Pseudoelastic cycling between austenite, 18R and 6R phases in CuAlBe single crystals

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Abstract

CuAlBe shape memory alloys exhibit successive reversible stress induced martensitic transformations from austenite to 18R phase and from 18R to 6R phase. The particularities associated with these transformations result in CuAlBe being an attractive candidate material for damping applications. Recently, a stress-temperature phase transformation diagram has been proposed for this system, which, besides the above mentioned phases, also includes the structural distortion of the 18R previous to its stress induced transformation to 6R. In the present work, pseudoelastic cycling of CuAlBe single crystals has been performed at different test temperatures. Both transitions, i.e., austenite-18R and 18R-6R, have been studied. As hysteresis plays a significant role in shape-memory alloys intended to be used for energy dissipation, special attention has been devoted to its evolution during cycling. In addition, the kinetics of stabilization of martensites has been analyzed under dynamic (pseudoelastic cycling) and quasistatic (constant transformed fraction) conditions. A strong enhancement of martensitic stabilization under dynamic conditions compared with stabilization at quasistatic conditions was observed and the possible mechanisms responsible for the effect are mentioned.

Keywords: CuAlBe, single crystals, fatigue, pseudoelasticity

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1. Introduction

Pseudoelasticity is the particular behavior exhibited by shape memory alloys (SMA) where high deformations obtained upon loading are recovered after unloading. In Cu based systems, pseudoelasticity can be explained by the stress induced transition between the austenite phase (DO3 or L21 ordered structures) and the 18R martensite. In all cases, the required stress to induce the martensite is higher than the stress to retransform to austenite, leading to a hysteresis. This hysteresis represents an interesting alternative for energy dissipation in mechanical systems. A possible energy dissipation device should resist repeating cycling without fracture and also exhibit a reasonable stable functional behavior. Therefore, a good knowledge of the effects of pseudoelastic cycling on the response of SMA is necessary. In the particular case of CuAlBe SMA, reported papers have analyzed the stabilization of martensite in single crystals under conditions where a large concentration of vacancies is present [1,2]. Concerning pseudoelastic cycling between austenite (referred to as β here) and 18R martensite, CuAlBe single crystals show an interesting behavior: dynamic stabilization takes place during cycling and the austenite tends to recover its original state if cycling is stopped [3,4]. This behavior is present even for the equilibrium concentration of vacancies, to be used in the experiments of the present manuscript. Additional results were reported in CuAlBe single crystals mainly related with fatigue life during bending [5,6]. More recently, an unexpected mechanical behavior was reported: 18R martensite shows a structural distortion if tensile stressed (18R’ will be used to name the distorted 18R structure) [7]. This fact encourages us to extend the research on this matter considering the contribution of the structural distortion on the cycling behavior, a matter to be considered in the present work. Additionally, not much information is available concerning dynamic pseudoelastic cycling between martensitic structures, including the formation of the 6R structure. The 18R-6R pseudoelastic cycle shows two noticeable properties: the stress to induce the 6R phase is nearly independent of temperature and the involved hysteresis is considerably larger than the corresponding one of the austenite to 18R transition. If the hysteresis due to the β-18R transition is attractive for damping purposes, undoubtedly the 18R-6R transition might increase the potential use of Cu based alloys [8,9]. The pseudoelastic behavior of CuAlBe single crystals up to the formation of 6R martensite has been presented and discussed [8,9]. Preliminary results on rapid cycling up to 6R structure will also be presented introduced.

2. Experimental details

CuAlBe single crystals have been used for the present research. The nominal composition is Cu - 11.40 wt.% Al - 0.53 wt.% Be. Specimens were thermally treated by keeping them at 850 °C for 15 min and then quenching in water at 100 °C. A further treatment at 100 °C during 4 hs enabled to have a concentration of vacancies close to equilibrium. A similar thermal treatment with an annealing time of 1 h at 100 °C was used by Tidu et al. [10] who found this time sufficient to have the equilibrium concentration of vacancies. Additional comments on the effect of different thermal treatments on the martensitic transformation temperature and related properties can be found in [11]. Critical transformation temperatures were determined by electrical resistance measurements, being Ms = 23 °C and Af = 29 °C. Mechanical tests were performed using either electromechanical testing machines Instron 5567 or Instron 1123 updated to 5567. Either an MTS or an Instron extensometer was used. $\varepsilon$ is used for deformation obtained with extensometer. An environmental chamber was used in all tests for keeping constant temperature unless specifically stated.

3. Experimental Results

Experiments were performed at different temperatures and frequencies between the austenite and a complete stress induced martensitic single crystal. An example is shown in Fig.1 for sample A. The temperature selected for this test was 393K (120 °C), which is the highest temperature for this composition which enables to obtain the β-18R transformation without overlapping with the 18R-6R transition [12]. Fig. 1a shows cycles 1 and 1300 performed at a crosshead speed of 10 mm/min (0.17 mm/s) and frequency 1.5 cycles/min. A positive slope is observed in the last cycle indicating inhomogeneous stabilization of martensite. The maximum decrease of the stress to transform reaches approx. 60 MPa. The reason to disregard the effect of dislocations on the measured mechanical evolution has been shown in three different papers, which presented data on pseudoelastic cycling under tensile mode [3,4,10]. The mentioned papers show how pseudoelastic behavior recovers after cycling interruption and that a diffusive
mechanism correctly explains the obtained results. An additional experiment corroborating these results will be presented when Fig. 1b is analyzed (next paragraph). It can be noticed that after cycling the deformation to obtain the total transformation of the sample seems to decrease if compared with the initial one. This fact might be related with the distortion of the 18R martensite [7]. In order to check this point, an additional experiment was performed at 373 K.

Specimen B was cycled 500 times between austenite and the 18R structure at 100 °C (crosshead speed 10 mm/min, frequency 1.5 cycles/min). In this case both limits of the test were fixed at constant loads to assure, on the one hand, the complete return to austenite and on the other hand, the complete β-18R transition and further 18R-18R’ distortion. The last one is completed at a stress slightly smaller than the critical to induce 6R martensite. Rapid cycles 1 and 500, not shown here, present the same type of evolution as plotted in Fig.1a. In Fig.1b, slow cycles obtained at the same temperature before and after rapid cycling are shown. It is noticed that after cycling, critical stresses and hysteresis decrease. Additionally, a small deformation is retained. Those parts of the σ-ε curves corresponding to the deformation of the 18R single crystals partially overlap, which makes it rather difficult to check if a variation of the mechanical behavior at this stage is present. A zoom of this part, also shown in Fig. 1b, indicates that the inflection point which characterizes the 18R-18R’ distortion was shifted up 13 MPa after cycling. After rapid cycling stops, a recovery of critical stresses and hysteresis is observed after 9 h at the test temperature (see Fig.1b) although a longer time is required for a complete recovery. Additionally, the small retained deformation which increases during cycling disappears after the 9 hs at the test temperature (see Fig. 1c). This clearly shows that the mechanical evolution during cycling is a reversible process and not a consequence of an irreversible introduction of dislocations. This has been also reported by other authors [3,10]. In Fig. 1c, two magnitudes obtained from the rapid cycles are shown as a function of time in 18R martensite: the hysteresis measured as the difference between critical stresses and the stress corresponding to the inflection point of the distortion. It is noticeable that the shift of the 18R-18R’ structural distortion increases during cycling.

Additional tests were performed to analyze the behavior of the material after pseudoelastic formation of 6R. An example is shown in Fig. 1d for sample C which shows the slow σ-ε curves obtained before and after 200 rapid cycles (20 mm/min). The stabilization of both 18R and 6R structures, which strongly decreases the final hysteresis, is clearly observed. A small step of the retransformation curves at aprox.120 MPa corresponds to a small portion of the sample not transformed to 6R.

Discussion and conclusions

The obtained results indicate that although quasistatic stabilization of 18R martensite is rather weak in CuAlBe if compared with CuZnAl, under dynamic conditions, stabilization of martensite plays a significant role in the mechanical evolution after pseudoelastic cycling [13]. Recovery of austenite is also significant, which allows a strong recovery at rather high temperatures (100 °C or higher), if the material remains in austenite or the cycling frequency decreases. A previous work on pseudoelastic cycling performed at lower temperatures showed that the hysteresis of the β-18R cycle decreases after rapid pseudoelastic cycling and tends to recover if cycling stops[4]. In the present work, the results obtained at higher temperatures indicate that, at least partially, this anomalous behavior can be explained by the presence of the 18R-18R’ which characterizes the mechanical behavior of the 18R martensite. It has been shown that the stabilization of martensite can be explained by the pair interchange of Cu and Be atoms when the material is in martensite, provided that temperature is high enough [14]. It was also shown that the free energy of 18R decreases if the amount of pair interchanges is sufficiently high. The present results clearly show that, under dynamic cycling, stabilization is greater and more rapid. This leads to a larger difference between the critical stress to obtain 18R and the stress range corresponding to the 18R-18R’ distortion. As it has been reported, the overlapping of the β-18R transition and the 18R-18R’ increases the hysteresis and the deformation corresponding to the transformation [7]. Additionally the results shown in Fig.1b and Fig.1c indicate that the stress range corresponding to the 18R-18R’ distortion shifts up after rapid cycling. In this way both effects, the decrease of the hysteresis and the total deformation during cycling can be rationalized.

If pseudoelastic cycling involves the formation of 6R martensite, additional features must be considered. On one hand the hysteresis of the 18R-6R is considerably larger than the corresponding one of the β-18 transition [9,12]. On
the other hand it has been reported that the stress to retransform from the 6R martensite also determines the critical stress to retransform to austenite [12]. This is of interest and suggests potential applications of this huge hysteresis and large deformation (approx. 20% starting from the austenite). The result shown in Fig. 1d makes noticeable the fact that stabilization is also significant if rapid cycling is performed up to the formation of 6R martensite. Considering the remaining pseudoelastic behavior after cycling, it is clear that not only 18R must be retained but also part of the 6R structure is also stabilized after cycling. Plastic deformation of martensite might contribute to the retained deformation. This result can be considered preliminary. However it has been reported that slow cycles up to the formation of 6R martensite strongly stabilize the 18R martensite previously transformed to 6R [12].

Fig. 1. a) $\sigma$-$\varepsilon$ curves obtained for sample A cycled at 120°C; b) $\sigma$-$\varepsilon$ curves obtained at 100°C for sample B; c) Hysteresis and $\sigma^{18R-18R'}$ vs. time in 18R martensite during rapid cycling for sample B; d) $\sigma$-$\varepsilon$ curves evolution after 200 rapid cycles for sample C; curves obtained at 0.3 mm/min.

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References