

A study of the two-way shape memory effect in Cu–Zn–Al alloys by the thermomechanical cycling method

Hyoun Woo Kim*

School of Materials Science and Engineering, Inha University, Incheon 402-751, South Korea

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Abstract

We have examined the two-way shape memory effect (TWME) in Cu–Zn–Al alloys with a novel thermomechanical cycling method: bending the alloy strips around a cylinder mould and by using a constrained heating/cooling technique. The strength of TWME was affected by the number of training cycles and by the constrained heating temperature. We found that the presence of the β -phase is a crucial factor in generating TWME. After the thermomechanical cycling treatment, we observed the new martensite in addition to the existing martensite in Cu–Zn–Al alloys.

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1. Introduction

The two-way shape memory effect (TWME) is a phenomenon whereby a material can alternate between two distinct shapes as it undergoes a thermal cycle. TWME is not an intrinsic property of shape memory alloy, but can be obtained by several training methods, most of which are based on thermomechanical or superelastic training [1–7].

More attention has been paid to Cu-based shape memory alloys in the past few years owing to their low price, easy fabrication, and excellent conductivity of heat and electricity. Although there have been reports on the induction of TWME in Cu–Zn–Al alloys using thermomechanical cycling [8,9], there are few reports on obtaining TWME by bending alloy samples around cylindrical-shaped structures and employing a constrained heating/cooling technique. In this study, we have used a thermomechanical cycling method, consisting of a simple constrained heating/cooling technique, to generate TWME.

2. Experimental

70.3Cu–24.1Zn–5.6Al (wt.%) and 65.6Cu–33.1Zn–1.3Al (wt.%) alloys were prepared in an induction furnace and

subsequently forged and hot-rolled. Finally, rectangular specimens with dimensions of 170 mm \times 12 mm \times 2.2 mm were machined from an ingot. The specimens were then betatized at 800 °C for 30 min and quenched in 25 °C water. The transformation temperatures were calculated by measuring the electrical resistance of the sample, indicating that $M_s = 20$ °C, $M_f = 0$ °C, $A_s = 30$ °C and $A_f = 61$ °C for 70.3Cu–24.1Zn–5.6Al alloy, and $M_s = -70$ °C, $M_f = -100$ °C, $A_s = -48$ °C and $A_f = -20$ °C for 65.6Cu–33.1Zn–1.3Al alloy (M_s : start temperature of martensitic transformation; M_f : finish temperature of martensitic transformation; A_s : start temperature of austenitic transformation; A_f : finish temperature of austenitic transformation).

The strip-shaped specimens were then bent around a cylinder mould of 50 mm diameter placed in liquid nitrogen, and subsequently thermally heated in the temperature range 100–240 °C, in the constrained state. Then the specimens were rapidly cooled in liquid nitrogen in the constrained state; following this, the constraint was removed. To establish a training procedure, the above thermomechanical cycling was repeated several times.

The amount of TWME was assessed by cycling the samples in the unconstrained state between the temperature below M_f and above A_f . Measurements were carried out in the manner indicated in Fig. 1, in which the distances AB, CD, EF, and GH were measured at both ends of the sample. In Fig. 1, curve AB represents the cold-state

* Tel.: +82-32-860-7544; fax: +82-32-862-5546.

E-mail address: hwkim@inha.ac.kr (H.W. Kim).

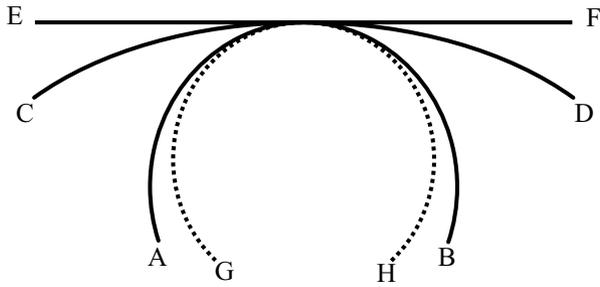


Fig. 1. Schematic representation of the shape of sample. AB: cold shape after the thermomechanical cycling; CD: hot shape after the thermomechanical cycling; EF: original shape; GH: deformation imposed during the thermomechanical cycling treatment.

shape of the sample after the constrained heating treatment, while curve CD represents the hot-state shape after the treatment; EF indicates the original shape of the sample and GH the deformation of the imposed shape during the treatment. In this work, TWME was assessed using the following equation: $\text{strength of TWME} = (CD - AB)/EF$. The structural characteristics of the films were analyzed by X-ray diffraction (XRD) using $\text{Cu K}\alpha_1$ radiation ($\lambda = 0.154056 \text{ nm}$) and by optical microscopy (OM) (Nikon FX-35). The etchant for the OM sample preparation was composed of water, hydrochloric acid (HCl), and FeCl_3 .

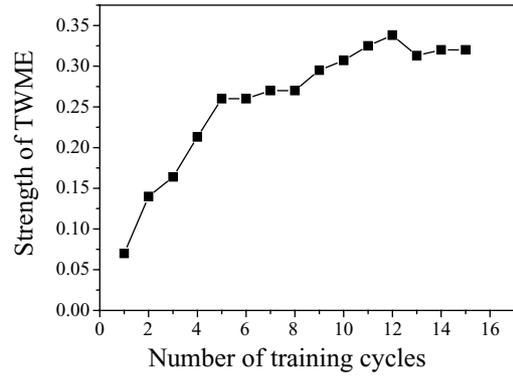


Fig. 2. Variation of the strength of TWMEs in 70.3Cu–24.1Zn–5.6Al alloys with varying number of training cycles with the constrained heating of 100°C .

3. Results and discussion

Fig. 2 shows the variation of the strength of TWME in 70.3Cu–24.1Zn–5.6Al alloy as a result of varying the number of training cycles, with the constrained heating at 100°C . The strengths of TWME are about 0.14 and 0.30 after 2 training cycles and 10 training cycles, respectively, indicating that TWME increases continuously at least up to 10 cycles.

In order to investigate the effect of the number of training cycles, we increased the number of training cycles and varied the constrained heating temperature in the range 1–4 cycles

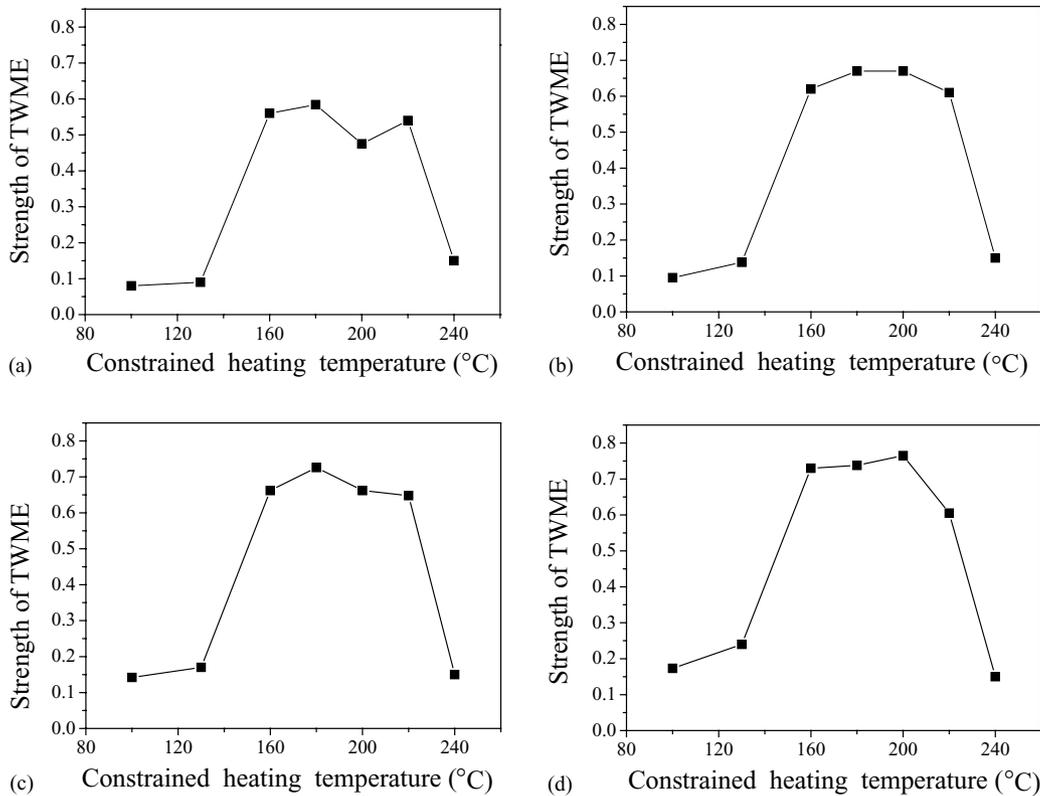


Fig. 3. Variation of the strength of TWMEs in 70.3Cu–24.1Zn–5.6Al alloys with varying constrained heating temperature in case of (a) 1, (b) 2, (c) 3, and (d) 4 training cycles, indicating that TWME is relatively strong in the range $160\text{--}220^\circ\text{C}$.

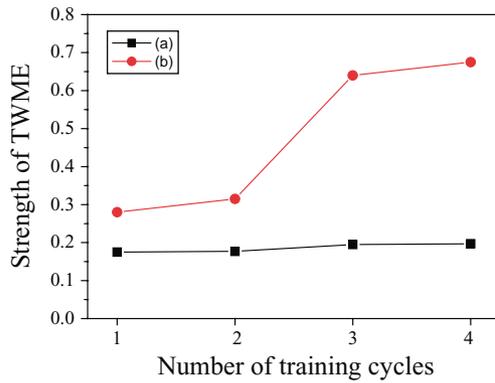


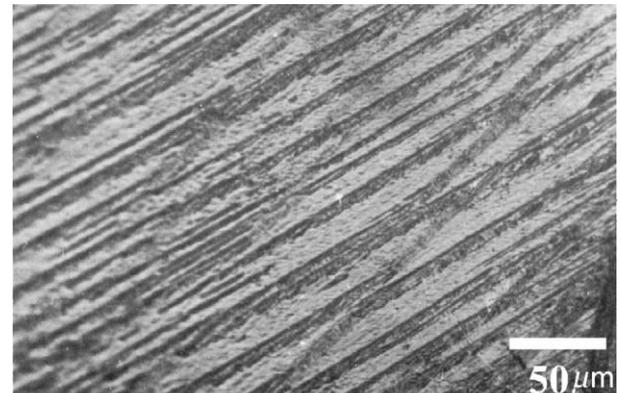
Fig. 4. Variation of TWME strength of the (a) 65.6Cu–33.1Zn–1.3Al alloys and (b) 890 °C β -treated 65.6Cu–33.1Zn–1.3Al alloys, with varying number of training cycles.

and 100–240 °C, respectively. Figs. 3a–d represent TWMEs in 70.3Cu–24.1Zn–5.6Al alloy in the case of 1, 2, 3, and 4 training cycles, respectively, indicating that TWME is relatively strong in temperatures ranging from 160 to 220 °C, regardless of the number of training cycles. The average TWMEs in the range 160–220 °C after 1, 2, 3, and 4 training cycles, respectively, are about 0.54, 0.64, 0.67, and 0.71, indicating that the average TWME in the range 160–220 °C increases with an increasing number of training cycles. It is noteworthy that there exists a constrained heating temperature range for obtaining TWME by a thermomechanical cycling method.

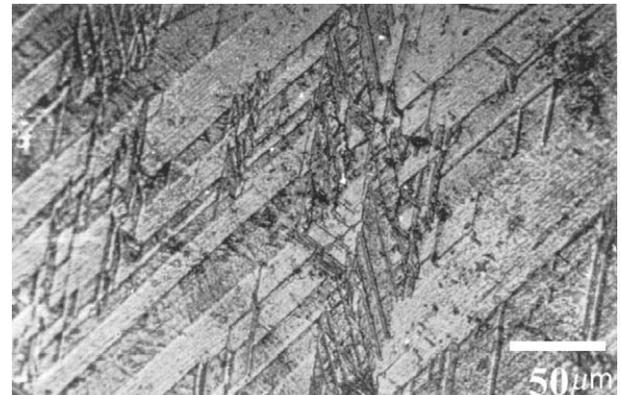
For a comparison study, we applied the thermomechanical cycling treatments on another alloy of 65.6Cu–33.1Zn–1.3Al (wt.%). Fig. 4a shows the TWME strength of the 65.6Cu–33.1Zn–1.3Al alloy at a constrained heating temperature of 140 °C. TWME is below 0.20 and it does not change significantly by increasing the number of training cycles. X-ray diffraction analysis (not shown here) indicates that the 70.3Cu–24.1Zn–5.6Al alloy has a high volume fraction of β -phase with negligible amount of α -phase, while the 65.6Cu–33.1Zn–1.3Al alloy is composed of a mixture of α - and β -phases with a considerable amount of α -phase. The martensite (β -phase) of 70.3Cu–24.1Zn–5.6Al alloy is observed to be 18R structure.

In order to investigate the effect of the presence of the β -phase and thus the generation of β martensite on the strength of TWME by thermomechanical cycling, we increased the volume fraction of β -phase in the 65.6Cu–33.1Zn–1.3Al alloy by treating the specimen at β -phase at a temperature of 890 °C for 30 min. Fig. 4b shows the TWME strength of 890 °C β -treated 65.6Cu–33.1Zn–1.3Al alloy at a constrained heating temperature of 140 °C, indicating that TWME increases with an increasing number of training cycles.

In order to compare the microstructures of alloys with and without thermomechanical cycling treatment, we used optical micrographs of the 890 °C β -treated 70.3Cu–24.1Zn–5.6Al alloy. The thermomechanical cycling treatment was



(a)



(b)

Fig. 5. Optical microscope images showing the microstructures of 890 °C β -treated 70.3Cu–24.1Zn–5.6Al alloys (a) without and (b) with thermomechanical cycling treatment.

performed with constrained training at 200 °C. Fig. 5a presents the typical microstructure of the as-quenched alloy. It is obvious that the as-quenched structure consists of plate- or spear-like martensites, which are the most commonly observed microstructures in the as-quenched Cu-based shape memory alloys. Fig. 5b shows the OM microstructure of the same alloy after the application of four training cycles, including new structures inclined at an angle to the existing martensite structures. We surmise that the new martensite structure is stress-induced due to the internal forces and related to TWME by the thermomechanical cycling. Although we discovered that the β -phase and thus the generation of β martensite is closely related to induction of TWME, the individual role of the α - and β -phases is still unclear. Furthermore, the origin and the effect of the new martensite requires a more detailed investigation. Additional study is necessary in order to uncover the details of the mechanism of TWME in this particular training route.

4. Conclusions

In summary, TWME in two Cu–Zn–Al alloys was induced by a training method with cycles of constrained heating/cooling. The mechanical strengthening of the alloys was

achieved by bending around a cylinder mould in liquid nitrogen. The strength of TWME tends to increase with increasing number of thermomechanical cycles. The constrained heating temperature also affects TWME significantly. Furthermore, the presence of the β -phase and thus the martensite structures is a crucial factor in generating TWME. After the thermomechanical cycling treatment, we observed new martensite inclined with some angle to the existing martensite structures.

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