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Characterization of cyclic properties of superelastic monocrystalline Cu–Al–Be SMA wires for seismic applications

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HIGHLIGHTS

- This study experimentally characterizes the properties of monocrystalline Cu–Al–Be SMA wires.
- Those properties of common interest in seismic applications are investigated.
- Cyclic properties of monocrystalline Cu–Al–Be wires are compared with those of Ni–Ti wires.
- Monocrystalline Cu–Al–Be SMA shows superior superelasticity and cold-temperature performance.

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ABSTRACT

Although Ni–Ti has been recognized as a promising type of shape memory alloys (SMAs) for seismic response mitigation devices in civil structures, its temperature-dependent mechanical behavior prevents its practical use in cold temperature environment. This study experimentally characterizes the cyclic properties of monocrystalline (also known as single-crystal) Cu–Al–Be SMA wires. The emphasis is put on those properties of common interest in seismic applications, e.g. "yield" stress, energy dissipation capability, stabilization of hysteretic shapes (also known as training effect), sensitivity to loading frequency and ambient temperature, large-strain fatigue, and so on. The testing results of another two types of SMA wires, namely Ni–Ti and polycrystalline Cu–Al–Be wires, are also presented for comparison. The monocrystalline Cu–Al–Be specimens show great superelastic strain of up to 23%. Insignificant degradation of transformation stress or accumulation of residual deformation is observed with increasing number of loading cycles. Meanwhile, their cyclic properties show minimal sensitivity to the variation of applied loading frequency or ambient temperature. The tested specimens maintain stable superelasticity down to −40 °C. Compared with Ni–Ti SMAs, the monocrystalline Cu–Al–Be SMA wires are found to be superior in both superelastic capacity and cold-temperature performance and have comparable performance in terms of fatigue, training effect and energy dissipation. Moreover, these wires also have significantly higher superelastic capacity than polycrystalline Cu–Al–Be or other copper-based SMAs. This experimental study proves that monocrystalline Cu–Al–Be SMA has good potential for seismic applications, which is particularly favorable in outdoor environment with cold winter. Additionally, the hysteresis of monocrystalline Cu–Al–Be wires exhibits remarkable dependence on strain amplitude and complex internal loops. This fact necessitates the future development of more sophisticated constitute models for their complex superelastic behavior.

1. Introduction

Owing to their excellent superelastic behavior, shape memory alloys (SMAs) have gained considerable attention in seismic protection of civil structures. Both numerical and experimental studies have validated the efficacy of SMAs in controlling the residual deformation of seismic resistant structures. Wilde et al. [1] designed SMA-based isolator for elevated highway bridges. Dolce et al. [2–4] proposed SMA-based brace and isolator for seismic response mitigation of reinforced concrete frames, and these devices were proven effective by shaking table tests. Zhu and Zhang [5] proposed an SMA-based damping brace that successfully limited the residual deformation of multi-story steel frames. Padg-

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ett et al. [6] demonstrated the control effectiveness of SMA restrainers in a four-span concrete bridge through shaking table tests. Related research in this field remains active [7–20]. Song et al. [21] and Ozbulut et al. [22] reviewed versatile applications of SMAs in the field of civil engineering.

Among the available SMAs, Ni–Ti (also known as Nitinol) has attracted the most attention for their high superelasticity (6–8% strain) [7], high fatigue life [23], and good anti-corrosion feature. However, temperature-induced austenite-to-martensite ($A \rightarrow M$) phase transformation makes Ni–Ti lose its superelasticity at low temperature. For example, Zhang et al. [24] reported the phase transformation temperature of their tested superelastic Ni–Ti wires to be $A_f \approx 0$ °C, where A_f is the austenite finish temperature. Although the transformation temperature of Ni–Ti can be designed to some extent, its narrow superelastic temperature window makes it difficult to achieve $A_f < -20$ °C. Such temperature-dependent mechanical behavior practically limits the outdoor application of superelastic Ni–Ti SMAs in cold-temperature conditions. In view of this fact, the feasibility of using another type of superelastic SMA, called copper-based SMA, in seismic applications has recently been explored, because of its reliable superelasticity at low temperatures [13,24–26]. For example, polycrystalline Cu–Al–Be wires measured have considerably low transformation temperature of -85 °C [24]. Thus, copper-based SMA is a very appealing alternative to Ni–Ti SMAs in outdoor applications (e.g. seismic base isolators for bridges).

According to crystal arrangement, copper-based SMAs can be classified as polycrystalline or monocrystalline (also known as single-crystal) types. Although the former type is relatively cheaper, it exhibits very limited superelastic strain, typically between 2% and 6%. For example, Montecinos et al. [27] tested two different compositions of Cu–Al–Be under cyclic tension or tension–compression loading, in which both show limited superelastic behavior within nearly 2% strain. Beltran et al. [28] measured the superelastic strain of polycrystalline Cu–Al–Be strands to be 3% under cyclic axial loads as well. Therefore, polycrystalline copper-based SMAs have considerably lower superelasticity than Ni–Ti SMAs, which may compromise self-centering capability under earthquakes. The comparative study presented in this paper reveals more limitations associated with polycrystalline copper-based SMAs in terms of ductility, energy dissipation and fatigue. These limitations render the practical applications of polycrystalline copper-based SMAs in seismic resistant structures very difficult, if not impossible.

Meanwhile, monocrystalline copper-based SMAs exhibit superior superelasticity. Wu [29] found that the successive martensite-to-martensite ($M \rightarrow M$) transformation enables SMA wires to achieve very high superelastic strain levels. Otsuka et al. [30] showed that a monocrystalline alloy with composition Cu81.8Al14Ni4.2 can achieve 18% superelastic strain with full recovery upon unloading. Later, Sakamoto et al. [31] continued Otsuka's test and observed that two distinct stress-induced transformations produced 25% superelastic strain. The recent testing results of monocrystalline Cu-based alloys validated their excellent superelasticity as well (e.g. [32–34]).

Although monocrystalline copper-based SMAs have shown unique features from other SMAs, very limited research has been conducted to characterize their hysteretic properties relevant to potential seismic applications. Gencturk [35] recently tested superelastic Cu–Al–Mn alloys with nearly single-crystal structure and found superelastic strain up to 12%. But the material properties of fully monocrystalline copper-based SMAs relevant to seismic applications have never been systematically reported. To fill in this knowledge gap, this paper presents seismic application-oriented characterization of monocrystalline Cu–Al–Be wires through cyclic loading tests. Research aspects of interest include basic hysteretic characteristics, "training" effect, loading amplitude effect, internal hysteretic loops, loading frequency effect, temperature effect, and fatigue life. The superelastic strain of monocrystalline Cu–Al–Be SMAs is around 23%. By evaluating the sensitivity of the concerned performance under different conditions, this paper clearly demonstrates that monocrystalline Cu–Al–Be SMA has numerous advantages over Ni–Ti or polycrystalline copper-based SMAs in seismic applications, and will be a very promising material for future seismic response mitigation devices, particularly in outdoor environment with very cold winter.

2. Investigated cyclic properties

Fig. 1(a) shows a typical flag-shaped hysteresis that is frequently used to describe the superelastic behavior of Ni–Ti SMA when $T > A_f$; whereas Fig. 1(b) shows a representative hysteresis of monocrystalline Cu–Al–Be SMA when $T > T_c$, where T is the environmental temperature, A_f is the austenite finish temperature of SMAs, and T_c is the critical temperature of monocrystalline Cu–Al–Be. The following material properties that are of common interest in seismic applications are investigated and discussed through the experimental program in this paper:

E_i – the initial modulus of elasticity when SMA is in an austenite state;
α – the ratio of phase transformation stiffness to the initial stiffness, which is analogous to post-yield stiffness ratio of steel material in seismic applications.
σ_L – the forward transformation stress in the loading path, which is analogous to yield stress of steel material in seismic applications. Notably, two distinct forward transformation stresses $\sigma_{L,1}$ and $\sigma_{L,2}$ can be observed in Fig. 1(b).
σ_{UL} – the reverse transformation stress in the unloading path. Again, two distinct reverse transformation stresses $\sigma_{UL,1}$ and $\sigma_{UL,2}$ can be observed in Fig. 1(b);
ε_f – the ultimate strain of SMAs at the moment of fracture;
ε_{se} – the maximum recoverable strain that is upper bound of superelasticity;
ε_R – the residual strain after fully unloading;
e_{dis} – the dissipated strain energy density that is equal to the total area enclosed by the stress–strain loop in one cycle divided by the material volume;
ζ_{eq} – the equivalent damping ratio calculated by $\zeta_{eq} = E_D/(4\pi \times E_S)$, where E_D is dissipated energy, and E_S is strain energy;

The above fundamental properties are essential factors in determining seismic behavior of SMA-based damping devices installed in civil structures. For example, the "post-yield" stiffness and energy dissipation of flag-shaped hysteresis play important roles in controlling seismic peak displacement of self-centering structural systems [36]; the maximum recoverable strain and residual strain determine the self-centering capability after earthquakes. In addition to these properties, the effects of strain amplitude, loading frequency and temperature on the superelastic behavior, and large-strain fatigue life are experimentally studied as well.

3. Experimental setup and method

The tested superelastic monocrystalline Cu–Al–Be wires were obtained from NIMESIS Technology Inc. The chemical composition in terms of weight is close to Cu ≈ 87%, Al = 12.0%, and Be = 0.45–0.68%. According to the manufacturer, the austenite finish temperature A_f of the wires is around -91 °C. The monocrystalline Cu–Al–Be wires have a diameter of 1.9 mm. The wire specimens were taken from two different parent lots, namely Lot A and Lot B. The stress–strain relationships obtained in the cyclic tests show slight difference between the specimens from these two lots, whereas those from the same lot show quite consistent results. The difference may be due to many factors, such as the composition, crystal