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The Effect of Thermomechanical Training on the Microstructures of Fe-Mn-Si Shape Memory Alloy

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Abstract. The shape memory effect and the microstructures of Fe-30Mn-6Si(wt%) alloy subjected to different training treatments have been studied in present paper. It has been found that the recovery strain increases significantly through the training treatment of 4% tensile pre-strain followed by recovery annealing at 700 °C (treatment A) while the recovery strain decreases after the training treatment of 4% tensile pre-strain plus recovery annealing at 300 °C (treatment B). The microstructures of the alloy after the above training treatments were investigated by TEM. It was found that the treatment A favoured the formation of oriented dislocations and stacking faults which results in the improvement of shape memory effect in Fe-Mn-Si alloy.

1. INTRODUCTION

Since the shape memory effect (SME) in Fe-Mn-Si alloy was discovered in early 1980's[1,2], this type of alloy has attracted more and more attention due to its good cold and hot workability, cheap cost and the potential of practical application. However, it is still a problem for the engineering application of Fe-Mn-Si alloy because of its low recoverable strain. Improving SME of Fe-Mn-Si alloys has been the major purpose of many studies on one hand. It has been found that SME could be improved effectively by an appropriate thermomechanical treatment (called as training)[3,4]. On the other hand, it was found that a decrease of strain recovery with increasing number of training cycles occurred when the total strain was kept constant[5]. Therefore, a systematic study on the microstructures of the alloy during the training is important to understand the influence of the training on SME. In this paper, the effect of thermomechanical training on SME of Fe-30Mn-6Si(wt%) alloy was investigated and the corresponding microstructures were also examined with TEM in order to clarify the mechanism of the training on SME.

2. EXPERIMENTAL

Fe-30Mn-6Si(wt%) alloy was melted by induction furnace under argon. The 5kg ingot was annealed at 1100 °C for 1 hour and then hot rolled to 3.5mm plate in thickness. The test samples were cut from the hot rolled plate, solution treated at 700 °C for 1 hour and then oil-quenched. The transformation temperatures of the alloy were measured by electrical resistance yielding: $M_s=10^{\circ}\text{C}$, $A_s=120^{\circ}\text{C}$, $A_f=300^{\circ}\text{C}$. SME of the alloy was examined by tensile deformation at ambient temperature followed by recovery annealing at 700 °C and 300 °C for 30 minutes after unloading, respectively. The foil specimens for TEM examination were prepared through the following steps: spark-cut -- mechanical polishing -- chemical polishing -- ion thinned. TEM observation was carried out by JEM-100CXII transmission electron microscope.

3. RESULTS AND DISCUSSION

3.1 Influence of training on SME of Fe-Mn-Si alloy

The good strength and plastic properties (or the initial structural state) are essential to the alloy which is conducted to effective training. The pre-strain amplitude and the recovery annealing temperature (or training temperature) are two key factors to the training effect. The effect of training temperature on SME of Fe-Mn-Si alloy is shown in Fig.1. The specimens were hot rolled and solution treated at 700°C for

Fig.1 The recovery ratio as a function of training cycles at different recovery annealing temperature

1 hour before training. Tensile deformations were carried out at ambient temperature and the strain amplitude of each tensile deformation kept at 4% after unloading. The subsequent recovery annealing treatments were carried out at 700°C and 300°C for 30 minutes, respectively. From Fig.1, we can see that the training temperature is the key factor to the training effect when the pre-strain kept constant (4% in this study). When the training temperature was lower (300°C), the strain recovery ratio increased slightly during the initial three training cycles, and then decreased rapidly with the further training, until lower than that before training. This means that the decrease of SME is related to the lower recovery annealing temperature of training. However, the strain recovery ratio increased with training cycles when the training temperature was moderate high (700°C). Through training of recovery annealing at 700°C, the strain recovery ratio increased from 45% to 90% after the sixth training cycle and the increasing trend of SME was still kept with the further training. Apparently, an appropriate training treatment (especially the training temperature) is very important and necessary to the effective improvement of SME of Fe-Mn-Si alloys.

3.2 Influence of training on the microstructures of Fe-Mn-Si alloy

The microstructures and the corresponding selected area diffraction patterns of the specimens observed by TEM after the sixth training cycle are shown in Fig.2. In Fig.2 (a) (b) (treatment A), we can see that a configuration of some definite orientations consisting of short segments of stacking fault (marked A) and small angle boundaries of dislocation (marked B), as well as a small amount of ϵ martensites (marked C) is formed in the parent matrix. It is necessary to point out that the ϵ martensites which might be formed during the preparation of the specimen has just the same orientation as the small angle boundaries of dislocation. In Fig.2 (c) (d) (treatment B), large amount of intersected ϵ martensites (marked A) were left in the parent matrix with few stacking faults and high density of tangled dislocations (marked B).

Fig.2 TEM microstructures and the corresponding selected area diffraction patterns: (a) and (b): heated at 700°C after the 6th training cycle; (c) and (d): heated at 300°C after the 6th training cycle

3.3 Discussion

It is well known that a total of 12 ϵ martensite variants can be formed from corresponding $\{111\} \langle 112 \rangle$ shear systems (by shearing along $a/6 \langle 112 \rangle$ Burgers vector on alternate $\{111\}$ plane of γ phase) according to the $\gamma - \epsilon$ martensite transformation crystallography [6]. The orientation of strain-induced ϵ martensite variants mainly depends on the sum stress of both applied external stress and internal stress existing in the matrix. It is suggested that the purpose of training is to remove the unfavourable variants of ϵ martensite and remain the favourable variants to SME in the meantime. It is also well known that the $\gamma - \epsilon$ transformation requires the motion of $a/6 \langle 112 \rangle$ partial dislocations in the γ / ϵ interface [7]. So, a high enough driving force for the motion of partial dislocations (i.e. $\gamma - \epsilon$ transformation) is necessary. When the training procedure is carried out at lower recovery annealing temperatures (for example at 300 °C), the $\epsilon \rightarrow \gamma$ transformation and so the removal of the unfavourable ϵ variants will not be easy to take place due to the small driving force for the reverse motion of partial dislocations as well as the low energy of the stacking faults between the partial dislocations at lower temperatures. During the subsequent training cycles, the new strain-induced ϵ variants will be easy to intersect with the unremoved ϵ variants, and the degree of the intersection will naturally increase with the training cycles. In addition, the crystal defects (dislocations and stacking faults) introduced by deformation will increase with the increasing number of training cycles, and can not be rearranged or reoriented but form tangles while heated at lower temperatures. The combination of the two effects mentioned above makes difficult for the reverse motion of partial dislocations (i.e. $\epsilon \rightarrow \gamma$ transformation) on recovery heating thus leads to the decrease of SME of the alloy. In contrast to the effect of training at 300 °C mentioned above, the $\epsilon \rightarrow \gamma$ transformation and so the removal of the unfavourable ϵ variants will be easy to take place

because of the high driving force for the reverse motion of partial dislocations and the increasing of stacking fault energy at higher temperature when the training is carried out by recovery annealing at 700 °C. In addition, the crystal defects (dislocations and stacking faults) can easily be rearranged or reoriented and tend to form some definite orientations under moderate recovery annealing temperature (the upper limit of restoration temperature, or just below the recrystallization temperature). Therefore, more and more oriented ε variants favourable to SME will be formed with the oriented dislocations and stacking faults as the references during subsequent training cycles, and hence contribute to the improvement of SME of the alloy. It is necessary to point out that too high recovery annealing temperature (more above the recrystallization temperature) of training has not good effect on the improvement of SME. The reason is that the references of oriented dislocations and stacking faults formed in the initial training cycles will diminish or disappear on heating at too high recovery annealing temperature, and thus no oriented ε martensites can be formed by deformation in subsequent training cycle. Therefore, SME of the alloy can not be improved.

4. CONCLUSION

- 1). SME of Fe-30Mn-6Si(wt%) alloy is influenced significantly by the training way. The training of moderate recovery annealing temperature (700 °C) can improve SME effectively, while a decrease of SME will be related to the training of lower recovery annealing temperature (300 °C) or higher recovery annealing temperature (above the recrystallization temperature).
- 2). The microstructure configuration of oriented dislocations and stacking faults can be formed through effective training, and this is the microstructural reason for the improvement of SME of the alloy.

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