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Stress-induced deformation at $A_p \sim M_p$ and thermal cycling behavior of Cu-Al-Ni single crystals ①

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[Abstract] Stress-induced deformation in $A_p \sim M_p$ and concomitant shape recovery behavior of Cu-13.4Al-4.0Ni single crystals were studied. Abnormal high stress-induced deformation exists in $A_p \sim M_p$ under the conditions of either heating with load or cooling with load. The recovered deformation is successively composed of four parts, the recoveries from superelasticity, normal reverse transformation, thermally activated reverse transformation of partially stabilized martensite and reverse transformation of stabilized martensite by over-heating. With increasing cycling number, the recovery part from normal reverse transformation decreases, while that from reverse transformation of stabilized martensite by over-heating increases, which shows a typical stabilization of martensite.

[Key words] CuAlNi single crystal; stress-induced deformation; two way shape memory; superelasticity; stabilization of martensite

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1 INTRODUCTION

In the past two decades much attention has been paid to the study of Cu-Al-Ni shape memory alloys[1~7]. Results show that the alloys have relatively good phase stability[8], good aging stability[9] and high superelasticity[10, 11]. In the research of superelasticity and training for obtaining two way memory effect[12], it was found that when the post-quenched single crystal was cooled for the first time from a temperature above A_f with load through the transformation temperature range of $A_p \sim M_p$ (A_p and M_p represent respectively the peak temperature from austenite to martensite and from martensite to austenite measured by DSC[9]), there was an extremely high strain peak in the strain—temperature curve. Therefore it would be of engineering importance to study the stability of the strain, corresponding superelasticity and relationships between strain and temperature. Based on the previous work, the authors study the stress-induced deformation in the temperature range of $A_p \sim M_p$ and thermal cycling behavior of Cu-Al-Ni single crystals.

2 EXPERIMENTAL

The alloy used was single crystal with a composition of Cu-13.4Al-4.0Ni (mass fraction, %). The dimension of the specimen for stress-induced deformation measurement was d 3 mm × 200 mm. After being heated at 800 ℃ for 20 min and then quenched into water at room temperature, the transformation temperatures of the specimen measured by DSC[9] were M_s = 96 ℃, M_p = 84 ℃, M_f = 60 ℃; A_s = 73 ℃, A_p = 96 ℃ and A_f = 102 ℃. The axial direction of the sample was close to ⟨001⟩ of β phase at high temperature. The deformation and thermal cycling tests were carried out with the apparatus described in Ref. [13], by which the parameters of temperature, stress and time can be logged, monitored and processed by computer. A thermocouple (with precision of 0.1 ℃) was connected directly with the sample and the temperature was adjusted by the combination of oil bathing, resistance heating, water-cooling coil and a stirring element. The temperature range measured was 60~ 178 ℃. The tensile stress was applied at precision of 1 N. The strain measurement was made by a LVDT (Linear Variable Differential Transformer) that connected with the sample by quartz rods, and the precision was 2 μm. The gauge length was 100 mm. Both the loading and unloading speed were 73 MPa/min.

Enough experimental data[9~12] showed that there was a difference between the temperatures measured by DSC and the real actuating temperatures of the single crystal. Although the transformation temperature ranges of $M_s \sim M_f$ and $A_s \sim A_f$ measured by DSC were quite wide, the actual shape memory temperatures were generally at the sharp narrow tempera-

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tures near M_p and A_p respectively, which might be caused by the great differences in the dimensions and the volume constraint conditions (for example very small flake, small disc or bulk) of the sample. Therefore, it might be reasonable to express both the transformation behavior and the real actuating temperature of the shape memory by together using of M_s, M_p and A_s, A_p respectively, from the engineering point of view.

Considering the fact that the transformation temperatures were above room temperature and the sample was heated from room temperature, we set the measuring temperature at 87 ℃ (in the range of M_p~ A_p). Before the occurrence of main reverse transformation at 87 ℃, the stress was applied and released and then thermally cycled so as to study the relationships among stress, strain and temperature.

3 RESULTS AND DISCUSSION

3.1 Shape memory effect in A_p~ M_p

Fig. 1 shows the strain—temperature relationship at different stages of thermomechanical cycling. Through thermal cycling, for the post-quenched Cu-Al-Ni single crystal in 50~ 136 ℃ in the initial two thermal cycles, the obtained two way shape memory effect is only about 0.20%, which occurs at 92~ 100 ℃ and its actuating temperatures correspond well with M_p and A_p measured by DSC. When the sample is loaded (p = 87.8 MPa) at a temperature of (M_f- 20 ℃), a deformation of 0.35% is produced due to martensite reorientation and this deformation recovers in the next heating process. When the sample is loaded (p = 48.1 MPa) at temperature of (A_f+ 20 ℃) and cooled with the load to (M_f- 20 ℃) and unloaded, followed by thermal cycling between (M_f - 20 ℃) and (A_f+ 20 ℃), it was found that in the first cooling cycle from (A_f+ 20 ℃) with load, a very high stress induced deformation (7%) is produced in A_p ~ M_p. Another experiment[12] also proves that when the post-quenched single crystal sample is loaded (p = 120.3 MPa) for the first time at temperature below M_f, 3% deformation is produced by martensite reorientation; and when heating with the load a stress-induced deformation is further produced in M_p~ A_p, which makes the total deformation up to 6%.

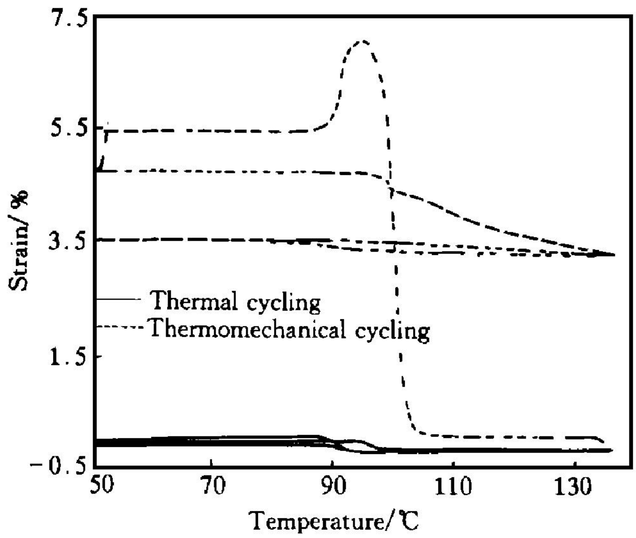

Fig. 1 Stress—temperature curve at different stages

3.2 Stress-induced deformation between A_p and M_p and characteristics of recovery

Normally the practical application stress of Cu-Al-Ni alloy is no more than 100 MPa, so a stress of 72.2 MPa is loaded at 87 ℃ as testing stress in following experiments.

Figs. 2(a) and (b) show respectively the strain—temperature curve and stress—strain curve around 87 ℃ in the first cycle. After the stress is applied, a total deformation of 3.98% is produced at around 87 ℃, and this stress-induced strain typically linearly increases with stress, as shown in Fig. 2(b). Its mechanism is that some of the same kind variants in parent phase gradually start to form martensite in the single crystal[1]. By releasing the stress there is a superelastic recovery of 0.41%. The rest deformation

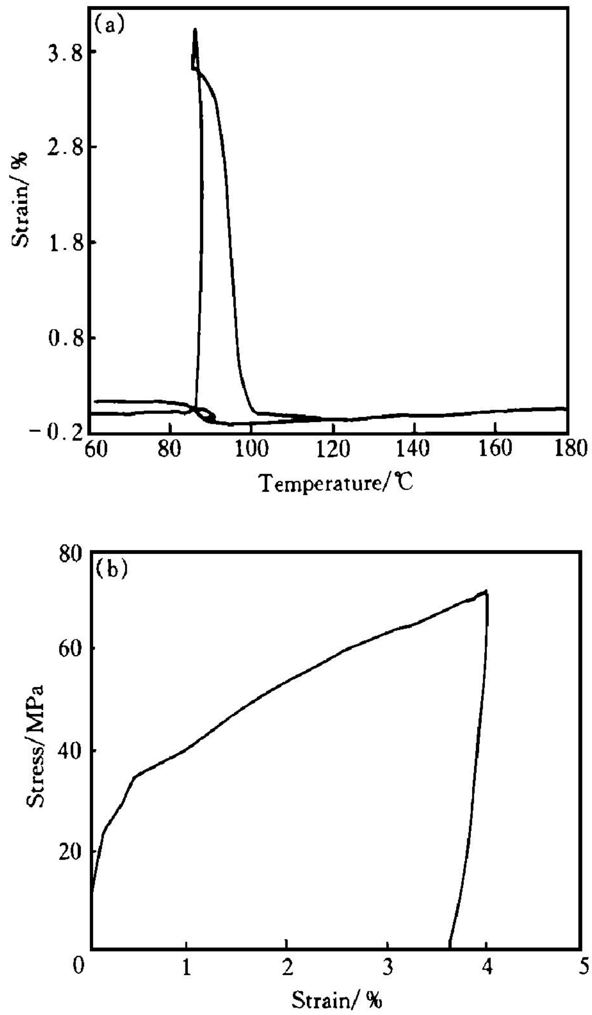

Fig. 2 Strain—temperature (a) and stress—strain (b) curves around 87 ℃ in first cycle

is almost recovered in the regular reverse transformation temperature range of 87~ 102 ℃.

The above stated deformation behavior and its recovery characteristics change greatly with cycling going on. Figs. 3(a) and (b) show respectively the strain—temperature and strain—stress curves around 87 ℃ in the 7th cycle. By comparing these with results in Fig. 2, it can be seen that although the total stress-induced deformation at 87 ℃ by applying stress of 72.2 MPa is almost 4%, the deformation component is changed gradually from the typically linear to nearly plateau-like. The corresponding start plateau stress is lowered gradually, and the corresponding strain increases gradually with the cycling number. The mechanism can be rooted in the easy start of individual variant of the same kind variants to form martensite in the single crystal with the cycling going on. The total shape recovery in every stress-thermal cycle is composed of the following four parts, as indicated in Fig. 3(a) by mark 1, 2, 3 and 4, respectively:

$$\varepsilon = \varepsilon_e + \varepsilon_{sate} + \varepsilon_t + \varepsilon_{stab} \quad (1)$$

where ε_e is superelastic recovery upon the release of stress, and it increases gradually with the cycling number within a certain stress limit[14]. The recovery process after unloading can be divided into the following three reverse transformation parts of different mechanisms. ε_{sate} can be regarded as reverse transformation of stress assisted transformation effect (SATE) which occurs normally at 87~ 102 ℃, and it decreases with the stress-thermal cycling; the part of ε_t can be regarded as the thermally activated reverse transformation of partially stabilized martensite; the part of ε_{stab} can be regarded as the reverse transformation of stabilized martensite in the overheating process, and it increases with the stress-thermal cycling[15]. Experimental results prove that for every fixed training stress the corresponding reverse transformation temperature of ε_{stab} is almost the same. In Fig. 3(a), the reverse transformation temperature of stabilized martensite caused by applying stress of 72.2 MPa around 87 ℃ is 146 ℃.

3.3 Two way memory effect

Fig. 4 shows the strain—temperature curves of the first and the 8th thermal cycle after trained for 13 cycles with stress of 72.2 MPa around 87 ℃. It can be noted that the two way memory effect is increased to 0.4%, and such two way memory effect after training is very sensitive to temperature at A_p~ M_p

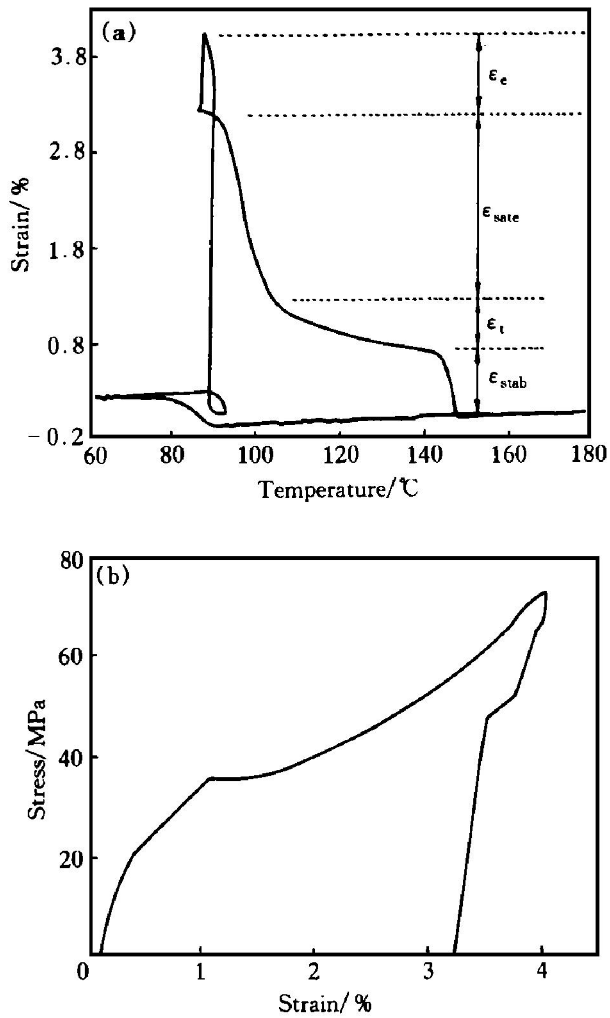

Fig. 3 Strain—temperature (a) and stress—strain (b) curves around 87 ℃ in 7th cycle

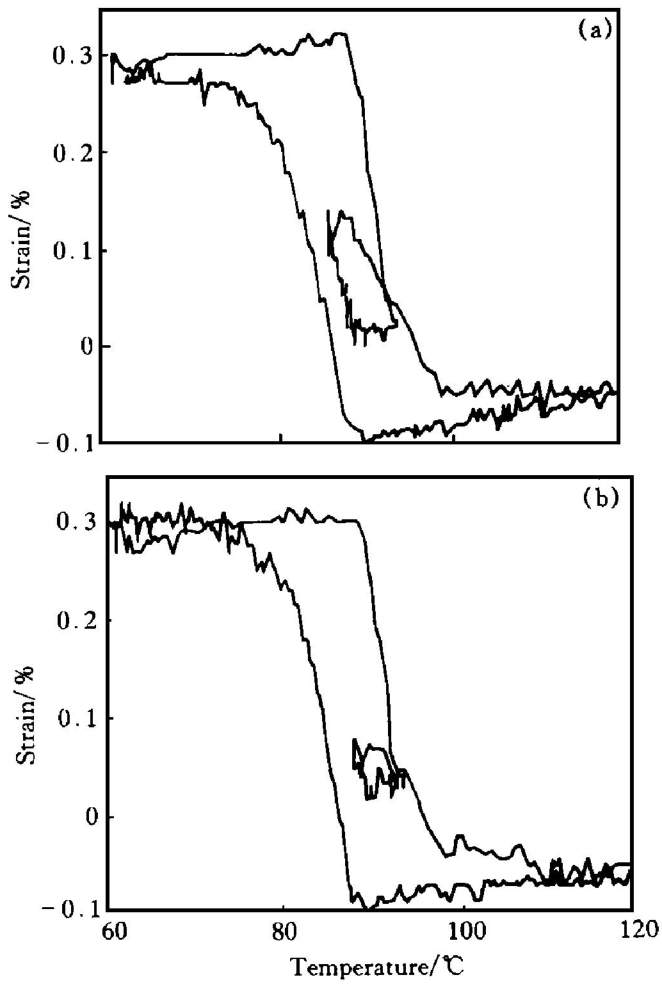

Fig. 4 Strain—temperature curves after trained for 13 cycles
(a) —In first thermal cycling; (b) —In 8th thermal cycling

(84~ 96 ℃). If the reverse shape recovery temperature is lowered at the stage of incomplete recovery, there is a forward shape change due to forward transformation, which likes the partial (or incomplete) two way memory effect within a very narrow temperature range in NiTi alloy[16]. When the temperature is further increased, the reverse transformation continues. It is found by comparing the curves in Figs. 4(a) and (b) that the obtained two way memory effect is relatively stable. Even the sample subjected to thermal cycling for 8 times at temperature up to (A_f+ 76 ℃), the loss of two way shape memory is little.

4 CONCLUSIONS

1) Abnormal high stress-induced deformation phenomena exists at A_p~ M_p under the condition of either heating with load or cooling with load to the studied Cu-Al-Ni single crystals.

2) The recovered deformation is successively composed of four parts of recoveries from superelasticity, normal reverse transformation, thermally activated reverse transformation of partially stabilized martensite and reverse transformation of stabilized martensite by over-heating.

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