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Investigation on the two-way shape memory effect and alternating current electrothermal driving characteristics of TiNiCu shape memory alloy

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Two-way shape memory effect (TWSME) was introduced in a narrow hysteresis TiNiCu shape memory alloy spring by thermomechnical training after heat treatment. The TWSME spring can contract upon heating and extend upon cooling. The effect of heat treatment on the TWSME of the shape memory alloy springs has been investigated. The results showed that the TWSME recovery rate of the spring could be high up to 58% after being thermomechnical trained 75 cycles for the specimen heat treated at 500°C for 1 h. The transformation temperatures were also investigated by Differential Scanning Calorimeter (DSC) during thermomechanical training. The electrothermal driving characteristics of the TWSME springs were also investigated with alternating current density of 2.55–17.8 A/mm^2. It is found that the time response (the time interval between the start and the end of the spring's shape change) and the maximum contraction rate were greatly depended on the magnitude of the electrical current density.

1. Introduction

Two-way shape memory effect (TWSME) in shape memory alloys represents a reversible spontaneous shape changes during cooling and heating process. This is the consequence of reversible phase transformations observed without application of any external stress. However, TWSME is not an inherent property of shape memory alloys, but can only be obtained by a suitable themomechanical treatment, usually termed training. Several new training routes were describes, such as constrained heating method [1], reheat treatment [2–4], electrochemical hydrogenation [5], but the physical original of TWSME is still unclear. The recovery velocity of two-way shape memory effect is also important parameter, which can be reflected by the hysteresis of transformation. As the shape memory alloy is an intermetallic alloys, so it can be driven by electrical current via Joule heating, which was an easy and efficient way [6]. There has been no report on the alternating current electro-thermal driving characteristics of two-way shape memory coil springs in the literatures to our knowledge.

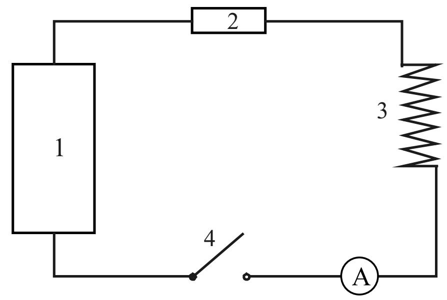
Certain parameters such as composition and annealing procedures can affect the transformation temperatures, hysteresis and two-way shape memory effect. In this article, TiNiCu alloy two-way shape memory springs were trained by the thermomechanical treatment after heat treatment. The effect of the thermomechanical training on the transformation temperatures were studied by Differential Scanning Calorimeter (DSC). The electrothermal driving characteristics of the TWSME springs were also investigated with alternating current. The purpose of this article is to investigate the TWSME and alternating current electrothermal driving characteristics of TiNiCu shape memory alloy.

2. Experimental

The investigations have been carried out on wire specimen of Ti-43 at%Ni-7 at%Cu shape memory alloy with diameter of 0.5 mm, provided by the Northwest Institute of Non-Ferrous Metal of China. The springs are prepared by a simple method in which the TiNiCu wire is wound on a cylindrical jig. Then the springs are annealed at 400–550°C for 1 h followed by air cooling. The mean diameter of the spring is 4.5 mm and the pitch of the spring is 0.1 mm. The number of active coils of the spring is 10. The training procedure has been presented in our previous work [7]. The springs are extended till the pitch reached 12 mm at a temperature of 5°C (in martensitic state) before relaxing the force and heating up to 100°C, a temperature slightly higher than the austensite finished temperature (A_f). The spring contracted as a result of reverse martensitic transformation. The length of the spring is recorded at 100°C and recorded again after cooling to 5°C. Then the TWSME is induced into the TiNiCu shape memory alloy spring after many training cycles. During the training procedure plastic deformation was induced, and the final parameters of the spring are: the mean diameter of the spring 5 mm and the pitch of the spring 16 mm. The effect of training cycles on the two-way shape memory recovery rate η also have been investigated. Here η defined as $\eta = (L_M - L_A)/L_M \times 100\%$, L_M and L_A represent the length of the spring at martensite and austensite phase, respectively.

In order to investigate the concomitant effects of training, e.g., change of the transformation temperature and hysteresis, and to study the origin of the TWSME, the transformation temperatures and hysteresis had been measured using Differential Scanning Calorimetry (DSC) during training. For the calorimetric measurements, the samples were cut from the spring trained at different cycles. The measurements were performed with a Differential Scanning Calorimeter with a scanning rate of 10°C/min under atmospheric pressure. The specimens were placed in an aluminum pan. The pans were sealed and placed in the measured chamber of a Differential Scanning Calorimeter (Seiko Exstar 6000, Japan). The start and the end of the transition were determined as the intersections of a base line and the tangents to each peak. The endothermic processed are assigned with upward curves (positive direction), and the exothermic ones with downward curves (negative direction).

For practical application, the TWSME actuators can be driven by electrical current, so the electrothermal driving characteristics of the TWSME springs are also investigated. The electrical driving set-up has schematically shown in Fig. 1. When the switch is turned on, the current passes through the TiNiCu alloy and electric energy is converted into thermal energy according to the Joule's law. TiNiCu spring is heated and elongates as the temperature is higher than the transformation temperature. When the switch is turned off, the spring recoveres to its original shape by air convection cooling. The two-way shape memory effect is actualized by Joule heating and air convection cooling. In this experiment, the current densities of 2.55–17.8 A/mm^2 are used to drive the two-way shape memory spring.



1-Adjustable alternative current power transformer; 2-Electrical resistance; 3-Two way shape memory spring; 4- Switch

Figure 1 Schematic diagram of electrothermal driving.

3. Results and discussion

3.1. Effect of annealing temperature and thermomechanical training cycles on the TWSME

Fig. 2 shows the relations between TWSME recovery rate of the different heat treatment temperatures and thermomechanical training cycles. As can be seen, the results show that the recovery rate of the springs increases with increasing the training cycles for all samples. The optimal spring is one that was annealed at 500°C for 1 h and the TWSME recovery rate can be high up to 58% after thermomechnical training for 75 cycles. Furthermore, with increasing the annealing temperature the maximum recovery rate increase first, then decrease.

By martensitic transformation in an untrained specimen without external stress, all martensitic variants are crystallographically and thermodynamically equivalents, i.e., they have the same free energy. The probability of the formation among them is the same for each variant and the same amount of each one is formed upon cooling, where they accommodate in such a way that no macroscopic form change are observed in the body. Through the training however, the applied stress causes a free energy decrease in one or in a group of variants and they become no longer thermodynamically equivalent. Then upon cooling, a bigger amount (which has a smaller free energy) is formed, leading to a macroscopic shape change as observed in the trained samples. The physical model has shown in Fig. 3.

The training cycling results in the formation of complex dislocation arrays, which have the lowest energy in the repeatedly induced "trained" variants. Since the density of the dislocation arrays increases to a saturation value during training cycling, the thermodynamic favoring of the trained variants also increases to a saturation value. It follows that during training cycling the magnitude of the TWSME increases towards the strain induced during training. Analogously, the stability and reproducibility of the TWME increase to a saturation value during training cycling.

The difference of TWSME between different annealing heat treatment maybe attributed to the distribution of dislocations and the strength of parent phase after cold-working. At lower annealing temperatures, the higher initial dislocation density of the materials

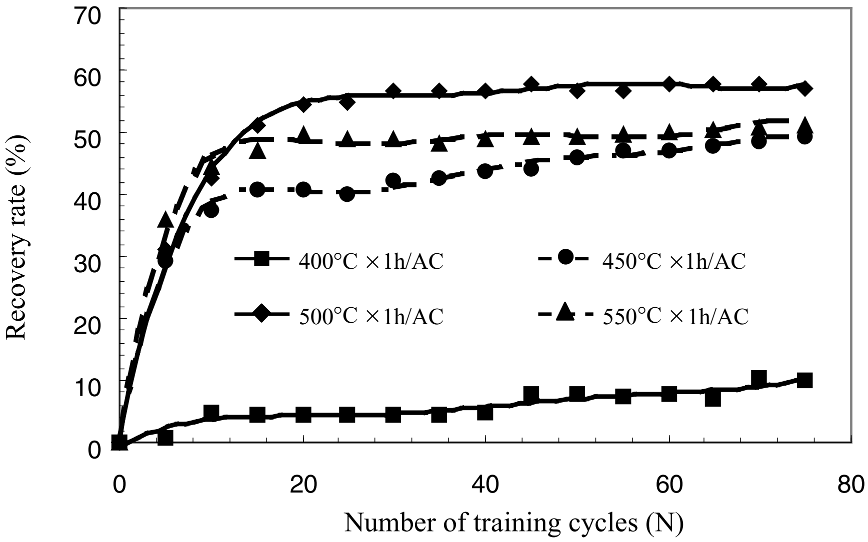


Figure 2 TWSME recovery rate of TiNiCu shape memory alloy spring vs. thermomechanical training cycles after annealing at 400–550°C for 1 h.

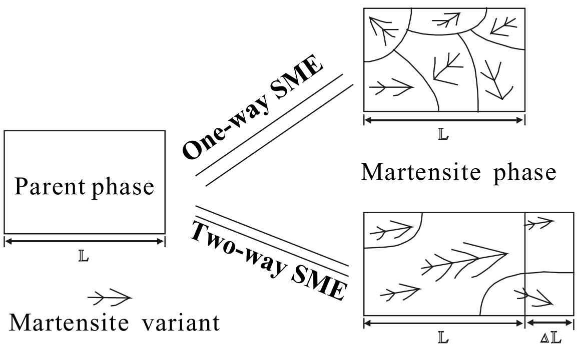


Figure 3 Physical model of TWSME.

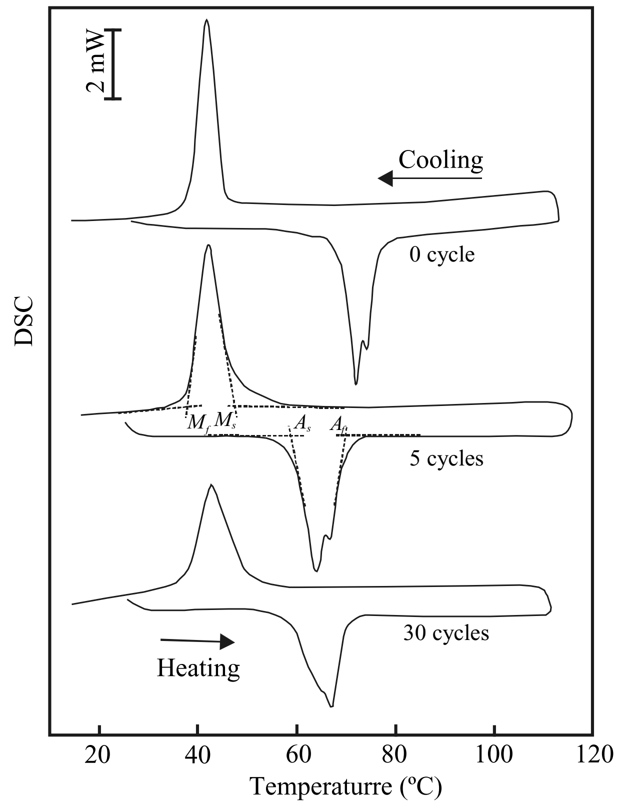


Figure 4 DSC curves for TiNiCu spring trained at 0, 5, 30 cycle.

impeded the motion of the martensite variant interface, resulting in the small two-way shape memory effect. With increasing annealing temperature, the initial dislocation density reduced, after deformation the reorientation of matensite happened very easy, which led to the change of internal stress field. So the shape memory recovery rate increased also. However, after much higher temperature annealing, the plastic deformation happened, which relaxed the stress-field and destroyed the two-way shape memory effect [8].

3.2. Effect of thermomechanical-training cycles on the transformation behavior

Fig. 4 shows the DSC curves for the spring thermomechanical trained at different cycles (0, 5, 30) after heat-treating at 500°C for 1 h. The start and the end of the transition were determined as the intersections of a base line and the tangents to each peak. The points A_s and A_f are the start and finished temperatures of the inverse martensitic transformation, and points M_s and M_f are that of martensitic transformation. In the three curves an exothermic peak accompanying transformation is noted during temperature reduction, and an endothermic peak accompanying reverse transformation during temperature elevation. The transformation temperatures are listed in Table I. It is obvious from Fig. 3 and Table I that the transformation temperatures A_s and A_f of the spring decrease after training. This is consistent with previous result [9], the shift in the transformation temperatures is created by the existence of dislocations.

When the SMAs with one-way shape memory effect (OWSME) are cooled, martensite transformation

TABLE I Transformation temperatures TiNiCu spring trained at 0, 5 and 30 cycles

Training cycles	A_s (°C)	A_f (°C)	M_s (°C)	M_f (°C)
0	68	77	46	38
5	58	69	47	37
30	57	69	49	37

happens by the self-accommodation of martensite variants, which is very effective in reducing strain. However, there exist stress field induced by dislocation during training in the in the SMAs with TWSME either at martensite or austensite phase. By cooling, the dislocation structure guides the formation of martensite variants of preferential orientations, thus resulting in a macroscopic shape change during subsequent thermal transformation cycles. Xu *et al.* [10] find that the martensite variants are not able to self-accommodated very well. Thus a lot of elastic energy is stored in the martensite variants, the elastic energy is benefit for the austensite transformation [11], so the A_s decreased after thermomechanical training.

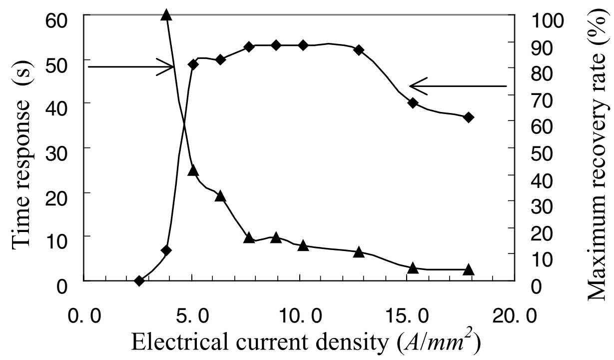


Figure 6 Curves for the maximum recovery rate and the time response at different electrical current density for TiNiCu spring heat treated at 500°C for 1 h.

3.3. Alternating current electrical-thermal driving characters

Fig. 5 shows the contraction rate-time curves for different alternating electrical current density. The time interval between the start and the end of the spring's shape change (termed time response) and the maximum contraction for different electrical current density deduced from Fig. 5 have been shown in Fig. 6.

As can be observed from Fig. 6, the spring shows no shape change at a current density of 2.55 A/mm^2. When the electrical current density is lower than 10.2 A/mm^2, the maximum contraction rate increases and the time response decreases with increasing the electrical current. The maximum contraction increases from 0 to 53% and time response decreases from 100 to 4 s. When the electrical current was higher than 10.2 A/mm^2, the time response continually decrease with increasing current, but the maximum contraction decreases. The time response decreases with increasing electrical current very quickly at first then slows down. However, too large electrical current would destroy the maximum recovery rate.

When the current passes through the TiNiCu alloy electric energy is converted into thermal energy according to the Joule's law. The magnitude of the thermal energy produced depends on the magnitude of the electrical current and time. For a small electrical current density, a long time is needed to lead to the transformation of the TiNiCu alloy spring, and vice versus. As the TiNiCu spring is heated by the electrical current, the air convection cooling happened at the same time, because the experiment proceeded at the atmosphere. So at a lower electrical current density not all the martensite transforms to austensite, which leaded to a small maximum recovery rate. When the electrical current is too high, annealing heat treatment will be happen for the electrical-thermal. The dislocation pattern contributed to the two-way shape memory effect will be change by the electrical-thermal heat treatment. Thus leaded to the decrease of the maximum contraction.

The most important two-way shape memory effect characteristic is its magnitude [12] and time response [13, 14]. So 7.6–10.2 A/mm^2 is the optimum electrical current to drive the two way shape memory spring.

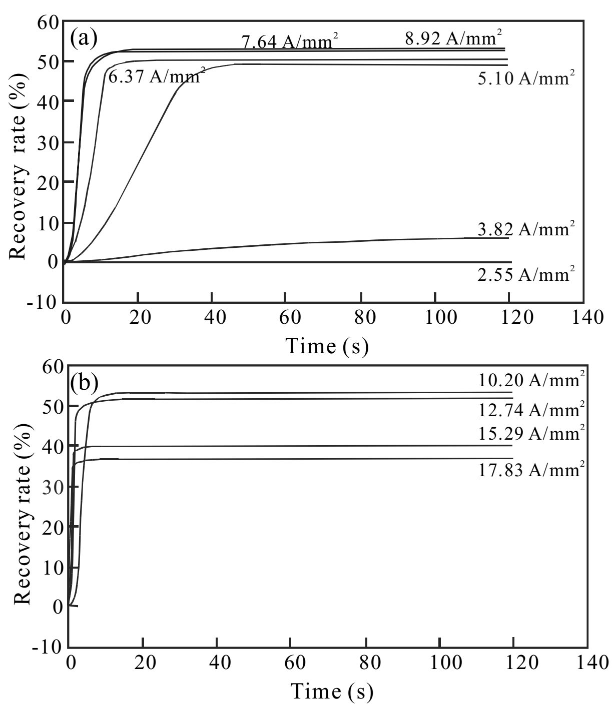


Figure 5 Recovery rate of TiNiCu TWSME spring vs. time at different electrical current density: (a) 2.55–8.9 A/mm^2 and (b) 10.2–17.8 A/mm^2.

4. Conclusions

A TWSME spring that can contract upon heating and extend upon cooling using the narrow hysteresis TiNiCu shape memory alloy is manufactured by thermomechnical training after annealing heat treatment. The result shows that optimal spring is one which is annealed at 500°C for 1 h and the TWSME recovery rate can be up to 58% after thermomechnical training for 75 cycles. The transformation temperatures A_s and A_f decreases after the thermomechnical training. It is considered that the dislocations played an important role on the contribution to the TWSME. The electrical-thermal driving characteristics show that the time response and the maximum contraction rate greatly depend on the magnitude of the electrical current density. The time response continually decrease with increasing current very quickly at first stage then slows down. The optimum driving current density is 7.6–10.2 A/mm^2. The maximum contraction increases with increasing current first and then decreases.

Acknowledgements
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