ELSEVIER

Materials Science and Engineering A 481–482 (2008) 183–189

MATERIALS SCIENCE & ENGINEERING A

www.elsevier.com/locate/msea

# Stresses related to the shape memory effect in Fe–Mn–Si-based shape memory alloys

N. Van Caenegem [a,*], L. Duprez [b], K. Verbeken [a,1], D. Segers [c], Y. Houbaert [a]

[a] *Department of Metallurgy and Materials Science, Ghent University, Technologiepark 903, B-9052 Ghent, Belgium*
[b] *Arcelor Research Industry Gent, J.F. Kennedylaan 3, B-9060 Zelzate, Belgium*
[c] *Department of Subatomic and Radiation Physics, Ghent University, Proeftuinstraat 86, B-9000 Ghent, Belgium*

Received 26 May 2006; received in revised form 15 January 2007; accepted 9 February 2007

**Abstract**

The shape memory behaviour of two Fe–Mn–Si-based alloys has been investigated. Two compositions were studied, *i.e.* Fe29Mn7Si and Fe29Mn7Si5Cr (numbers indicate mass%). Characterizations of the martensitic transformation and the different structural constituents were performed using optical microscopy and X-ray diffraction methods. Transformation temperatures were determined by thermodilatometry on undeformed and deformed samples. The shape recovery was quantified by means of bending tests and dilatometry experiments on compressed samples. A procedure was designed to measure the recovery stresses caused by the dimensional changes of the sample due to the shape memory effect. The recovery stress is defined as the stress that is generated when the recovery of deformation is impeded under constraint. The mechanical results are discussed on the basis of the underlying transformation and deformation processes.


*Keywords:* Fe–Mn–Si; Shape memory effect; Recovery stress; Martensitic transformation; Epsilon martensite

## 1. Introduction

Fe–Mn–Si alloys are one-way shape memory alloys (SMAs) with a high potential for engineering applications. By deforming the material, the fcc $\gamma \rightarrow$ hcp $\varepsilon$ stress-induced martensitic transformation takes place. During subsequent heating, the reverse $\varepsilon \rightarrow \gamma$ transformation occurs. Not only the initial $\gamma$-fcc crystal is obtained but also the initial shape is partially recovered.

Murakami et al. [1] have developed polycrystalline Fe–Mn–Si SMAs and reported the nearly complete shape recovery in alloys containing 28–33% Mn and 6% Si (mass%). By adding Si the yield stress of the austenite increases. An increase in yield strength restricts plastic deformation at the tip of a $\varepsilon$ martensite plate and enhances the back stresses that favor the reverse transformation. In addition, the stacking fault energy, which has to be low for good shape recovery is lowered by Si. The addition of Cr improves the corrosion resistance. The increase of Cr requires the addition of Ni to suppress the formation of the $\sigma$ phase which reduces the fracture toughness [2].

Low cost Fe–Mn–Si-based SMAs have the disadvantage of incomplete shape recovery. Much research has been done to improve their shape recovery, by means of a special thermo-mechanical treatment called 'training' [3] and by the addition of other elements such as Nb and C [4,5]. The training raises the production cost of Fe–Mn–Si-based SMAs and severely limits their industrial applicability.

For some applications, *e.g.* pipe joints [6], it is not the amount of shape recovery that is important, but the stresses that occur if during heating the recovery to the austenite structure is constrained by an external obstacle. This process is called constrained recovery. In this work, a procedure will be proposed to measure those stresses related to the shape memory effect (SME).

## 2. Experimental procedure

Two different Fe–Mn–Si-based compositions were prepared for the present study. The materials were cast in a furnace in air, then cooled in air, reheated to 1200 °C and hot rolled on a laboratory mill from 20 mm to 2.5 mm or 6 mm for different samples,

* Corresponding author. Tel.: +32 9 264 57 76; fax: +32 9 264 58 33.
*E-mail address:* Nele.VanCaenegem@UGent.be (N. Van Caenegem).
[1] Postdoctoral fellow with the Fund for Scientific Research, Flanders, Belgium (F.W.O.-Vlaanderen).

0921-5093/$ – see front matter © 2007 Elsevier B.V. All rights reserved.
doi:10.1016/j.msea.2007.02.159

Table 1
Chemical composition of the investigated SMA (in mass%)

| Alloy | Mn | Si | Al | Cr | Ni | C |
|---|---|---|---|---|---|---|
| Fe29Mn7Si | 28.3 | 6.8 | 0.009 | 0.02 | 0.03 | 0.013 |
| Fe29Mn7Si5Cr | 29.0 | 6.9 | 0.007 | 5.0 | 0.01 | 0.018 |

again followed by air cooling. Their chemical compositions are listed in Table 1.

The identification of the different phases, the distinction between ε martensite and twins and the study of the morphology evolution of the ε martensite during deformation were carried out by means of optical microscopy (OM) and X-ray diffraction (XRD). The OM specimens were first mechanically polished and then electrolytically polished in a solution of 20% perchloric acid and 80% butylcellosolve. Afterwards, the specimens were color etched in an aqueous solution of 1.2% $K_2S_2O_5$ and 0.5% $NH_4HF_2$. XRD measurements were done using a Siemens D5000 diffractometer with Mo radiation ($\lambda_{Mo} = 0.071$ nm) in the $2\theta_{Mo}$ range of 18–55°.

In order to determine the transformation temperatures of the alloys, a Bahr dilatometer was used. The dilatation specimens of 4 mm diameter and 10 mm length were machined from 6 mm-thick hot rolled sheets. The samples were first heated to 800 °C and then cycled between −100 °C and 400 °C at a heating and cooling rate of 10 K/s.

The shape memory effect was evaluated by means of bending and compression tests in the dilatometer. Samples of

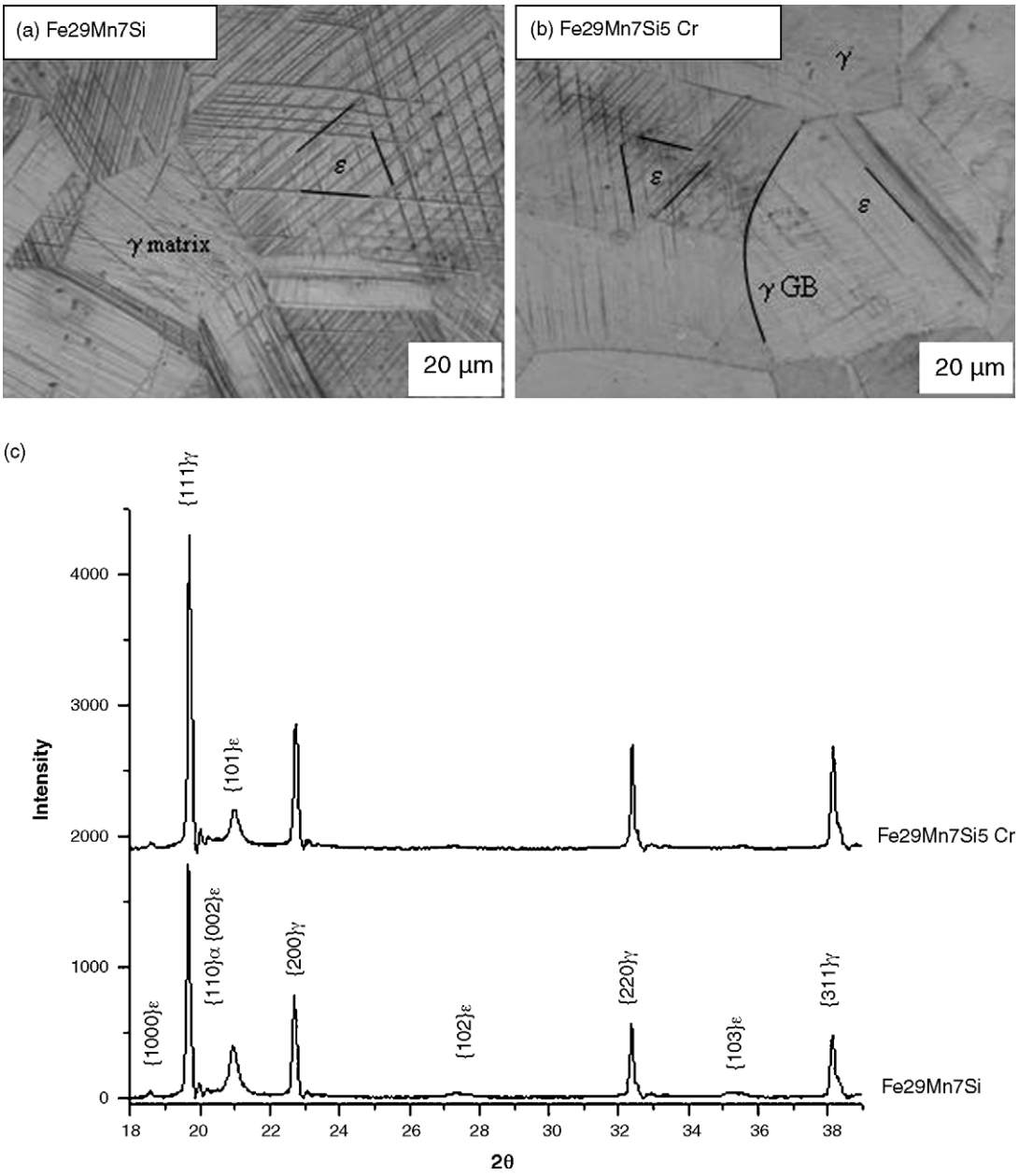


Fig. 1. OM microstructure of (a) Fe29Mn7Si and (b) Fe29Mn7Si5Cr. (c) XRD patterns of the two alloys. All samples were hot rolled, air cooled, annealed at 1100 °C for 15 min and then water quenched to room temperature.