Effects of deformation on microstructure and mechanical properties of a Cu–Al–Ni shape memory alloy

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ARTICLE DATA

Article history:
Received 5 June 2007
Accepted 30 July 2007

Keywords:
Shape memory alloy (SMA)
Cu–Al–Ni alloy
Martensite transformation
Stress-strain curve
Fracture behaviour
Plastic deformation
Mechanical twins

ABSTRACT

In Cu-11.92 wt.%Al-3.78 wt.%Ni shape memory alloy, the influence of deformation and thermal treatments on the microstructure and mechanical properties under the compression test were studied by means of scanning electron microscopy (SEM), transmission electron microscopy (TEM), and differential scanning calorimetry (DSC). Experiments show that the mechanical properties of the alloy can be enhanced by convenient heat treatments. The alloy exhibits good mechanical properties with high ultimate compression strength and ductility after annealing at high temperature. However, it exhibits brittle fracture and dramatic strain hardening, with linear stress-strain behavior after annealing at low temperature. The changes in the mechanical properties have been linked to the evolution of the degree of order, occurrence of precipitation, and variation of the grain size. From microstructural observations, it is seen that the β_1' (18R) and γ_1' (2H) martensite phases coexist at different fractions in the undeformed and deformed states. Deformation induces the changes between the β_1' and γ_1' martensites and deformation-induced martensites form at preferred orientations as mechanical twins. The β_1' martensite variants are twin-related with respect to the $(\bar{1}\bar{2}8)_{18R}$ mirror plane and a new orientation relationship for these twin variants is derived as $(\bar{1}\bar{2}8)_A \| (\bar{1}\bar{2}8)_C$: $[\bar{4}61]_A \| [\bar{4}61]_C$. Additionally, an increase in the amount of deformation causes martensite reorientation, de-twinning, and dislocation generation; also, the martensite plates are seen to have rearranged in the same orientation to be parallel with each other.

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1. Introduction

Shape memory alloys (SMAs) and their associated thermoelastic martensitic transformation have been the subject of extensive study for many years, since they have many technological applications utilizing the shape memory effect [1–3]. Among the numerous SMAs, the Cu-based SMAs are commercially attractive alloys for practical applications owing to their low cost, together with a reasonable shape memory effect. However, they have some limitations for industrial applications due to their low thermal stability, brittleness, and unsatisfactory mechanical strength. They suffer from martensite stabilization and finally lose the thermoelastic properties [4,5]. Among the Cu-based SMAs, the CuAlNi alloys have better thermal stability and offer possible use at higher temperatures. On the other hand, the practical applications of the CuAlNi alloys are restricted to those requiring very small shape changes due to their poor workability and susceptibility to brittle intergranular cracking [6]. Hence, improving the mechanical properties is an important goal for the CuAlNi alloys. Until now, research has shown that the mechanical properties of the CuAlNi alloys can be improved by adding alloying elements and by heat treatment [7–9].

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1044-5803/$ – see front matter © 2007 Elsevier Inc. All rights reserved.
doi:10.1016/j.matchar.2007.07.017

As is well known, the shape memory effect involves the deformation of a material in the martensitic state (below M_f). In Cu-based SMAs, several effects can occur during the deformation that contribute to the macroscopic shape change. Generally, the thermoelastic martensitic structure consists of self-accommodating plate variants. These variants coalesce and rearrange through the movement of intervariant boundaries during the deformation. Mechanical twins can also develop in this process. Thus, the most favorably oriented martensite variants form in response to the applied stress. Additionally, martensite → martensite transformations involving changes in the stacking sequence of close packed planes can also form in response to the deformation; austenite → martensite transformations may also occur [10–12].

It is important to study the process of deformation in the martensitic state in order to understand the origin of the shape memory effect. It is also necessary to understand the tensile and compressive behaviors to utilize the useful properties of SMAs in some applications. Recently, the effects of deformation in the martensitic state have been extensively studied in SMAs. Schroeder and Wayman [13] studied the morphology resulting from the formation and deformation of martensite in CuZn alloys. The motion of martensitic interfaces under stress has been observed in some SMAs [14]. In a CuZnAl alloy, the substructure of martensite and the intervariant boundary structure in deformed martensite were investigated in detail by high-resolution electron microscopy [11]. Martensitic transformation and the mechanical and thermoelastic properties in CuAlNi SMAs have been widely studied under tensile stresses [8–10], whereas little work has been done concerning these properties under a compressive stress [15,16]. In the present work, the effects of deformation on the martensitic structure in the CuAlNi SMA have been characterized by means of SEM and TEM. In addition, the mechanical properties of the alloy have been studied under compressive loading.

2. Experimental Procedures

The alloy used for this study was prepared by melting the (99.9%) pure elements in an argon atmosphere and quenching as cylindrical rods with 1 cm diameter and 10 cm length. The chemical composition of the alloy was determined as Cu-11.92 wt.%Al-3.78 wt.%Ni by electron dispersion spectroscopy (EDS).

The arc-melted ingots were cut by a diamond cutter at room temperature. Compression samples were prepared in the shape of rectangular pieces with dimensions 6×3×3 mm. The samples were sealed into evacuated quartz tubes and then heat treated. To investigate the effect of different heat treatments on the mechanical properties of the alloy, three β-homogenization heat treatments were used. The specimens were annealed at 650 or 950 °C for various times and then quenched into ice water. The heat treatments and plastic deformation applied to the specimens are given in Table 1.

The transformation characteristics of the alloy were examined by differential scanning calorimetry (DSC). The DSC measurements were made with a Perkin-Elmer Sapphire model thermal analyzer at heating and cooling rates of 10 °C/min in the 25–500 °C range.

The compression tests were performed in an INSTRON 8510-type machine operated at a constant strain rate of 0.2 mm/min. The tests were carried out in two stages at room temperature. In the first stage, the compressive stresses were applied to different heat treated samples until failure occurred, and thus the fracture behavior and the cracking limits of the samples were determined under the compressive loading. Later, in order to investigate the effect of deformation in the martensitic state, partial deformation above the yield point was applied to specimens which had been heat treated at 950 °C for 120 min (samples D and E in Table 1).

The microstructures of the heat treated and deformed samples were examined by SEM and TEM. For SEM observations, the surfaces of the specimens were first mechanically polished and then the damaged surface layers were eliminated by etching in a solution composed of 2.5 g $FeCl_3.6H_2O$ and 48 ml methanol in 10 ml HCl for 4 minutes. SEM observations were made in a JEOL 5600 scanning microscope operated at 20 kV. Samples for TEM observations were prepared from deformed and undeformed specimens. Discs of about 0.4 mm thick were cut from the specimen with a low-speed diamond saw and then thinned to 0.1 mm with 800 and 1200 grit emery papers and punched into 3-mm diameter discs. Finally, these discs were prepared by double jet electro-polishing in Streurs-Tenupol jet unit with a solution of 30% HNO_3–70% methanol at the temperature of −10 °C and a voltage of 10 V. The TEM observations were performed on a JEOL 3010 electron microscope operated at 300 kV with a double tilt specimen stage.

3. Results

3.1. *Effects of Heat Treatments on Mechanical Properties*

The mechanical properties of the alloy were determined for three differently-heat treated materials (samples A, B, and C). In order to investigate the influence of thermal treatments on the grain size responsible for the mechanical and transformation properties of the alloy, SEM observations of the samples were made before the compression tests. The microstructures of the specimens are shown in Fig 1. As seen from the figures, all the samples exhibit martensitic structures at room temperature.

Table 1 – Heat treatments and plastic deformation

Samples	Nature of heat treatments and plastic deformation
A	Homogenized at 950 °C for 120 min. and quenched into ice water
B	Homogenized at 950 °C for 40 min. and quenched into ice water
C	Homogenized at 650 °C for 40 min. and quenched into ice water
D	Homogenized at 950 °C for 120 min., quenched into ice water and then compressed by 4.5% deformation at room temperature
E	Homogenized at 950 °C for 120 min., quenched into ice water and then compressed by 7% deformation at room temperature

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