Effect of Heat-treatment Time on Performance Recovery of Ti-50.4at%Ni Shape Memory Alloy

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In this research, the effect of heat treatment time on the performance recovery of Ti-Ni shape memory alloy (SMA) is investigated. The chemical composition of specimen is Ti-50.4 at%Ni, and cold working ratio is 30 %. At first, the specimen is heat-treated at 673 K for 3.6 ks. And then, the specimen is heat-treated for recovery of function after isothermal 1000 times loading-unloading test under constant strain. The heat-treatment temperature for performance recovery is 573 K, and heat-treatment time is varied from 0.6 to 3.6 ks. The functional deterioration process of specimens heat-treated for performance recovery is investigated by the isothermal loading-unloading tests under constant strain.

Recovery strain and critical stress for inducing martensite increase with increasing heat-treatment time, and are saturated when heat-treatment time is more than 1.8 ks. Moreover, the number of cycle to failure increases with increasing heat-treatment time up to 1.8 ks, has a maximum at 1.8 ks, and then followed by a decrease. These tendencies are caused by a variation of the dislocation density owing to the variation of the heat-treatment condition. From these results, the optimal heat-treatment time for performance recovery is 1.8 ks when heat-treatment temperature is 573K.

Key words: Ti-Ni alloy, shape memory alloy, actuator, function deterioration process

1. INTRODUCTION

Shape memory alloy (SMA) are well known as a functional material, since they exhibit not only shape memory effect and superelasticity but also good mechanical properties [1, 2]. Shape memory properties and the superelasticity are repeatedly used in some applications of SMA. However, functions of SMAs are deteriorated by using repeatedly. Several authors reported the effect of manufacturing process on function deterioration of Ti-Ni shape memory alloy [3-6]. We reported the effect of cold working ratio on function deterioration process of Ti-Ni shape memory alloy by repeated loading-unloading cycle tests with constant strain condition [7-9]. From these experiments, we found that the function deterioration process is caused by the increase of dislocation density during the repeated loading-unloading (deformation-shape recovery). From this result, it is thought that performance of SMA should be recovered if the dislocation of SMA is decreased by heat-treatment. Thus, we investigated the effect of heat-treatment for performance recovery (HT_R) of Ti-Ni SMA. The effect of heat-treatment temperature on performance recovery of Ti-Ni SMA was investigated [9].

In this study, the effect of heat-treatment time on performance recovery of Ti-Ni SMA was investigated by repeated loading-unloading cycle tests with constant strain condition.

2. EXPERIMENTAL PROCEDURE

The chemical composition of alloys used in this study is Ti-50.4 at%Ni which is widely applied to the medical / industrial application using superelasticity. The specimen shape is a wire with about 1 mm diameter and 60 mm gage length. The specimen was processed in the following manner; the Ti-Ni shape memory alloy ingot was made by using a high frequency induction vacuum furnace, and then was hot forged and hot extruded followed by cold drawing and intermediate annealing. Cold working ratio of the specimen is 30.1 %.

Fig. 1 Schematic drawing of stress-strain curve.

To investigate the effect of heat-treatment time on performance recovery, isothermal loading-unloading cycle tests with constant strain condition were carried out. At first, the specimen is heat-treated at 673 K for 3.6 ks. It is initial condition of sample. After that, the specimen is heat-treated for performance recovery after isothermal 1000 times loading-unloading test under constant strain. The heat-treatment temperature for performance recovery (T_R) was at 573 K. And the heat-treatment time for performance recovery (t_R) is varied from 0.6 to 3.6 ks. Next, to investigate the effect of heat-treatment temperature on performance recovery, the functional deterioration process of specimens heat-treated for recovery of function was investigated by the isothermal loading-unloading tests under constant strain.

Figure 1 shows the schematic drawing of stress-strain curve in the loading-unloading test with constant strain. The atmosphere temperature is 310 K. The applied strain ($\varepsilon_{\max}$) is 5 %. The strain rate is 10 %/sec. The number of repeated cycle is 1000. The notations of ε_A , ε_p , σ_{Ms} , $\sigma_{\max}$ and E_L indicate recovery strain, plastic strain, critical stress for inducing martensitic phase, maximum loading stress and elastic modulus of the first cycle, respectively.

3. RESULTS AND DISCUSSION

3.1 Effect of heat-treatment time on performance recovery

Figure 2 shows three stress-strain curves of the sample in the initial condition before ($N=1$) and after ($N=1000$) the repeated loading-unloading test, and also the sample heat-treated at 573 K for 1.8 ks after the repeated loading-unloading test ($t_R=1.8$ ks, $N=1$). The value of ε_A and σ_{Ms} after last cycle of initial condition ($N=1000$) is lower than those of the first cycle ($N=1$). However, the ε_A and σ_{Ms} of the sample heat-treated after repeated loading-unloading test ($t_R=1.8$ ks, $N=1$) are recovered almost equal to those in initial condition. Namely, it is indicated that functional deterioration proceeds by the repeated loading-unloading test and the performance recovery of SMAs occurs by the HT_R .

Figure 3 shows relationships between recovery strain (ε_A) of each sample and the number of cycles. The ε_A of first cycle of $t_R=0.6$ ks is almost the same as that of 1000th cycle of $t_R=\text{non}$. Namely, the performance recovery hardly occurs for $t_R=0.6$ ks. However, in the case of t_R is more than 1.2 ks, ε_A of the first cycle is articulately larger than that of 1000th cycle of $t_R=\text{non}$. Moreover, ε_A of the first cycle becomes the same as the first cycle of $t_R=\text{non}$ when t_R is more than 1.8 ks.

Figure 4 shows relationships between critical stress for inducing martensite (σ_{Ms}) of each sample and the number of cycles. The σ_{Ms} of first cycle increases with increasing t_R . However, σ_{Ms} is not recovered to the same level as the initial condition.

Figure 5 shows the relationship between recovery rate of ε_A (r_e), recovery rate of σ_{Ms} (r_{Ms}) of first cycle and t_R . The r_e and r_{Ms} increase with increasing t_R , and they are saturated when heat-treatment time is more than 1.8 ks. The maximum of r_{Ms} is approximately 80 %, although that of r_e shows

Fig. 2 Stress-Strain curves of the sample in the initial condition before and after the repeated loading-unloading test, and the sample heat-treated at 573 K for 1.8 ks after the loading-unloading test.

Fig. 3 Relationships between recovery strain (ε_A) of each sample and the number of cycles.

Fig. 4 Relationships between critical stress for inducing martensite (σ_{Ms}) of each sample and the number of cycles.

Fig. 5 Relationship between recovery rate of ϵ_A (r_e), recovery rate of σ_{Ms} (r_{Ms}) and heat-treatment time.

Fig. 6 Relationship between the Vickers hardness and heat-treatment time.

approximately 100 %.

In previous research, it was cleared that the performance recovery is caused by the decrease of dislocation density owing to the heat-treatment. Moreover excessive decrease of dislocation density causes the function deterioration [9]. For this reason, it is thought that the tendency of performance recovery of this study is caused by the variation of dislocation density due to the heat-treatment. In general, the hardness of metals increases with increasing dislocation density. Hence, the relationship between the Vickers hardness and heat-treatment time is investigated.

Figure 6 shows the relationship between the Vickers hardness and t_R . The Vickers hardness (which can be regarded as the dislocation density) shows an abrupt decrease up to 1.8 ks, and then a gradual decrease. This tendency is in harmony with the Fig. 5. For these results, it is cleared that the performance recovery is caused by the decrease of dislocation density owing to heat-treatment, and more than 1.8 ks heat-treatment time is necessary for enough performance recovery in the experiment condition of this study.

3.2 Effect of heat-treatment time on durability

Figure 7 shows the relationship between the number of cycle to failure (N_f) and t_R . The N_f increases with

Fig. 7 Relationships between the number of cycle to failure (N_f), and heat-treatment time.

increasing t_R up to 1.8 ks, has a maximum at 1.8 ks, and then is followed by a decrease.

Figure 8 shows relationships between maximum loading stress (σ_{max}), elastic modules of the first cycle (E_L) and t_R . σ_{max} has a minimum at $t_R=1.8$ ks. Meanwhile, E_L increases with increasing t_R . The increasing E_L means the increasing stabilization of austenitic phase.

Form these results, it is thought that the durability of sample is affected by the σ_{max} , and the variation of σ_{max} is caused by the variation of dislocation density and stabilization of austenitic phase. Fig.9 shows the explanatory drawing of the variation of σ_{max} , dislocation density (H_v) and stabilization of austenitic phase (E_L) with t_R . The decreasing dislocation density causes the decreasing σ_{max} because the internal stress inhibiting transformation decreases. However, the increment of stabilization of austenitic phase leads to the increasing σ_{max} . The effect of decreasing dislocation density is larger than that of stabilization of austenitic phase when t_R is up to 1.8 ks. And then this relation is reversed when t_R is more than 1.8 ks. Therefore, σ_{max} has a minimum at $t_R=1.8$ ks. From this result, it becomes clear that the optimal heat-treatment time in the condition of this study is 1.8 ks.

Fig. 8 Relationship between recovery rate of σ_{Ms} (r_{Ms}) and heat-treatment time.

4. CONCLUSION

The effect of heat-treatment time on the performance recovery of Ti-50.4 at%Ni shape memory alloy was investigated. The obtained results are summarized as follows:

- (1) To recover the performance of Ti-Ni shape memory alloy (SMA) after repeated loading-unloading test, heat-treatments at 573 K for various times (t_R) were carried out. The recovery strain and critical stress for inducing martensite of SMA increase with increasing of t_R up to 1.8 ks and then are saturated. The maximum recovery rate of recovery strain is approximately 100 %. On the other hand, the maximum recovery rate of critical stress for inducing martensite is approximately 80 %.
- (2) The Vickers hardness shows an abrupt decrease with increasing t_R up to 1.8 ks and then a gradual decrease. The Vickers hardness is to be the dislocation density. Thus, the dislocation density decreases with increasing t_R .
- (3) The tendency of performance recovery with t_R is harmony with the tendency of dislocation density with t_R . From this result, it is cleared that the performance recovery is caused by the decrease of dislocation density owing to heat-treatment and more than 1.8 ks heat-treatment time is necessary for enough performance recovery in the experiment condition of this study.
- (4) The number of cycle to failure (N_f) increases with increasing of t_R up to 1.8 ks, has a maximum at 1.8ks, and then is followed by a decrease. The decreasing of N_f is caused by the decrease of dislocation density and increasing of stabilization of austenitic phase with increasing t_R . From this result, it becomes clear that the optimal heat-treatment time in the condition of this study is 1.8 ks.

Fig. 9 Explanatory drawing of the variation of σ_{max} , Hv and E_L with t_R .

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