Strength asymmetry of ductile dendrites reinforced Zr- and Ti-based composites

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We report on significant asymmetry phenomena, including failure mode, fracture strength, and plasticity under compression and tension, for Zr- and Ti-based composites containing ductile dendrites. The failure of the Zr-based composite always occurs in a shear mode with a small strength asymmetry and different plasticity under tension and compression. In contrast, the Ti-based composite exhibits a significant high strength asymmetry and zero tensile plasticity although its compressive plasticity is high. We propose that the ratio, $\alpha = \tau_0/\sigma_0$ ($\tau_0$ and $\sigma_0$ are the intrinsic shear and cleavage strengths), is a substantial parameter controlling the strength asymmetry and the failure mode of various materials.

I. INTRODUCTION

The deformation, failure mode, and fracture strength of high-strength materials often strongly depend on the stress state. In nature, there exists a significant asymmetry phenomenon between compression and tension strengths for a variety of brittle materials, such as graphite, rock, ceramics, intermetallics, and so on. However, the strength asymmetry of conventional metallic materials can be neglected. In the past decade, several severe plastic deformation (SPD) techniques have been developed to refine the grain size for the production of ultrafine-grained or even nanostructured materials with extremely high strength. It is often found that the strength asymmetry becomes obvious for ultrafine-grained or nanostructured materials. In contrast to the grain refinement mechanism, creating dislocation-free materials, such as whisker or metallic glass, is another novel challenge for the purpose of achieving high strength. Since the 1990s, bulk metallic glasses (BMGs) have been successfully fabricated, and as expected, displayed extremely high strength. However, the final fracture of BMGs often happens catastrophically and the tensile fracture stress is also lower than that under compression. Consequently, this gives rise to the interesting question why those high-strength or brittle materials often display a significant strength asymmetry under compression and tension? However, there is so far no adequate theory or model available to explain this question. Recently, in situ formed Zr- and Ti-based (glassy/nanostructured) composites containing ductile dendrites have been synthesized, which show very high compressive strength and an improved compressive plasticity. In this article, we will elucidate the intrinsic difference in the asymmetries, including failure modes, fracture strength, or plasticity by means of two typical Zr$_{56.2}$Ti$_{13.8}$Nb$_{5.0}$Cu$_{6.9}$Ni$_{5.6}$Be$_{12.5}$ and Ti$_{60}$Cu$_{14}$Ni$_{12}$Sn$_{4}$Nb$_{10}$ composites containing ductile dendrites to gain a better understanding of their strengthening and toughening mechanisms.

II. EXPERIMENTAL

The processing and microstructure information about the two kinds of composites, Zr$_{56.2}$Ti$_{13.8}$Nb$_{5.0}$Cu$_{6.9}$Ni$_{5.6}$Be$_{12.5}$ and Ti$_{60}$Cu$_{14}$Ni$_{12}$Sn$_{4}$Nb$_{10}$, have been reported by Hays et al. and He et al. The Zr-based composite is composed of homogeneously dispersed bcc β-dendrites.
mechanical properties and fracture modes for the Zr- and Ti-based composites. The Zr-based BMG composite always fails in a shear fracture mode with only slightly different shear fracture angles (θ_C = 45° and θ_T = 48°, respectively) and has a small strength asymmetry $\sigma_C^F/\sigma_T^F = 1.04$. However, the compressive and tensile fracture angles of the Ti-based composite are significantly different (i.e., equal to 45° and 90°), respectively. Moreover, it exhibits a distinctly higher strength asymmetry ($\sigma_C^F/\sigma_T^F = 2.38$) than the Zr-based composite ($\sigma_C^F/\sigma_T^F = 1.04$). Besides, the ductility is also quite different under compression and tension for the two composites. This indicates that the Ti-based composite is more sensitive to the stress state (tension or compression) than the Zr-based composite. Similar phenomena were also widely observed for a variety of materials, such as graphite, rocks, ceramics, intermetallics, nanostructured materials, etc.\(^5\)–\(^9\),\(^13\),\(^14\) This strongly suggests that a common mechanism controlling the failure of those materials with high strength asymmetry should exist. In the

FIG. 2. SEM micrographs revealing deformation and fracture features of Zr-based composite under (a) and (b) tensile loading; (c) and (d) compression loading.

FIG. 3. SEM micrographs revealing deformation and fracture features of Ti-based composite under (a) and (b) tensile loading; (c) and (d) compression loading.
following section, we will elucidate the intrinsic difference in the asymmetries occurring in the Zr- and Ti-based composites for a better understanding of the strengthening and toughening mechanisms in a variety of materials.

As is well known, the compressive failure of brittle materials is either controlled by the Tresca criterion \(^1\) or by the Mohr-Coulomb criterion.\(^1\)–\(^4\) For the compressive failure of the Zr- and Ti-based composites, their shear fracture occurs approximately along the maximum shear stress plane [see Figs. 2(c) and 3(c)]. For brevity, the Tresca criterion can be used to describe the critical failure condition, i.e. \(\tau_{\text{max}} = \tau_0 \) (\(\tau_0\) is the intrinsic shear strength of material). Therefore, the compressive fracture strength of the two composites should be equal to \(\sigma_{\text{C}}^f = 2\tau_{\text{max}} = 2\tau_0\). When the two composites are subjected to tensile loading, they fail either in a normal fracture mode (\(\theta_T = 90^\circ\) for the Ti-based composite) or in a shear fracture mode (\(\theta_T = 48^\circ\) for the Zr-based composite). To explain the difference in the observed fracture modes, a unified tensile fracture criterion\(^26\) (i.e., ellipse criterion) was proposed:

\[
\left(\frac{\sigma_n}{\sigma_0}\right)^2 + \left(\frac{\tau_n}{\tau_0}\right)^2 = 1 .
\]

Here, \(\sigma_0\) is defined as the intrinsic cleavage strength of a material under the condition without shear stress \(\tau_n\). Accordingly, the tensile fracture strength \(\sigma_T^f\) can be derived in terms of the unified tensile fracture criterion\(^26\).

Otherwise stated:

\[
\sigma_T^f = 2\tau_0 \sqrt{1 - \alpha^2} \quad (\alpha = \tau_0/\sigma_0 \leq \sqrt{2}/2) .
\]

\[
\sigma_T^f = \sigma_0/\alpha \quad (\alpha = \tau_0/\sigma_0 \geq \sqrt{2}/2) .
\]

Here, \(\alpha = \tau_0/\sigma_0\) is the ratio of shear strength \(\tau_0\) to cleavage strength \(\sigma_0\) of a material.\(^26\) The details of the failure mode of a material are strongly controlled by the ratio \(\alpha = \tau_0/\sigma_0\), which is a function of the tensile shear fracture angle \(\theta_T\).\(^26\) Otherwise stated:

\[
\alpha = \tau_0/\sigma_0 = \sqrt{\cos(2\theta_T)/(\cos(2\theta_T) - 1)} .
\]

This indicates that the tensile fracture of a material is controlled by both shear and normal stresses \((\sigma_n, \tau_n)\) on the shear plane, and depends on the two intrinsic strengths \((\sigma_0, \tau_0)\).

Based on the theoretical analysis above, the failure conditions of the Zr- and Ti-based composites under tension and compression can be schematically illustrated as in Figs. 4(a) and 4(b). According to the two failure
The strength asymmetry $\frac{\sigma_C^F}{\sigma_T^F}$ can be expressed as:

$$\frac{\sigma_C^F}{\sigma_T^F} = 1/\sqrt{1 - \alpha^2} \quad (\alpha = \frac{\tau_0}{\sigma_0} \leq \sqrt{2}/2) \quad (4a)$$

$$\frac{\sigma_C^F}{\sigma_T^F} = 2\alpha \quad (\alpha = \frac{\tau_0}{\sigma_0} \geq \sqrt{2}/2) \quad (4b)$$

The strength asymmetry $\frac{\sigma_C^F}{\sigma_T^F}$ increases when increasing the ratio $\alpha = \frac{\tau_0}{\sigma_0}$. From Eqs. (1)-(4) and the measured values of $\sigma_T^F$, $\sigma_C^F$, $\tau_0$, and $\alpha$ were calculated and are listed in Table I. Apparently, the two composites have nearly the same shear strength $\tau_0$ and compressive fracture strength $\sigma_C^F$ when they fail in a shear failure mode. Therefore, shear bands were observed for both of the two composites under compression, as shown in Figs. 2(d) and 3(d). This indicates that the compressive strength $\sigma_C^F$ of a material is mainly controlled by its shear strength $\tau_0$, but is independent of the cleavage strength $\sigma_0$. According to the unified criterion,\textsuperscript{26} it is known that when $\alpha = \frac{\tau_0}{\sigma_0} \leq \sqrt{2}/2$ or $\sigma_0 \geq \sqrt{2} \tau_0$, the specimen will fail in a shear mode under tension or compression loading, as schematically illustrated in Fig. 4(a). From Table I, it can be seen that the ratio $\alpha = \frac{\tau_0}{\sigma_0}$ is equal to 0.31 for the Zr-based composite (i.e., is smaller than $\sqrt{2}/2$). Therefore, shear bands are easily activated under both compression and tension, resulting in a very small strength asymmetry and obvious shear plasticity, as shown in Figs. 2(b) and 2(d). In contrast, the ratio $\alpha = \frac{\tau_0}{\sigma_0}$ for the Ti-based composite is 1.19, obviously higher than the critical value of $\sqrt{2}/2$. Hence, shear bands can only be formed under compression, but are absent under tension in the case of the Ti-based composite, as shown in Figs. 3(b) and 3(d). Therefore, cleavage or normal fracture (i.e., $\theta_T = 90^\circ$) becomes the more preferred failure mode than shear deformation for the Ti-based composite, as schematically illustrated in Fig. 4(b). This causes an early normal fracture prior to shear deformation under tension, leading to zero tensile plasticity. Because the tensile fracture strength $\sigma_T^F$ depends on both shear strength $\tau_0$ and cleavage strength $\sigma_0$, it is deduced that the very low tensile fracture strength $\sigma_T^F$ of the Ti-based composite should be attributed to a large decrease in its cleavage strength $\sigma_0$. Therefore, materials with a ratio higher than $\sqrt{2}/2$ will exhibit a substantial strength asymmetry under compression and tension. It is believed that the low cleavage strength $\sigma_0$ can be attributed to the casting flaws or pores in the Ti-based composite. Normally, it seems that there are no obvious flaws or pores in the microstructure of the Ti-based composite. However, it is often observed that there exists inhomogeneous microstructure or occasionally some coarse Nb particles in the Ti-based composite as reported previously.\textsuperscript{27} Those inhomogeneous microstructures or occasional coarse Nb particles will affect the tensile properties to some extent. If the Ti-based composite is made into a specimen with a smaller size, it can display certain tensile plasticity due to the exclusion of the inhomogeneous microstructure or occasional coarse Nb particles.\textsuperscript{24} Eliminating the inhomogeneous microstructure should be important for the increase in the cleavage strength, moreover to improve the tensile fracture strength, even the tensile plasticity for the Ti-based composite with high performance.\textsuperscript{25} Moreover, it seems that the deformation mechanism of such kind of composites should be very interesting and we will further reveal the relationship between the mechanical property and the microscopic deformation mechanism in the future study.

### V. CONCLUSIONS

In summary, the essence of strength improvement for traditional metallic materials is mainly due to the increase in the shear strength $\tau_0$ leading to a high $\alpha = \frac{\tau_0}{\sigma_0}$ ratio. The compressive strength $\sigma_C^F$ is only controlled by its shear strength $\tau_0$, however, the tensile strength $\sigma_T^F$ is a function of shear strength $\tau_0$ and cleavage strength $\sigma_0$. With increasing the ratio $\alpha = \frac{\tau_0}{\sigma_0}$, according to Eq. (4a), the strength asymmetry $\frac{\sigma_C^F}{\sigma_T^F}$ becomes substantial, which results in the widely observed strength anisotropy in a variety of materials, such as ceramics, graphite, rock, intermetallics as well as ultra-fine grained and nanostructured materials or glasses.\textsuperscript{5-9,13,14} When the ratio $\alpha = \frac{\tau_0}{\sigma_0}$ is larger than $\sqrt{2}/2$, increasing the shear strength $\tau_0$ has no influence on the tensile strength $\sigma_T^F$ according to Eq. (2b). In this case, shear bands will not be activated before fracture, resulting in zero tensile plasticity, as observed for the Ti-based composite. This indicates that one should control the ratio $\alpha = \frac{\tau_0}{\sigma_0}$ to be...
below the critical value of $\sqrt{2}/2$. Otherwise, there should be no tensile plasticity. It is suggested that one should not only consider the shear strength $\tau_0$ itself, but also the cleavage strength $\sigma_0$ when aiming for strengthening a material. Maintaining a higher shear strength $\tau_0$ is substantially important for achieving both tensile and compressive strengths ($\sigma_F^T$ and $\sigma_F^C$). However, for the first time, it is suggested that a good balance ($\alpha = \tau_0/\sigma_0$) between shear strength $\tau_0$ and cleavage strength $\sigma_0$ is also necessary for the improvement of the tensile plasticity. This new strategy is important for the optimum design of high-performance materials, not only for the new BMG composites but also for nanostructured materials.

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