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Technical note

Cyclic mechanical properties of copper-based shape memory alloys: The effect of strain accommodation at grain boundaries

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ABSTRACT

Fatigue behavior of shape memory alloys depends on deformation mechanisms (e.g., martensitic transformation, variant conversion, slip, and elastic deformation) and how they interact with microstructure. In this paper, we examine fatigue properties of Cu-based shape memory alloys, focusing on the effect of strain accommodation at grain boundaries on fatigue life and fracture mode under various deformation mechanisms in polycrystals. Comparisons with single crystals and static test results are also made. As lack of plastic accommodation at grain boundaries often leads to brittle intergranular fracture, incorporation of a ductile intergranular phase is promising for providing strain accommodation for transformation nearby and improving superelastic fatigue life.

Superelasticity of Shape Memory Alloys (SMAs) is enabled by a stress-induced displacive martensitic phase transformation that reverts upon unloading [1,2]. Ni-Ti SMAs exhibit excellent superelasticity, but their transformation stresses and stress hysteresis change rapidly with mechanical cycling [3,4]. Cu-based SMAs are cheaper and have excellent shape memory and superelasticity in single crystalline forms [5,6]. However, polycrystalline Cu-based SMAs often fracture during superelastic deformation. Intergranular fracture is often observed, and might be attributed to poor accommodation of transformation strain, high elastic anisotropy, and resulting stress concentration in grain boundary regions [7–9]. In this paper, we perform a critical review of cyclic mechanical properties of Cu-based SMAs, focusing on the effects of grain boundaries and deformation mechanisms on fatigue failure. We also introduce new results on cyclic superelastic testing of grain boundary engineered Cu-Zn-Al alloys, showing improvement in superelastic and fatigue properties with the incorporation of a strain-accommodating grain boundary phase.

Fig. 1(a)–(d) summarizes cyclic testing results of Cu-based SMAs in ε–N and σ–N plots, where ε is the maximum strain, σ is the maximum stress, and N is the number of cycles. Because cyclic tests of SMAs typically involve unloading to zero strain or stress, ε and σ are $\Delta\varepsilon$ and $\Delta\sigma$. Fig. 2 assembles the parametric space of testing temperatures and maximum stresses, and shares a common legend with Fig. 1.

(I) *Fatigue of martensitic polycrystals (test temperature T is below martensitic start temperature M_s).* In the ε–N plot of Fig. 1(a), filled blue symbols represent fatigue testing of martensitic polycrystals (including Cu–13.2Al–3.8Ni (wt%) [10] and Cu–20.25–27.5Zn–4.1–6.25Al (wt%) [8,11]) in tension at room temperature (R.T.). Almost all samples failed (N is equal to the fatigue life N_f). Plotting ε vs. $2N_f$ in Fig. 1(e) and fitting to data with $\varepsilon > 0.02$, we obtain $\varepsilon \propto (2N_f)^{-0.182}$. A Manson-Coffin scaling exponent of 0.182 is much lower than conventional exponents of 0.5–0.6 for low-cycle fatigue by plastic deformation, which might be attributed to unique superelastic deformation mechanisms of martensite such as variant reorientation and conversion (and twin boundary motion) [12]. In the σ-N plot of Fig. 1(b), the blue symbols for fatigue strength of martensitic samples include Cu-Al-Ni [10,13] and Cu-Zn-Al [11,14] in tension as well as Cu-21.25Zn-6.25Al (wt%) tested under rotating bending at R.T. [7]. N_f increases with decreasing stress. Fracture surface of a fatigue fractured martensitic sample showed both intergranular and transgranular features [10] (while martensite statically tested to failure exhibited mostly transgranular fracture, showing both dimples and cleavage features [15], and transgranular fraction increases with decreasing grain size [13]). It is believed that deformation by twin or variant activity can be easily accommodated by similar activity in adjacent volume to minimize system energy. During cyclic loading, interactions among these activities and their interactions with grain boundaries may lead to accumulation of dislocations

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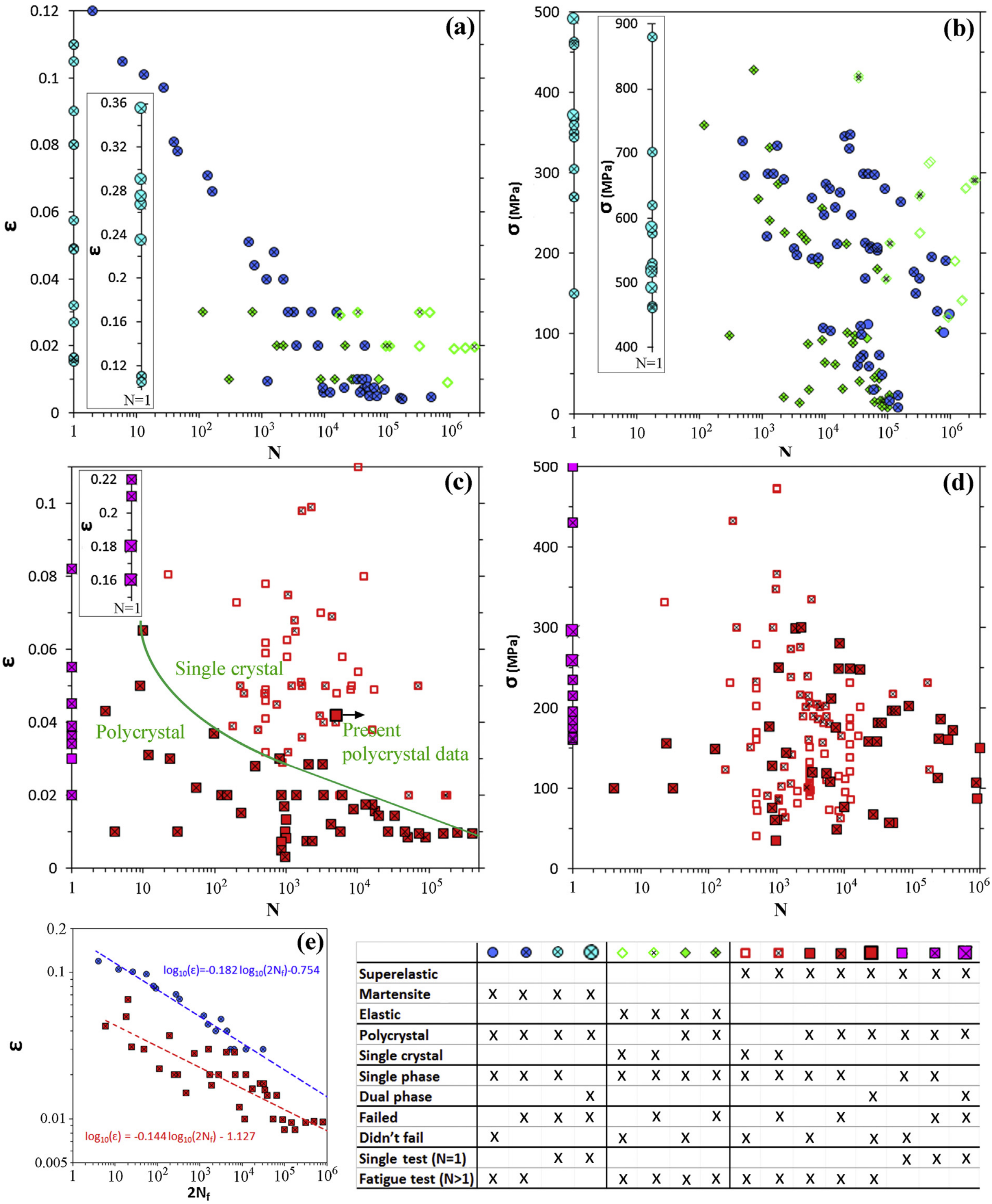

Superelastic									X	X	X	X	X	X	X	X
Martensite	X	X	X	X												
Elastic					X	X	X	X								
Polycrystal	X	X	X	X			X	X			X	X	X	X	X	X
Single crystal					X	X			X	X						
Single phase	X	X	X		X	X	X	X	X	X	X	X		X	X	
Dual phase				X									X			X
Failed		X	X	X		X		X		X		X			X	X
Didn't fail	X				X		X		X		X		X	X		
Single test (N=1)			X	X										X	X	X
Fatigue test (N>1)	X	X			X	X	X	X	X	X	X	X	X			

Fig. 1. Literature survey for fatigue properties of Cu-based SMAs, showing strain or stress vs. fatigue life for martensitic samples and elastic deformation of austenite samples in (a) and (b) and for superelastic deformation of austenite in (c) and (d). (e) Shows Manson-Coffin type power law fitting. Data are extracted from Refs. [7,8,10,11,13–16,18,19,22–44].

(localized plastic deformation) and formation of critical crack nuclei [10]; intergranular fracture is believed not to be a main factor in determining N_f of martensitic samples [10].

(II) *Cyclic elastic deformation of austenitic polycrystals (T is above austenite finish temperature A_f and the stress σ is below martensitic transformation stress σ_c).* Filled green[1] symbols in Fig. 1(a) and (b) represent cyclic elastic deformation of austenitic polycrystals, including Cu–14–14.9Al–4–4.1Ni (wt%) [10], Cu–20.5–22.25Zn–6.25Al (wt%) [7], and Cu-Zn-Sn [16], all tested at R.T. In Fig. 1(a), the elastic strain ranges from 0.01 to 0.03, and N_f mostly ranges from 117 to 2.95×10^4. In general, N_f for elastic loading of austenitic samples is lower than that for deformation of martensitic samples at a given strain or stress in Fig. 1(a) and (b). Fractography of a Cu-Al-Ni sample shows both intergranular and transgranular crack-

[1] For interpretation of color in Fig. 1, the reader is referred to the web version of this article.