Intrinsic lengths govern failure mode transition in metallic glasses

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Summary It was reported that a switch from highly inhomogeneous to fully homogeneous deformation occurs when the sample size is small enough, from the tests on micropillars of metallic glasses (MGs). This suggests that the deformation in MGs is strongly size-dependent. However, what sizes controlling the mode transition remains unclear. In this paper, two intrinsic lengths a_{cI} and a_{cII} are proposed, respectively relating to the size of shear transformation zones and the sample dimension. Homogeneous deformation, intermittent shear banding and highly localization can be characterized by these two lengths. Furthermore, it is found that the two length scales measure the macro-plasticity of MGs and reveal the mechanism underlying the size effect of plasticity.

INTRODUCTION

Due to their unique structures, Metallic glasses (MGs) show very high yield strength but near zero tensile plasticity at room temperature. Great efforts have been dedicated to understanding and possibly controlling the plastic behaviour in MGs. In Particular, the size effect of plasticity has caused extensive interest of researchers[1-2]. With decreasing specimen size, the plastic capability is improved. When the specimen size reaches a critical value, a transition was clearly found from unstable shear band propagation to homogeneous yet ductile deformation[2]. By in situ micropillar tests, three typical deformation modes are observed, including the highly localization, intermittent shear banding, and homogeneous deformation. The influencing factors for the mode transition can be flow defects, specimen size and geometry, and the stiffness ratio of instrument frame and specimen[3]. However, how to determine the threshold sizes for the mode transition? And what are the correlations between the critical sizes and these intrinsic and extrinsic factors? To unravel these puzzles would lead to a better understanding of the plasticity and its size effect in MGs. In this paper, from the energy point of view, two intrinsic lengths governing the mode transition and size effect of plasticity in MGs are derived.

THEORETICAL MODELS

It is well accepted that the basic carriers of plasticity in MGs are the shear transformation zones (STZs). The shear banding occurs as a consequence of formations and self-organizations of STZs. Compared with the homogeneous deformation via uniform activation of STZs, the inhomogeneous deformation in MGs is accommodated by shear bands[4].

The propagation of the shear band is governed by the stored elastic energy. Consider a deforming volume V that accommodates an individual flow defect with length a. For uniaxial deformation, when the flow defect develops from a to a', the energy released is estimated by $\Gamma_c = V(\sigma^2 - \sigma'^2)/2E$, where E is the Young's modulus, σ and σ' are the stresses before and after the growth. Treating the defect as a crack, it can be approximated that $\sigma = K_c/\alpha\sqrt{\pi a}$ and $\sigma' = K_c/\alpha\sqrt{\pi a'}$, where K_c is the fracture toughness, and α is a geometrical factor (~1). Therefore, the energy released in the deforming volume is expressed as $\Gamma_c = VK_c^2(1/a - 1/a')/2E\alpha^2\pi$. For homogeneous deformation, the yield strength keeps the same during the deforming process, and the total potential energy barrier for an STZ in an unstressed solid is given by [5] $\Gamma = 8\tau_y^2\varsigma\Omega/\pi^2 G$, where τ_y is the yield strength, Ω is the volume of an STZ, ς ~(2-4) and G is the shear modulus. To activate a homogeneous deformation of volume V, the plastic work required is $\Gamma_p = 8\tau_y^2\varsigma V/\pi^2 G$.

(i) $a' = a + r$, r being the size of a STZ. When $\Gamma_c \ge \Gamma_p$, the homogeneous activation of STZs is preferential than the growth of defects, we can get $a \le \sqrt{R_p r + r^2/4} - r/2$ with $R_p = \pi K_c^2/32(1+\nu)\alpha^2\tau_y^2\varsigma$. Therefore, the critical length from inhomogeneous deformation to homogeneous deformation is $a_{cI} = \sqrt{R_p r + r^2/4} - r/2$.

(ii) $a' = L$, L measures the size of the specimen. When $\Gamma_c \le \Gamma_p$, dominant shear band develops cross the whole sample, then $a \ge R_p L/(R_p + L)$, the critical length from intermittent shear banding to fast cracking is $a_{cII} = R_p L/(R_p + L)$. When $R_p << L$, we have $a_{cII} = R_p$.

RESULTS AND DISCUSSIONS

Failure mode transition

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The inherent length a_{cI} is related to the size of STZ while a_{cII} is dependent on sample size. As seen in Fig.1, these two lengths behave as the threshold sizes of mode transition. When the flow defects $a \le a_{cI}$, material experiences a homogeneous activation of STZs. When $a_{cI} < a < a_{cII}$, STZs would evolve into small shear bands to form intermittent shear process. When $a \ge a_{cII}$, the flow defects would develop into several dominant shear bands and lead to fast fracture. In other words, if a sample size is below a_{cI}, the size of defects would restricted and smaller than a_{cI}. Therefore, a homogeneous deformation would be expected in this sample.

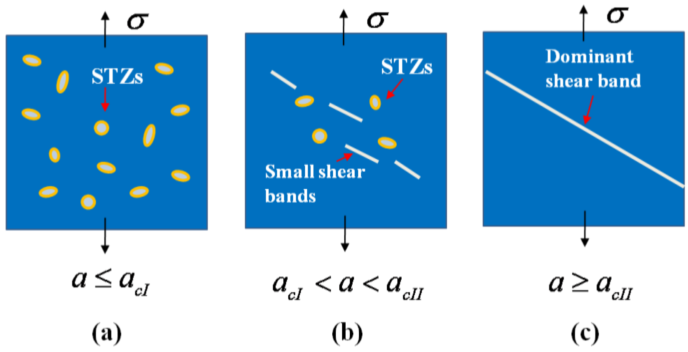

Fig.1 failure mode transition governed by intrinsic lengths a_{cI} and a_{cII}.

Size effect of plasticity

The macro plasticity can be measured by $\gamma = \chi(a_{cI}/(L - a_{cI}) + a_{cII}/L)$, where χ is a scaling factor ($\chi \sim 5$). Apparently, when $L \to a_{cI}$, $\gamma \to \infty$, indicating a super ductility in material. From Fig. 2(a), the plastic strains for three typical MGs, i.e. Zr-, Mg-, Fe-, are plotted as a function of sample dimension. With the decrease of sample size, the plastic strain increases. Every individual curve can be divided into three sections, respectively corresponding to the cracking, intermittent shear banding, and homogeneous deformation. The threshold sizes a_{cI} and a_{cII} for Zr-based MGs (i.e., ~200nm and ~38μm) is much bigger than that for Mg-based MG (i.e., ~8nm and ~71nm) and Fe-based MGs(i.e., ~2nm and ~5nm). To be further, the plastic strain in ductile MG shows a more flat change with sample size and it can experience a relatively ductile failure mode (homogeneous deformation or intermittent shear banding) in a wider range of sample size. Fig. 2(b) shows that the theoretical prediction is in accord with the experimental results.

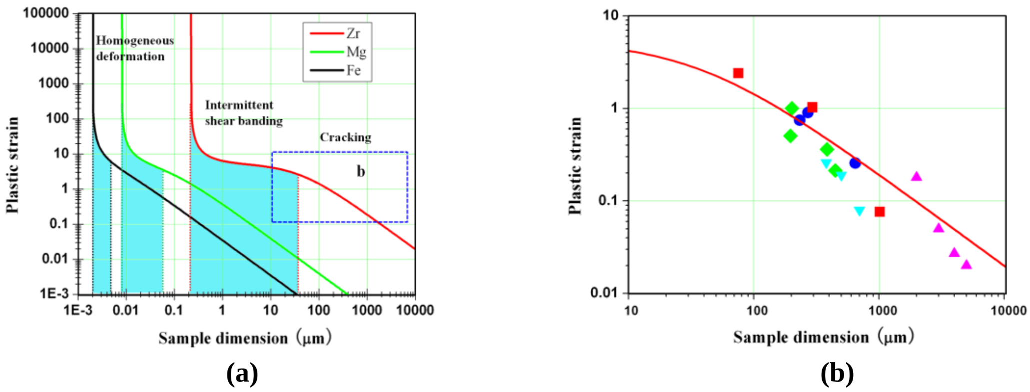

Fig.2. (a) size dependence of plastic strain; (b) comparison between the theoretical prediction and experiments[6,7].

CONCLUSIONS

In summary, the intrinsic lengths a_{cI} and a_{cII} govern the transition among homogeneous deformation, intermittent shear banding and highly localization. They further measure the macro-plasticity of MGs and reveal the mechanism underlying the size effect of plasticity.

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