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 800ºC and annealed at 650ºC, the recovery temperature, shows the best shape memory behavior.

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

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) → 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 appropriated, 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<112> SShockley partial dislocations, before than a/2<110> 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 responsible 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 1100°C 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 600°C for 15 min, i.e. above the Af temperature, under Ar atmosphere to avoid oxidation. The degree of uniaxial shape recovery (DSR_u) was calculated as:

\[
    DSR_u = \frac{l_2 - l_1}{l_1 - l_0} \times 100
\]

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 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 650°C, 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 650°C 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. Furthermore, 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 600°C. In this case the combined effect of the increased value of SFE 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 800°C and
annealed at 650°C, where suitable density of stacking
faults and dislocations arrays were introduced in the
matrix, shows the best degree of shape recovery, of
nearly 100 %.

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**REFERENCES**

effect and mechanical behaviour of an Fe-30Mn-1Si
alloy single crystal”, *J. Physique* C4:797-802.

“Orientation and composition dependencias of shape
memory effect in Fe-Mn-Si alloys”, *Acta Metall.*
32:539-547.

ties controlling shape memory effect in Fe-Mn-Si

structures formed during hot and cold working”,

rolling Fe-Mn-Si based shape memory alloys:
mechanical properties and TEM observations”, *Mat.
Sc. & Eng.* A 481:574-577.

(2008), “Texture evolution during thermomechanical
treatments in F-Mn-Si shape memory alloys”, *Mat.

martensitic transformation and stacking fault energy
of γ in Fe-Mn binary system”, *Met. and Mat. Trans