an annealed Zr-based BMG and discussed comparing to that of the as-cast alloy. The difference of flow behaviour between as-cast and annealed BMGs was attributed to the change of free volume resulted from isothermal annealing.

2. Materials and Experimental procedures

- Materials characteristics:

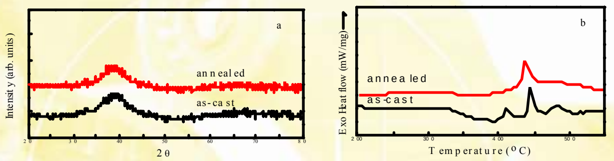

Fig. 1. Characteristics of as-cast and annealed $Zr_{41}Ti_{14}Cu_{12.5}Ni_{10}Be_{22.5}$ BMG (a) XRD and (b) DSC (20 K/min). They shows the as-cast and annealed alloys possess glassy nature.

- Experimental produces:
  - ✓ annealing rule: 250°C 12 h
  - ✓ Vickers indentation: load: 196, 49, 9.8 N, holding time: 30 s
  - ✓ nanoindentation: maximum load: 10 mN, loading rate: 0.1 mN/s

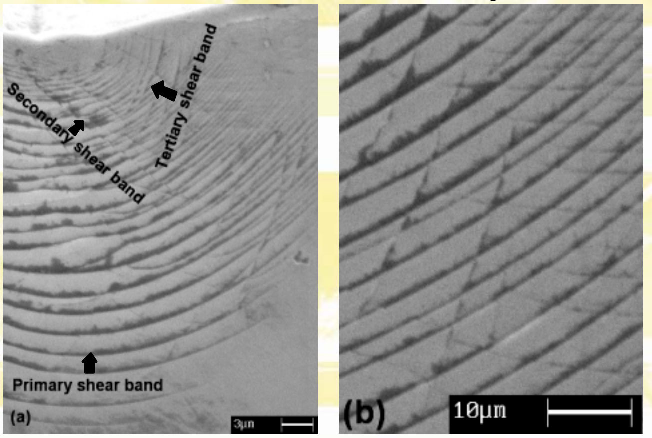

Fig. 2. The plastic deformation under Vickers indenter for the $Zr_{41}Ti_{14}Cu_{12.5}Ni_{10}Be_{22.5}$ BMG annealed at 250 °C for 12 h. (a) The half view of the deformation region at 9.8 N load and 30 s holding time. (b) The local view locating at the lower right of the deformation region at 196 N load and 30 s holding time.

3. Deformation morphology beneath Vickers indenter

- The plastic deformation conducted by Vickers indenter in the annealed $Zr_{41}Ti_{14}Cu_{12.5}Ni_{10}Be_{22.5}$ BMG below the glass transition temperature is governed by the semicircular shear bands (primary), radial shear bands (secondary) and tertiary shear bands.
- Comparing to the as-cast alloy, the tertiary shear bands was observed in the corresponding annealed alloy. This can be attributed to the change in the properties, such as embrittlement, of the materials induced by the annealing treatment.
- The average density of shear bands of the semicircular shear bands in the annealed was smaller than those in the as-cast alloy.

4. Inter-band spacing of shear band

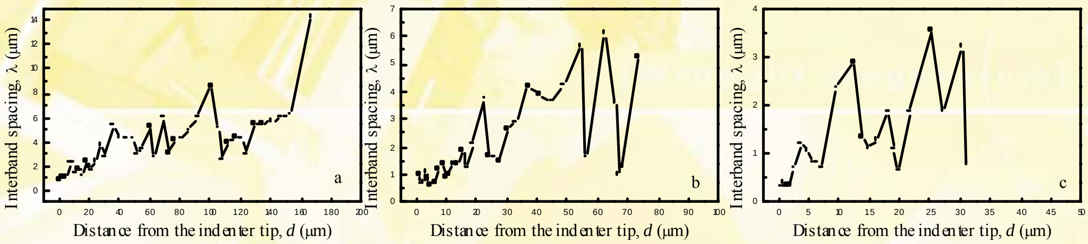

Fig.3 Variation of the inter-band spacing as a function of distance from the indenter tip for different load in the annealed $Zr_{41}Ti_{14}Cu_{12.5}Ni_{10}Be_{22.5}$ BMG at 250 °C for 12 h. (a) 196 N, (b) 49 N and (c) 9.8 N.

- The inter-band spacing λ increased with the increase of d, the distance from the tip of the indentation.
- The shear band spacing in the annealed BMG exhibited an applying load dependency while in the as-cast is independent of the load.

5. Nanoindentation

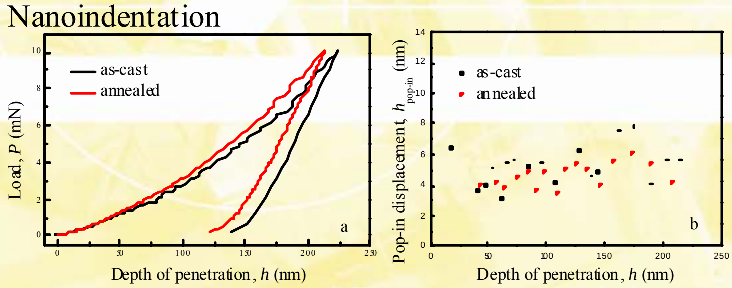

Fig.4 (a) Nanoindentation response of the as-cast and annealed $Zr_{41}Ti_{14}Cu_{12.5}Ni_{10}Be_{22.5}$ BMGs at the loading rate of 0.1 mN/s with a maximum load of 10 mN; (b) Variation of the width of the pop-in displacements, $h_{pop\text{-}in}$, as a function of indentation depth, h.

- Both P–h curves for the as-cast and annealed BMGs were similar, decorated with several displacement jumps.
- The displacement jumps in the annealed alloy were relatively flat vis-a`-vis those seen in the as-cast BMG.
- The average magnitude of serrations is different in the two BMGs at the same loading rate.
- The pop-in displacements, $h_{pop\text{-}in}$, was almost independent on indentation depth, h, for both of the as-cast and annealed samples.

6. Conclusion

- **The plastic deformation conducted by Vickers indenter in the annealed $Zr_{41}Ti_{14}Cu_{12.5}Ni_{10}Be_{22.5}$ BMG below the glass transition temperature is governed by the semicircular shear bands (primary), radial shear bands (secondary) and tertiary shear bands. Compared to the as-cast alloy, the tertiary shear bands was observed in the annealed alloy.**
- **The average density of shear bands of the semicircular shear bands in the annealed alloy was smaller than those in the as-cast alloy.**
- **The nanoindentation test revealed that the annealed alloy exhibited a more flat serrated flow.**
- **The annihilation of free volume caused by the annealing treatment was responsible for the embrittlement of the annealed sample.**

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