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Notch Effect of Materials: Strengthening or Weakening?

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Notch is a very important geometry with widespread applications in engineering structural components. Finding a universal equation to predict the effect of notch on strength of materials is of much significance for structural design and materials selection. In the present work, we tried to find this universal equation from experimental results of metallic glasses (MGs) and other materials as well as theoretical derivations based on a universal fracture criterion (Qu and Zhang, Sci. Rep. 3 (2013) 1117). Experimental results showed that the notch effect of the studied MG was affected by the notch geometry characterized by the stress concentration factor K_t. As K_t becomes smaller, the notch strength ratio (NSR, which is the ratio of nominal ultimate tensile strength (UTS) of the notched sample to UTS of the unnotched sample) increases. By comparing MGs with other materials like brittle ceramics and ductile crystalline metals, we find that when K_t is same, the NSR is larger for ductile metals but smaller for brittle ceramics. Theoretically, we derived a universal equation for notch effect on strength of materials: NSR $= M/K_t$, where M is a constant related to materials. This universal equation was found to be consistent with the experimental results.

KEY WORDS: Notch; Strength; Metallic glass; Fracture; Plastic deformation

1. Introduction

Notch, which is one source of stress concentrations in engineering components, plays very important roles during safety designing. The study on notch effect of materials is of much significance for assessing the sensitivity of materials to notches, holes, grooves or other geometrical discontinuities[1–4]. For this reason, diverse efforts were expended in past several decades, and a large number of great advances have been made. For examples, the notch effects in different kinds of materials such as crystalline metals and alloys, ceramics, and some composites have been well summarized by Zheng et al.[2]; and several methods, such as slip line field theory, finite element analysis (FEA) and Neuber's stress analysis, etc., have also been applied to reveal the effects of notch[4–7]. However, a universal understanding on the notch effect from a new perspective by overlooking all kinds of materials is still lacking, especially for the question: how does notch affect the strength of materials, strengthening or weakening?

The lack of a universal understanding on notch effect may originate from the lack of a universal fracture criterion applicable for all kinds of materials ranging from ductile crystalline metals to brittle ceramics. In 2005, Zhang and Eckert[8] proposed a criterion named the ellipse criterion, which is proved to be a unified fracture criterion unifying the classical four criteria[1,9], i.e., the maximum normal stress (M–N) criterion, the Tresca criterion, the von-Mises criterion and the Mohr–Coulomb (M–C) criterion. The subsequent experiments on some advanced high strength materials such as metallic glasses, nanocrystalline and ultra-fine grained metallic materials have shown that the ellipse criterion can be used to effectively predict the tensile fracture behaviors of these materials[10–12]. Very recently, the ellipse criterion was further extended into a universal fracture criterion by Qu and Zhang[13]. Experimental data of abundant materials have been used to examine the extended ellipse criterion. It is concluded that this criterion has the ability to quantitatively interpret the critical fracture strength of various materials from ductile crystalline metals to brittle ceramic materials in various stress states including tension, compression, shear and others. This newly developed universal fracture criterion may provide us such an opportunity to theoretically analyze the effects of notch for a wide range of materials.

In a previous work[14], we investigated the notch tensile behaviors of pure Cu, Ti_3SiC_2 ceramic and two Zr-based metallic glasses. Metallic glasses (MGs), which have many promising properties (especially the very high strength), are considered as one kind of newly emerging advanced materials with great potentials for structural applications[15]. We found that the studied MGs showed very unique notch behaviors: not only "notch strengthening" but also "notch toughening", which means that

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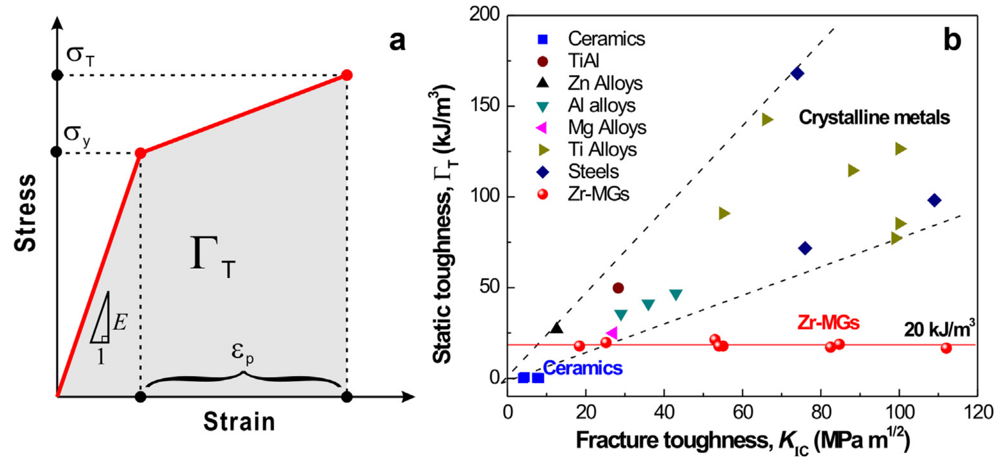

Fig. 1 (a) Illustrations of a simple stress−strain curve with linear-hardening behavior and the corresponding mechanical property parameters. (b) Comparison of tensile static toughness and fracture toughness of various different materials. The relevant data were collected from Refs.[17,19−28] and the tensile static toughness were approximately calculated according to Eq. (1).

both the nominal strength and plasticity of notched MG sample are larger than those of the smooth one. This is completely different from the conventional materials. For typical ductile crystalline metal Cu, it shows notch strengthening effect but a lower tensile plasticity for notched sample[14]. Typical brittle ceramic Ti_3SiC_2 displays only notch weakening, which means that the notch substantially reduces the original strength of Ti_3SiC_2. Besides the notch effect, the uniqueness of MGs can also be found in other aspects. For example, the tensile plasticity for most monolithic MGs is nearly zero[16], which endows MGs being called as brittle materials, while the fracture toughness can be very high (e.g., K_{IC} >100 MPa $m^{1/2}$ for some MGs[17,18]). These interesting behaviors of MGs may break down the traditional perceptions in textbook of materials science[1,3]. For example, the tensile static toughness Γ_T, which is the area of tensile stress−strain curve and represents the work done by external stress to break a tensile sample, is traditionally considered to be positively related to the fracture toughness K_{IC}, which characterize the crack propagation resistance and is consistent with the fracture energy. However, for MGs, this may not be true. To clearly elucidate this, we tried to compare Γ_T and K_{IC} for several kinds of materials. Since the data for Γ_T are very rare while the yield strength σ_y, ultimate tensile stress (UTS) σ_T and plastic elongation ε_p are easily obtained from stress−strain curve, as illustrated in Fig. 1(a), we approximately calculated the tensile static toughness Γ_T with the following expression by simply assuming that all materials behave in a linear-hardening mode during plastic deformation range and fracture at necking point:

$$\Gamma_T = \sigma_y^2 \Big/ 2E + (\sigma_y + \sigma_T)\varepsilon_p/2, \quad (1)$$

where E is Young's modulus. Although there must be some errors between the calculated Γ_T from Eq. (1) and the real one due to the deviation of the above simple assumption from the real situation of each material, the calculated results should be possible to reflect the trend of static toughness and can be used for qualitative comparison. We chose some engineering materials and several kinds of Zr-based MGs and summarized their calculated static toughness Γ_T and fracture toughness K_{IC} in Fig. 1(b). As expected, there is an increasing trend for traditional materials including ceramics and crystalline metals as increasing K_{IC}, while for all studied Zr-based MGs, Γ_T = 20 kJ/m^3, is nearly a constant, although the fracture toughness varied in a wide range of 20−110 MPa $m^{1/2}$. Since the yield strength and the elastic yield strain for Zr-based MGs are similar, the constant static toughness is actually consistent with the zero tensile plasticity. Then why are MGs so unique to show high fracture toughness but poor tensile plasticity? Owing to the similar stress field between crack tip and notch tip and the consistency between notch toughness and fracture toughness, the uniqueness associated with fracture toughness may be consistent with the uniqueness on notch effect of MGs.

In this work, we firstly conducted notch tensile tests of a Zr-based MG to study the effect of stress concentration factor K_t of notch geometry on the strength and plasticity. Then based on the previous and the present experimental results we will analyze the reasons for the unique notch effect and the high toughness of MGs. Finally, we will try to explain the mechanism of notch strengthening or weakening by deriving a universal equation to predict the different notch effect of various materials under various notch conditions based on the newly developed universal fracture criterion.

2. Experimental

$Zr_{52.5}Cu_{17.9}Ni_{14.6}Al_{10}Ti_5$ (Vit-105 MG) plates were prepared by copper mold casting in a high-purity argon atmosphere. The amorphous structure of the casted plates was confirmed by standard X-ray diffraction[29]. Dog-bone shaped tensile samples with gauge dimensions of 3 mm (length, l) × 1 mm (thickness, t) were cut from the casted plates by an electric spark cutting machine. Notches, which had a U-shape with dimensions of ∼0.2 mm in width and ∼0.1 mm in notch radius, were introduced also by the electric spark cutting machine. In the previous work, we mainly studied the differences in the notch effect between MGs and other conventional materials. In this study, we focus our attention on the effect of the stress concentration factor K_t, which was treated as a variable by varying the notch depth and sample width. The stress concentration factor K_t was calculated according to reference[30]. Detailed information such as the dimensions of samples and notches and the calculated K_t is