Effect of Thermal Cycling under Load on Martensite Transformation and Two-way Shape Memory Effect in a TiNi Alloy

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The effect of thermal cycling under loading on martensitic transformation and two-way shape memory effect was investigated for Ti-49.8 at. pct Ni alloy. It is shown that Ms and Mf temperature increase with increasing the number of cycles, while Aα and Aβ temperature decrease during thermal cycling. The total strain εT and permanent strain εp increase with increasing applied stress and number of cycles. The two-way shape memory effect can be improved by proper thermal cycling training under loading, while excessively high applied stress results in the deterioration of TWSME. The reason for the changes in martensitic transformation characteristics and two-way shape memory effect during thermal cycling under loading is discussed based on the analysis of microstructure by TEM observations.

1. Introduction

The two-way shape memory effect (TWSME) refers to an ability to generate spontaneous reversible changes of shape during cooling and heating through the transformation temperature range without any externally applied stress[1,2]. It is widely accepted that two-way shape memory behavior is associated with some microstructural asymmetry in the parent phase like stabilized martensite[3,4] or dislocation structure[5–8]. These microstructural asymmetries could favor the nucleation and growth of preferential martensite plates which could influence TWSME. In contrast to one-way shape memory effect, the TWSME is not an inherent characteristic, but can be obtained after special thermomechanical training. There are several training procedures to obtain the TWSME including shape memory training[4], pseudoelastic training[9] and thermal cycling training under a constant loading[10]. Among these three training procedures, thermal cycling training under a constant loading is the most effective way to introduce TWSME[11,12]. So far, the study about the effect of the thermal cycling training under a constant loading on the TWSME in the TiNi binary alloys is not very systematical, and no corresponding reasonable explanation is presented.

In this study, the effect of the thermal cycling training under a constant loading on the martensitic transformation characteristics and TWSME in a Ti-49.8 at. pct Ni alloy have been systematically investigated. On the basis of the analysis of microstructure by TEM observations, the possible mechanism of TWSME is initially discussed.

2. Experimental

Ti-49.8 at. pct Ni alloy was prepared from 99.7 mass fraction sponge Ti and 99.9 mass fraction electrolytic Ni by a high-frequency vacuum induction furnace using a water-cooled Cu crucible, followed by casting into an Fe mold. After homogenized at 850°C for 10 h, the ingot was hot swaged and rolled at 850°C into strips of approximately 1 mm thickness. Specimens of 50 mm × 1 mm × 1 mm for TWSME training were carefully cut from strips and annealed at 850°C for 1 h, in a 0.4 Pa vacuum, followed by furnace cooling. The gauge length for measuring strain was 25 mm. The transformation temperatures were measured by the electrical resistance method for the specimens before and after thermal cycling under loadings. The Ms, Mf, Aα, and Aβ temperatures of the present alloy before cycling were 366 K, 326 K, 349 K and 372 K, respectively.

TWSME training was carried out by thermal cycling under various constant loadings. The specimens were initially immersed into a silicon oil bath at about 293 K. A load was then applied to the specimen. The temperature of the silicon oil was controlled by slow heating and cooling. The temperature range was from 290 K to 473 K. The variation of strains during thermal cycling training was measured by recording displacement of specimens at different temperatures. Af-
3. Results

Figure 2 shows the effect of thermal cycling under loading on the transformation temperatures. It can be seen that martensitic transformation characteristics change apparently during the cycling. The $M_s$ and $M_f$ temperatures increased quickly during the first 8 training cycles and slightly increased during further cycling. It was also observed that $A_s$ and $A_f$ slightly decreased during the thermal cycling. This indicates that the transformation hysteresis decreases by thermal cycling under loading.

In order to investigate the effect of applied stress on thermal cyclic behavior, similar measurements were also carried out under constant stress of 30 MPa and 200 MPa. Figure 3 shows the transformation temperature versus the applied stress curve after 30 training cycles. From Fig.3, it is seen that $A_s$ and $A_f$ temperature decreased with an increase of applied stress, while $M_s$ and $M_f$ increased with increasing applied stress ($\sigma$) when $\sigma$ was less than 103 MPa and then decreased with the further increasing applied stress.

Figure 4 shows the change in permanent strain $\varepsilon_p$ (a), total strain $\varepsilon_t$ (b) and reverse martensite transforma-
Fig. 5. $\varepsilon_{tw}$ and $\varepsilon_{tr}$ as a function of training cycling number.

Fig. 6. $\varepsilon_{tw}$ and $\varepsilon_{tr}$ as a function of applied stress after 30 training cycles.

Fig. 7. Typical morphologies of trained samples with a 73.1 MPa applied stress (a) 1 cycle, (b) 30 cycles, (c) enlarged image of (b)

formation strain $\varepsilon_{tr}$ (c), as a function of training cycling under a variety of constant stress. It is seen that the total strain $\varepsilon_t$ and permanent strain $\varepsilon_p$ increased with increasing the number of training cycles. From Fig.4, it can also be seen that applied stress has greatly effected on the total strain $\varepsilon_t$ and permanent strain $\varepsilon_p$. The higher the constant stress, the more the changes in permanent strain $\varepsilon_p$ and total strain $\varepsilon_t$, as shown in Fig.4(a) and (b). Applied stress and the number of cycles also have great effects on the reverse martensite transformation strain $\varepsilon_{tr}$. When the applied stress was lower than 103 MPa, $\varepsilon_{tr}$ increased rapidly with increasing number of cycles during initial cycles and then increased slightly with further increasing thermal cycling numbers, as shown in Fig.4(c). When the applied stress was 200 MPa, $\varepsilon_{tr}$ reached the maximum value within two cycles and then decreased during further cycling.

The influence of thermal cycling under loading on the two-way shape memory strain $\varepsilon_{tw}$ and reverse martensite transformation strain $\varepsilon_{tr}$ is illustrated in Fig.5. It is shown that two-way shape memory strain $\varepsilon_{tw}$ increased quickly with increasing number of cycles during the initial cycling and then kept almost constant with further increasing number of cycles. Similar to $\varepsilon_{tw}$, the reverse martensite transformation strain $\varepsilon_{tr}$ also increased quickly during the first several training cycles and slightly increased during further thermal cycling.

The two-way shape memory strain $\varepsilon_{tw}$ and reverse martensite transformation strain $\varepsilon_{tr}$ are closely related to the training stress, as shown in Fig.6, for the specimen after 30 training cycles. It can be seen that both $\varepsilon_{tw}$ and $\varepsilon_{tr}$ increased with an increase of applied stress ($\sigma$) as $\sigma$ was less than 103 MPa and then decreased with the further increasing applied stress. This indicates that the TWSME can be improved by increasing applied stress, while excessively high training stress results in the deterioration of the TWSME.

4. Discussion

In order to understand the effect of thermal cycling under loading on martensitic transformation and two-way shape memory effect, the TEM observations have been carried out. Figure 7 is a typical BF micrograph of trained sample with a training stress of 73.1 MPa. After first cyclic deformation, the martensite variants were still self-accommodating. Inside most of the twin bands, no significant plastic deformation due to training can be observed, as seen in Fig.7(a). During the forward thermal cycling under load, the preferentially oriented martensite variants are developed by consuming the neighboring variants in the unfavorable
stress direction. These oriented martensite variants are repeatedly induced during the thermal cycling. After 30 training cycles, the orientations of martensite variants are almost identical and the twin bands become much wider, as shown in Fig.7(b). Dislocations also can be introduced by thermal cycling under load. During thermal cycling, the density of dislocation increases with an increase of number of cycles and then reaches the saturation value after 30 training cycles, as can be seen in Fig.7(c). The internal strain field of these dislocations assists the nucleation and growth of specific martensite variants without applied stress, which leads to TWSME.

During the thermal cycling under loading, the magnitude of the preferential oriented martensite variants increases with the increase of the number of cycles. Moreover, a complex dislocation arrangement is formed by the thermal cycling under loading at the same time. On the one hand, the original dislocation is rearranged by slip under the load. On the other hand, some new dislocations are gradually generated during the training. Therefore, the movement of these dislocations leads to the real plastic deformation εₚ increase with the increase of the number of cycles. It is proposed that these rearranged dislocations form a stress field with some certain orientation, which combine with the applied external stress to a relative complicated stress field. In this stress field, the preferential oriented martensite variants are largely formed during the training, which results in that the reverse martensitic transformation strain εᵣ and two-way shape memory strain increase with increasing the number of cycles, as shown in Fig.5. In the first several cycles, the self-accommodating martensite variants are changed to preferential oriented martensite variants and the stress field of the dislocations are formed by step by step, so εᵣ and εᵩ increase rapidly with increasing the number of cycles. The martensite variants are mainly preferential oriented and the dislocations saturated in the following cycles, leading to that εᵣ and εᵩ keep almost constant with further increasing number of cycles.

When the training stress is lower, the microscopic residual stress fields accompanying those dislocations arrays would favor the formation and growth of preferentially oriented martensite variants, which leads to the increase of εᵣ and εᵩ during cycling and reaches its peak. For a higher stress, in addition to the formation of martensite reorientation, the true plastic deformation is generated during the first several training cycles, leading to increase εᵣ too fast. As a result, an uncompleted restoration during heating to parent phase occurs, reducing the reverse martensite transformation strain εᵣ and two-way strain εᵩ. The higher the training stress, the lower the two-way strain εᵩ and reverse martensite transformation strain εᵣ, as shown in Fig.6.

5. Conclusions

(1) Mₛ and Mᵦ increases with increasing the number of cycles, while Aₛ and Aᵦ decreases during thermal cycling.

(2) Increasing applied stress and number of cycles cause the increase of the total strain εₚ and permanent strain εₚ.

(3) Two-way shape memory strain εᵩ and reverse martensite transformation strain εᵣ increase quickly with increasing number of cycles during the initial cycling and then keep almost constant with further increasing number of cycles.

(4) Mₛ, εᵩ and εᵣ increase with an increase of applied stress (σ) as σ is less than 163 MPa, and then decrease with the further increasing applied stress.

REFERENCES