EFFECT OF LATTICE DEFECTS ON SHAPE MEMORY PROPERTIES OF Fe-Mn-Si ALLOYS

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ABSTRACT
We have investigated two shape memory ferrous alloys, Fe-30Mn-4Si and Fe-15Mn-4Si-9Cr-5Ni, processed by different thermo-mechanical ways, in order to analyze the effect of processing conditions and the stacking fault energy values on their shape memory properties. Rolling was conducted at 20, 600-800 and 1000ºC, and afterwards the sheets were annealed between 650 and 1000ºC. The density and structure of dislocations, as well as the presence of stacking faults, strongly depend on the process temperatures. Among the investigated cases, the alloy containing 15% Mn, rolled at 800°C and annealed at 650°C, the recovery temperature, shows the best shape memory behavior.

Keywords: shape memory, Fe-Mn-Si, microstructures, rolling.

EFECTO DE LOS DEFECTOS CRISTALINOS SOBRE LAS PROPIEDADES DE MEMORIA DE FORMA DE LAS ALEACIONES Fe-Mn-Si

RESUMEN
Hemos investigado dos aleaciones ferrosas con memoria de forma, Fe-30Mn-4Si y Fe-15Mn-4Si-9Cr-5Ni, sometidas a diferentes tratamientos termomecánicos, con el objeto de analizar el efecto de las condiciones de procesamiento y los valores de la energía de falla de apilamiento, sobre sus propiedades de memoria de forma. Los laminados se llevaron a cabo a 20, 600-800 y 1000°C; posteriormente, las chapas fueron recocidas entre 650 y 1000°C. La densidad y estructura de dislocaciones, así como la presencia de fallas de apilamiento, depende fuertemente de la temperatura de los procesos. Entre los casos estudiados, la aleación que contiene 15% Mn, laminada a 800°C y recocida a 650°C -temperatura de recuperación- presenta el mejor porcentaje de recuperación de la forma.

Palabras clave: memoria de forma, Fe-Mn-Si, microestructura, laminado.

INTRODUCTION
During early ’80, Sato et al [1, 2] showed shape memory effect (SME) in Fe-Mn-Si alloys. Since that moment, these materials were extensively investigated, not only monocrystals but also in polycrystal, looking for industrial applications.

This amazing behavior is due to γ (fcc) $\rightarrow$ ε (hcp) martensitic transformation induced by an applied deformation that produces a change in the part. The reverse transformation is activated by heating up to a temperature over As. If the conditions are appropiated, the applied stress should not activate plastic slip in the austenite phase, and the reverse transformation should proceed backwards along the atomic path taken by the forward transformation. So the shape is completely recovered.

The parameters that influence this behavior are texture and microstructure [3]. A convenient texture anticipate the martensitic transformation by the movement of a/6 $\langle 112\rangle_{fcc}$ Schockley partial dislocations, before than a/2 $\langle 110\rangle_{fcc}$ perfect dislocations produce plastic deformation. The most suitable microstructure is that containing a number of dislocation to harden the matrix and many stacking faults acting as nuclei of ε martensite.

During thermomechanical industrial processes, texture and microstructure suffers important modifications [4, 5]. In particular, rolling and annealing temperatures are determinants in the final conditions.

On the other hand, chemical composition is responsable of the stacking faults energy (SFE) value. As low it is, more easily perfect dislocations can split into partials.

This work is focused on finding the processing parameters that introduce the appropriate microstructure in the studied alloys, in order to reach high degrees of shape memory.

MATERIALS AND METHODS

Two alloys, a low cost Fe-30Mn-4Si (wt.%) –named "30Mn"- and a corrosion resistant Fe-15Mn-5Si-9Cr-5Ni (wt.%) –named "15Mn"- were melted in an induction furnace, homogenized at 1100ºC for 12 h and then slowly cooled to room temperature. The ingots were rolled at 1000 °C to a thickness of 1,7 mm. Then different samples of both materials were deformed to a thickness of 1 mm. by conventional rolling and, in some cases, by reverse rolling and single-roller drive rolling. In reverse rolling, the sheet's lead in and tail are inverted after each reduction step. In the case of the single-roller drive processing, one roll is driven and the other roll is idle. Annealing temperature was either 650°C or 1000°C.

The SME was evaluated through bending tests and tensile tests at room temperature, using an Instron 1362 testing machine, at a strain rate of 2×10^{-4} s^{-1}. In both cases, tensile and bending, the reverse transformation was obtained by heating the samples up to 600ºC for 15 min, i.e. above the A_f temperature, under Ar atmosphere to avoid oxidation. The degree of uniaxial shape recovery (DSR_u) was calculated as:

$$DSR_u = \frac{l_2 - l_1}{l_1 - l_0}.100$$

where, l_0, l_1 and l_2 are the initial sample length, the length after deformation and the length after reverse transformation, respectively.

RESULTS AND DISCUSSION

When rolling is conducted at 20ºC, the 30Mn alloy undergoes a complete martensitic transformation induced by deformation [6], whereas the transformation is partial in the 15Mn alloy. A subsequent annealing of both sheets at 1000ºC leads to different microstructures: a greater number of stacking faults was observed in 15Mn alloy, it can be ascribed to its lower value of SFE (5 $mJ.m^{-2}$ for 15Mn and 22,41 $mJ.m^{-2}$ for 30Mn alloy), promoting the dissociation of perfect dislocations during annealing (Fig. 1a). On the other hand, the formation of the thermal martensitic plates, observed in the 30Mn (Fig. 1b) has a negative effect on the shape memory behavior: the stress induced martensite grows mainly by the widening of pre-existent plates and a martensitic phase with morphology of coarse plates is difficult to retransform to the austenite phase through a reversible path. In both cases the absence

a)

b)

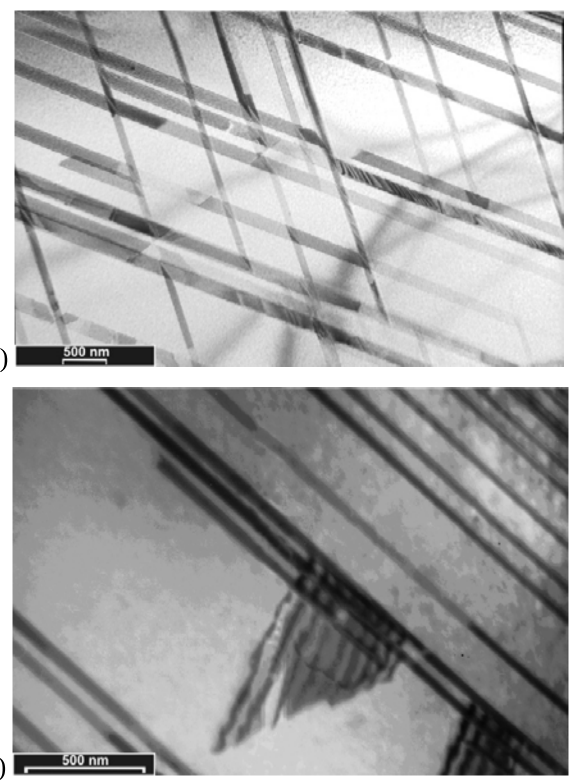

Fig. 1. Microstructure of the sheets rolled at 20ºC, annealed at 1000ºC, a)15Mn, b)30Mn

of dislocations due to high temperature annealing, softens the austenite and promotes plastic slip. When these sheets are rolled at room temperature and annealed at recovery temperature of 650ºC, leads to a microstructure of smaller grains and dislocations arrays inherited from the cold rolling stage.

Rolling at intermediate temperatures followed by annealing at recovery temperature of 650ºC provides the best degree of shape recovery for both alloys, which is only of about 55% in the 30Mn and near 100% in the 15Mn. Fig. 2a and 2b, show the corresponding microstructures. For the 30Mn alloy, dense dislocation bands with low dense arrays between the bands are observed (Fig. 2a). In the 15Mn sheet, dislocation arrays interacting with stacking faults are characteristic features of the microstructure (Fig.2b). This seems to be the most suitable microstructural condition, responsible of the nearly full shape recovery of the 15Mn alloy, since a high density of stacking faults provides nucleation sites to promote the formation of thin martensite plates. Further more, the dislocations left in the austenite after recovery annealing, harden the matrix enough to avoid plastic slip in a stress-induced transformation.

Other rolling conditions as geometric variables and friction can also play an important role on the shape memory behavior. We can see as an example (Fig. 3), the microstructure corresponding to a 30Mn specimen processed by single-roll driver rolling at 600ºC. In this case the combined effect of the increased value of SFE

a)

b)

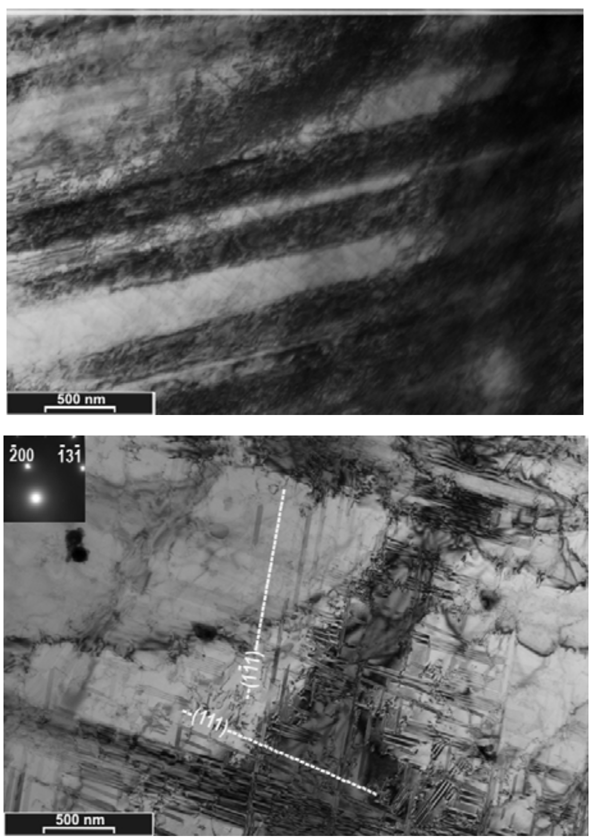

Fig. 2. Microstructure of the sheets rolled at 600ºC, annealed at 650ºC, a) 30Mn, b)15 Mn.

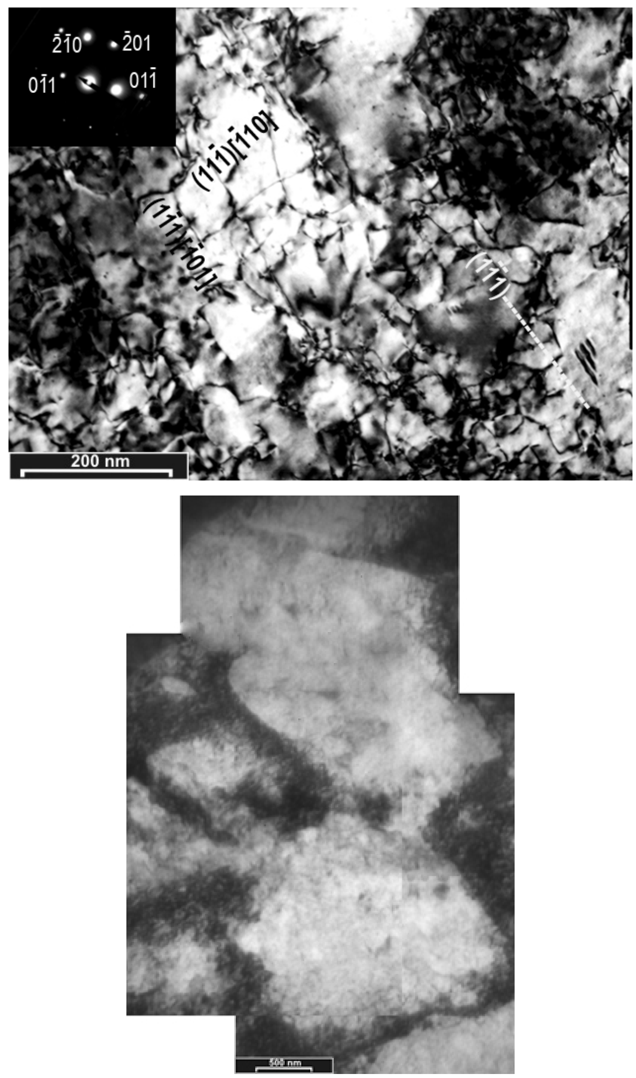

Fig. 3. Microstructures of the 30Mn sheet single-roller drive rolled at 600ºC, annealed at 650ºC

with temperature [7] and the deformation condition during rolling, leads to a cell structure, quite entangled, with a low density of stacking faults. These sheets had a low shape memory behavior, less than 25%.

CONCLUSIONS

Different thermo-mechanical processes were performed on two Fe-Mn-Si shape memory alloy: forming at 20 and 600-800°C by conventional rolling, reverse rolling and single-roller drive rolling, followed by annealing at different temperatures. The results suggest that the microstructure of Fe-Mn-Si based alloys can be tailored in order to optimize their shape memory properties taking into account parameters as SFE and by an appropriate selection of processing conditions. Among the analyzed cases, the 15Mn-4Si-9Cr-5Ni alloy rolled at 800ºC and annealed at 650ºC, where suitable density of stacking faults and dislocations arrays were introduced in the matrix, shows the best degree of shape recovery, of nearly 100 %.

ACKNOWLEDGEMENTS

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