ESOMAT 2009, 02015 (2009)
DOI:10.1051/esomat/200902015

Role of Si on the shape memory property of Fe-Mn-Si-C based alloys

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Abstract. Si content dependence of the shape memory effect (SME) associated with the ε-martensitic transformation has been investigated in Fe-17Mn-xSi-0.3C (x=0,2,4,6) alloys (mass%). By conducting tensile deformations and subsequent heating to above the A_f, it has been found that reduction of mere 2% Si content from 6% to 4% obviously deteriorates the SME. The Neel and M_s temperatures in both Fe-17Mn4%Si-0.3C and Fe-17Mn6%Si-0.3C alloys are content with the conditions concerning the good SME. By obtaining stress-strain curves at various temperatures, it has been found that the Fe-17Mn-4Si-0.3C alloy has similar critical stresses for ε-martensitic transformation and slip deformation to the critical stresses in the Fe-17Mn-6Si-0.3C alloy. As a consequence, the SME in Fe-Mn-Si-C system sometimes does not appear, even if ε-martensitic transformation preferentially occurs.

1. Introduction

FCC (γ) → HCP (ε) martensitic transformation occurs in a low stacking fault energy alloy. The shape memory effect (SME) in Fe-Mn-Si based alloys [1,2] arises from ε → γ reverse martensitic transformation. The reversibility of ε-martensitic transformation depends on several factors: combination of M_s and Neel temperatures [3], stacking fault energy [4,5], short range ordering [6,7], strength of parent phase against permanent slip deformation[8,9] and so on. Many researchers have attempted to substitute or add elements with reference to the factors to improve the SME. Although a number of success have been reported [10,11,12], the Si content is always approx. 6% (hereinafter compositions are shown in mass%). Tsuzaki et al. noticed that Si is quite effective to solution hardening, and consider that solution hardening is one of the most important key roles of Si. By comparison between alloys with and without Si, the strength against permanent slip definitely increases by addition of Si, which gives a new idea; addition of C which is also effective for solution hardening must increase the SME. As a result, an Fe-17Mn-6Si-0.3C alloy with an excellent SME was developed [8].

Assuming that the key role of Si is the enhancement of the strength against slip, Si content can be reduced for C content from the Fe-17Mn-6Si-0.3C alloy. We have investigated the Si content dependence of the strength and the SME in Fe-17Mn-xSi-0.3C alloys. The purpose of this work is to reveal the role of Si associated with mechanical properties, even as discuss why 6% Si is necessary for the SME.

2. Experimental

2.1 Sample

Fe-17Mn-xSi-0.3C (x=0, 2, 4, 6) alloys were melted in a vacuum induction furnace and ingots with 60 mm ×60 mm ×120 mm. The ingots were forged at 1273 K to 40 mm × 40 mm × 270 mm and hot rolled at 1273 K to a thickness of 15 mm. Solution treatment was performed at 1273 K for 3.6ks in Ar followed by water quenching. The specimens for tensile tests and Dynamic Mechanical Analysis (DMA) were cut with electric spark machining. Fig.1 shows the configuration of the tensile test sample. The specimens with dimensions of 5.0 mm × 1.0 mm × 60 mm were used for DMA.

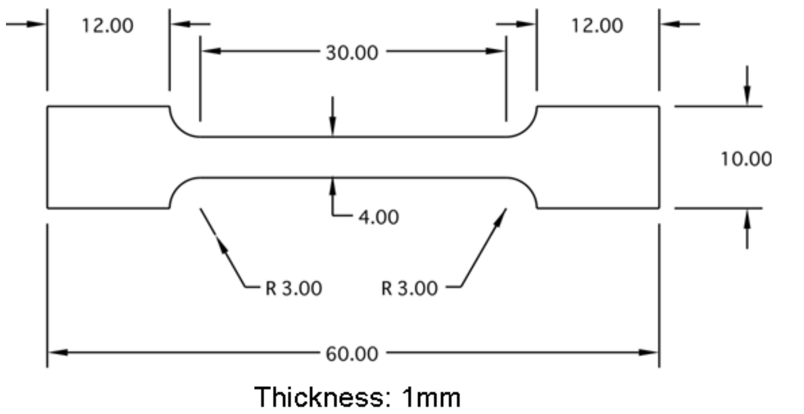

Fig.1 Configuration of the tensile test samples

2.2 Shape memory and mechanical properties

Shape recovery strain was measured with tensile deformations. The specimens were deformed up to proper amount of strain at a constant rate of 1.7×10^{-4} s^{-1} using an Instron type machine. Subsequently, the specimens were heated up to 873 K (above A_f), and kept at 873 K for 10min. The recovery strain was calculated from a change of a gauge length; $\varepsilon_r=(L_1-L_2)/L_0$. Where L_0, L_1, and L_2 are the gauge length before the deformation, after the deformation, and after the heating, respectively.

Stress-strain curves were measured at various temperatures from 273 K~523 K using strain gauges. In order to estimate the 0.2% proof stress against permanent slip at 294 K, the proof stresses at temperatures from 373 K to 523 K were extrapolated to 294 K.

2.3 Transformation and Neel temperatures

The M_s, A_s and Neel temperatures were measured with DMA, TA instruments model 2980. Details of the determination of transformation and Neel temperatures with DMA have been reported [13,14]. In this work, we used Young's modulus obtained by the DMA measurements to determine the transformation and Neel temperatures. An example of the relationship between temperature and Young's modulus is shown in Fig.2. The specimens were austenitized by heating up to 573 K in the DMA before the measurements. The relationships between temperature and Young's modulus were investigated by cooling to 133 K and subsequent heating to 573 K. The cooling and heating rates were 2 K/min. The amplitude and the strain amplitude were 10μm and 8.5×10^{-5}, and the vibration frequency was 1 Hz.

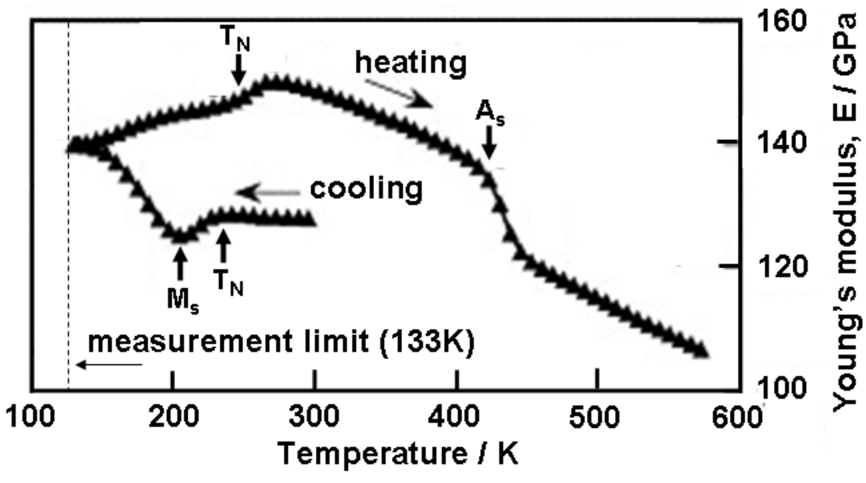

Fig.2 The relationship between DMA data and transformation temperatures in an Fe–28Mn–6Si–5Cr–0.53Nb–0.06C alloy[14)]

3. Results and discussion

3.1 Shape memory property and the transformation and Neel temperatures

Shown in Fig.3 is the relationship between Si concentration and recovery strain. The 4% initial strain was given by tensile deformation at room temperature. The accurate values of the initial strain are 4.47%, 4.35%, 4.32% and 4.22% for 0%Si, 2%Si, 4%Si and 6%Si alloys, respectively. Notice that the recovery strain leads to a large increase in addition of 6% Si. Contrary to our hypothesis; Si content can be reduced for C content, the result indicated that 4%Si does not have good SME. This raises the question of how 6% Si affects the SME. In this paper, I will concentrate on the following issues to settle the question: the relationship between transformation and Neel temperatures and solution hardening. Si concentration dependence of Neel temperature is shown in Table 1 and Fig.4. We could not obtain the T_N of 6%Si because of measurement limit in the DMA. The measurement limit for a low temperature side is 133 K. Where T_N lies above M_s, a SME is deteriorated because of the stabilization of austenite due to antiferromagnetic ordering. Although 2%Si and 4%Si have T_N below M_s, the recovery strain is poor compared with 6%Si. Namely, as far as the SME in 2%Si, 4Si and 6Si is concerned , we can rule out the effect of Neel temperature. Ms and As temperatures for 0~6%Si alloys were clearly shown in DMA results, indicating that ε-martensitic transformation definitely occurs in the all alloys.

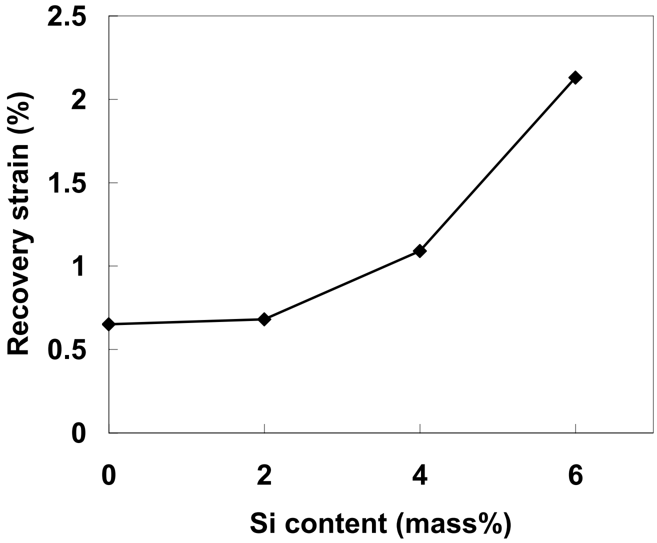

Fig. 3 Recovery strain versus Si content in Fe-17Mn-xSi-0.3C alloys. The initial strain was approx. 4%, and the recovery strain was obtained by heating at 873 K.

Table 1 M_s and A_s martensitic transformation temperatures along with Neel temperature

Alloy (mass%)	M_s	A_s	Neel
Fe-17Mn-0Si-0.3C	272 K	463 K	315 K
Fe-17Mn-2Si-0.3C	301 K	474 K	254 K
Fe-17Mn-4Si-0.3C	307 K	490 K	203 K
Fe-17Mn-6Si-0.3C	275 K	485 K	<133 K

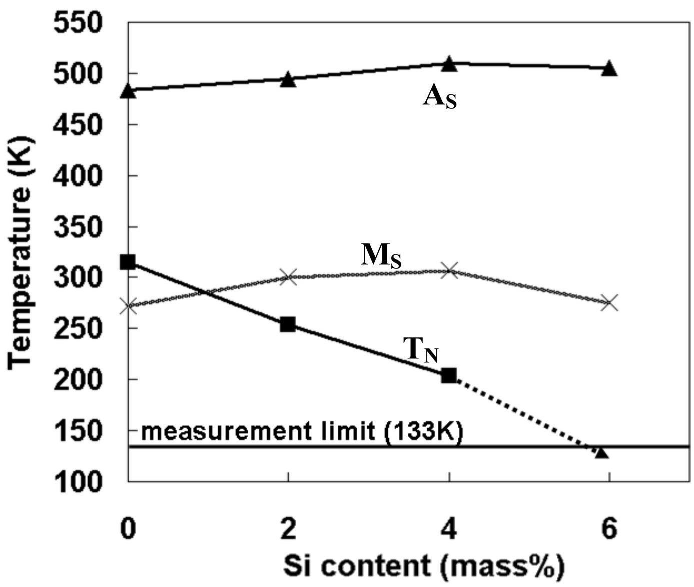

Fig. 4 Si content dependence of transformation and Neel temperatures

3.2 Mechanical properties

Table 2 and Fig. 5 show the effect of silicon on the difference between the critical stresses for ε-martensitic transformation and slip deformation at room temperature. We regarded the 0.2% proof stresses at room temperature as the critical stresses for ε-martensitic transformation. Although the critical stress for ε-martensitic transformation and slip deformation increase with the increase of Si content until 4% Si, the critical stress for ε-martensitic transformation and slip deformation of 4%Si and 6%Si are almost same. In addition, It was pointed out in the previous section that the recovery strain of 4%Si is unsatisfactory compared with 6%Si. The results clearly show that recovery strain is not always good, even if the strength against slip is sufficiently-high.

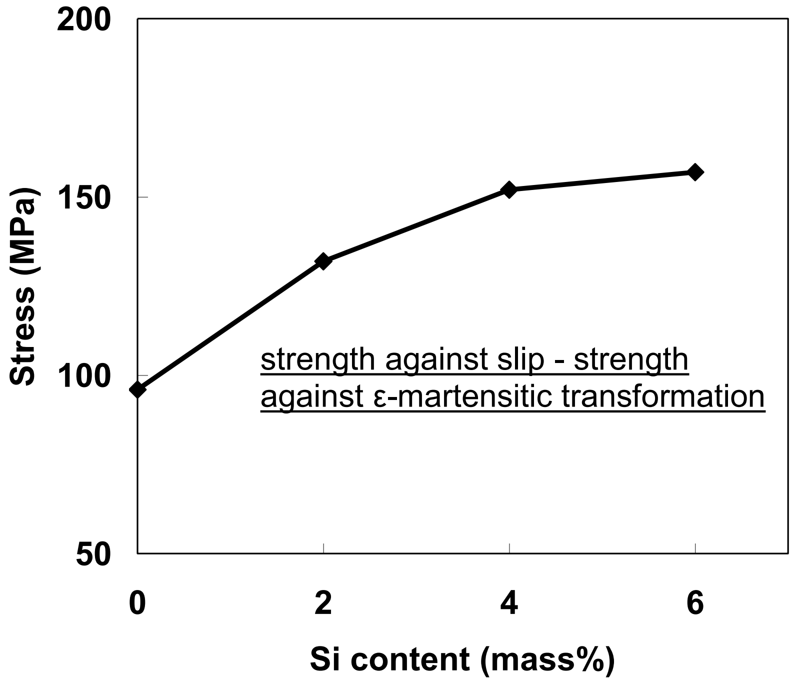

Fig.5 $\angle\sigma_y$ versus Si content in Fe-17Mn-xSi-0.3C alloys

Table 2 Si content dependence of the critical stresses for ε-martensitic transformation, $\sigma_y (\gamma\rightarrow\varepsilon)$, and slip deformation, σ_y (γ slip), and their difference, $\triangle\sigma_y$, at room temperature. $\triangle\sigma_y = \sigma_y$ (γ slip)- $\sigma_y (\gamma\rightarrow\varepsilon)$

Alloy (mass%)	$\sigma_y (\gamma\rightarrow\varepsilon)$	σ_y (γ slip)	$\triangle\sigma_y$
Fe-17Mn-0Si-0.3C	188 MPa	289 MPa	101 MPa
Fe-17Mn-2Si-0.3C	205 MPa	337 MPa	132 MPa
Fe-17Mn-4Si-0.3C	214 MPa	366 MPa	152 MPa
Fe-17Mn-6Si-0.3C	205 MPa	362 MPa	157 MPa

4. Summary

The effect of Si addition on the shape memory property associated with ε-martensitic transformation has been examined in Fe-17Mn-xSi-0.3C alloys. It is clearly shown that the shape memory property requires 6%Si. By comparison of some parameters in Fe-17Mn-xSi-0.3C alloys, it has been found that the increase of Si content linearly decreases the Neel temperature but does not affect the M_s temperature. The condition of the M_s and Neel temperatures of Fe-17Mn-2Si-0.3C, Fe-17Mn-4Si-0.3C and Fe-17Mn-6Si-0.3C alloys are satisfied for the shape memory effect. Moreover, by analyzing the critical stresses for ε-martensitic transformation and slip deformation in Fe-17Mn-4Si-0.3C and Fe-17Mn-6Si-0.3C alloys, it is suggested that good shape recovery, given sufficient enhancement of strength against permanent slip, is sometimes possible. It is also true that in some cases good shape recovery does not appear in spite of the high strength against permanent slip such as the Fe-17Mn-4Si-0.3C alloy.

The present work was supported by Japan Science and Technology agency (JST).

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