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The effect of deformation on γ-ε martensitic transformation in an Fe-Mn-Mo alloy

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Effect of prior plastic deformation of austenite on the martensite start temperature, volume fraction and strength of martensite have been studied in an Fe-14.3%Mn-3.7%Mo alloy. Mo was chosen to examine the possible effect of the third alloying element in an Fe-Mn based alloy and the obtained results were compared with those of the Fe-Mn binary alloys given in the literature. Predeformation of austenite created considerable changes on the formation characteristics and also the strength of the martensitic phase and the obtained results were discussed in terms of the dislocations formed during the deformation process.

1. Introduction

It is well established in the literature that prior plastic deformation of the austenite matrix structure changes the martensite start temperature (M_s) and the amount of martensite formed on subsequent cooling to any fixed temperature. Studies have also revealed that the change in M_s may be related to the change in austenitic yield strength produced by work-hardening and there is a correlation between the change in M_s temperature with composition for various Fe-based alloys and their yield strengths [1]. Recent investigations however showed the close relation between the austenite strength and the occurrence of shape memory effect in some Fe-Mn based alloys [2–4]. According to the obtained results a complete shape memory effect can only be obtained with the inhibition of permanent slip in the austenite matrix and therefore the strength and the martensite formation characteristics of a particular austenitic structure play important roles on the physical properties of such alloys.

Tsuzaki *et al.* [4] examined the possible effect of solution hardening on the shape memory effect in different Fe-Mn based alloys and reported that the addition of Mo makes a relatively small contribution to the strength of austenite compared with some other elements such as Si and C, and the shape memory effect observed in an Fe-25%Mn-3%Mo alloy is considerable small. Inegbenebor *et al.* [5] also studied the nature of martensite formation in some Fe-Mn-Mo alloys and revealed the correlation between the strength and composition of these alloys.

Since there have been relatively few studies on the formation mechanism and strength of martensite in Fe-Mn based alloy with Mo as the third alloying element, the present study was aimed to examine the effect of prior plastic deformation of austenite on the M_s temperature, volume fraction and strength of martensite in an Fe-Mn-Mo alloy.

2. Experimental

Fe-14.3%Mn-3.7%Mo alloy was prepared by induction melting in an argon atmosphere from pure (99.9%) alloy elements and the samples were homogenized at 1100 °C for 12 hours. The specimens were cut from the bulk samples in the form of cylinders of 6 mm diameter and 10 mm length and austenized at 900 °C in vacuum for 8 hours. The M_s temperatures and volume fractions of martensite were measured by dilatometry and an Adamel-Lhomargy LX-02 dilatometer was used during the examinations. The finish temperature of ε martensite to austenite transformation (A_f) was determined as around 280 °C and the specimens were deformed plastically to different strains by compressing at 600 °C temperature which is well above the A_f, then furnace cooled to room temperature to initiate the formation of martensite. An Instron compression test machine was used for compression experiments to examine the stress-strain behaviour of the samples and a crosshead speed of 100 μm min^{-1} was used during the tests. Compression specimens of dimensions $2 \times 2 \times 5$ mm were cut from the cylindrical samples, and the load cell output of the test machine was calibrated to 1% prior to each test to measure the applied stresses accurately.

Foil samples for transmission electron microscopy (TEM) were prepared from 3 mm discs trepanned with a spark-cutter and thinned by using double-jet polishing technique with a solution of 20% perchloric acid-80% methanol. The specimens were examined in a Jeol-200 CX TEM operating at 200 kV.

3. Results and discussion

Studies on the austenite to martensite phase transformations in Fe-Mn based alloys have revealed that the austenite matrix (γ) with f.c.c. crystal structure can be transformed to α' (b.c.c.) and ε (h.c.p.) martensites;

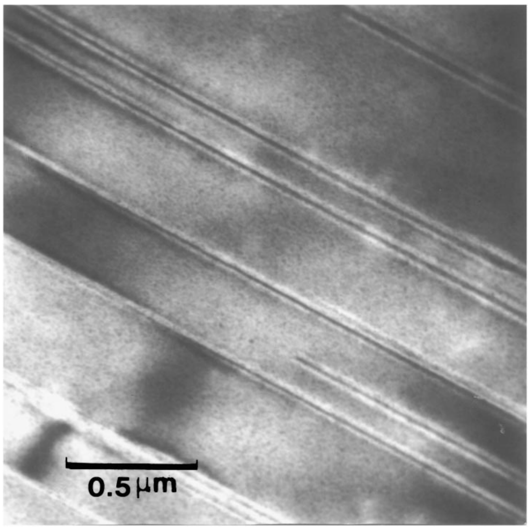

Figure 1 TEM micrograph of ε martensites formed in a 3% deformed austenitic sample.

and $\varepsilon \rightarrow \alpha'$ transformation is also possible under some physical conditions [6–8]. However, either phase can also be formed independently without the formation of the other. This transformation behaviour is quite sensitive to the percentage of Mn and mostly ε type product structure is formed as the Mn content is increased [8]. Examination of the austenite substructure with TEM showed no evidence of α' type martensite formation due to the composition of the alloy used during the present study, i.e., the observed martensitic structures were ε type. Fig. 1 shows a TEM micrograph of ε martensites formed in an austenitic sample of Fe-14.3%Mn-3.7%Mo alloy after 3% prior plastic deformation of the matrix structure at 600 °C.

The possible effect of prior plastic deformation of austenite matrix on the M_S temperature of the ε martensite formation was examined with the austenitic samples compressed in the range of 2–40% and the obtained results are given in Fig. 2. As shown in the figure, the M_S temperature of the non-deformed austenite was ~80 °C and continuously decreased with the increasing amount of plastic deformation. It is also shown that despite a sharp decrease in the M_S temperature until the deformations up to 25%, a relatively smaller change in M_S was observed between 25 and 40% deformations. Austenitic samples were also deformed under the similar conditions to investigate the effect of prior austenite deformation on the volume fraction of the transformed ε martensite and Fig. 3 shows the change of measured ε martensite volume fractions of the predeformed austenitic samples against temperature. A similar curve for a non-deformed sample is also given in the same figure to make quantitative comparison. It is obvious from the obtained curves that the amount of ε martensite is sharply increased in all samples tested between the M_S and 0 °C temperatures. However there are two interesting points to be considered. Firstly, as the samples were cooled from the M_S to 0 °C temperature the amount of ε martensite becomes smaller in the samples deformed to relatively higher ranges. Secondly, the change in the volume fraction of ε martensite against temperature for the non-deformed specimen is much sharper then those of the deformed ones and the slope of the curves were decreased with the increasing amount of plastic deformation. The obtained results show some agreements with those of the early studies on Fe-Mn alloys [9]. However according to their results predeformation of austenite did not change the volume fraction of ε martensite at room temperature and it was found almost same for the deformed and undeformed samples. Therefore there is an obvious difference between the present and early results on the amount of ε martensite formation at room temperature which might be caused due to the addition of Mo as the third alloying element. It was also observed that the volume fraction of ε martensite formed at the M_S temperature is relatively decreased as the size of the austenite deformation is raised.

Stress-strain curves of the samples deformed to various levels at 600 °C temperature and furnace cooled to room temperature for the austenite to ε martensite

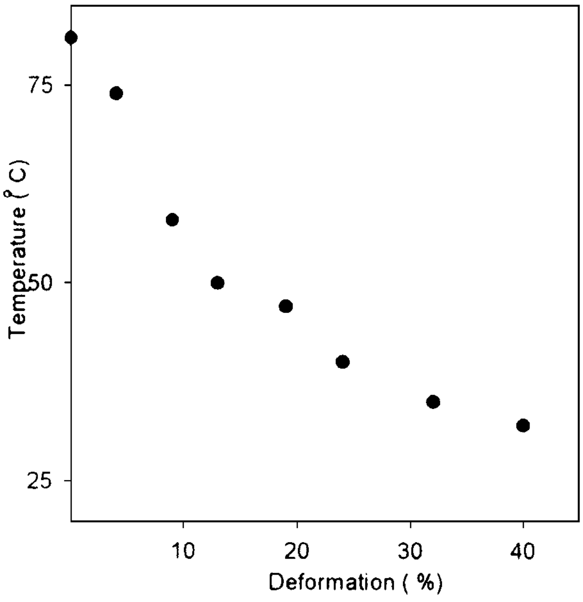

Figure 2 Change in M_S by the deformation of austenite.

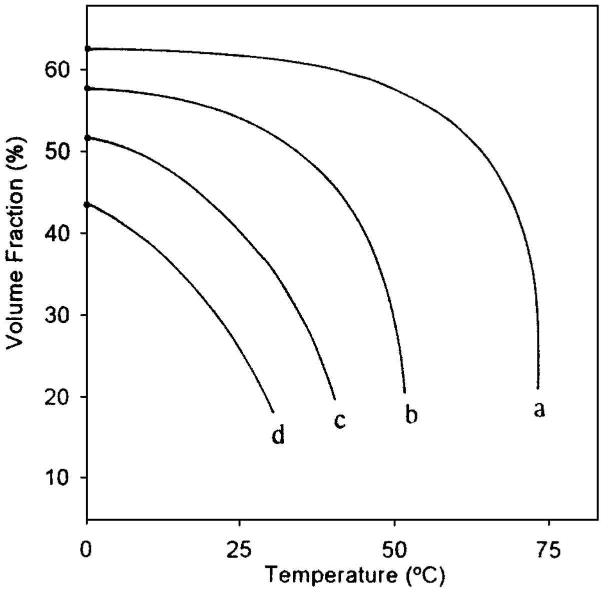

Figure 3 Change in volume fraction of ε martensite with the amount of austenite predeformation, (a) non-deformed, (b) 12%, (c) 20% and (d) 40% deformed.

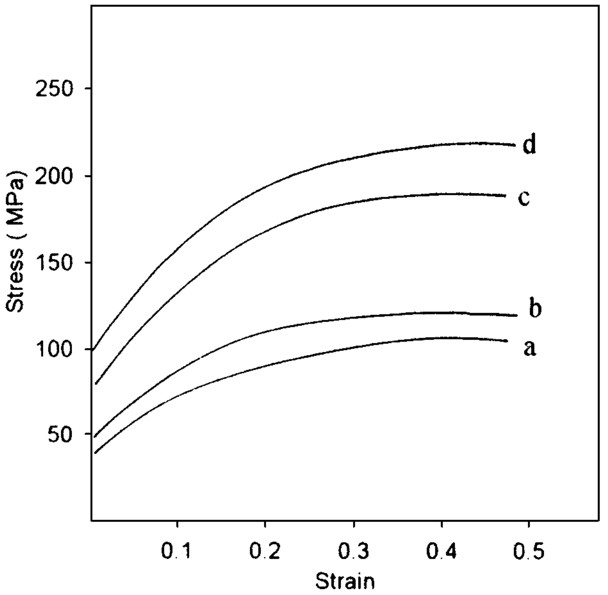

Figure 4 Stress-strain curves of the samples: (a) non-deformed tested at 600 °C, (b) non-deformed tested at the room temperature, (c) 20% deformed at 600 °C and tested at room temperature, (d) 40% deformed at 600 °C and tested at room temperature.

transformation is shown in Fig. 4. The same experiments were also performed with non-deformed samples at 600 °C and room temperatures to observe the contribution of ε martensite to the strength of material and make quantitative comparisons. Obtained results revealed that although ε martensite produces a relatively small effect on the strength of austenite in non-deformed samples, it is hardly possible to describe it as an hard phase. However a considerable change is created due to the plastic deformation of the austenite matrix prior to the ε martensite formation in heavily deformed austenites and despite the increasing amount of ε martensite in these samples still the observed raise in the strength of predeformed austenites is too large to be caused by their formation alone. Therefore the bigger contribution to the strength of material was assumed to be created by obstruction of the dislocation motion in the deformed austenite matrix.

It has been well established that the formation mechanism of ε martensite can be explained by using the assumption of over-lapping stacking faults on every second close-packed plane of the austenite matrix structure and the transformation occurs with the movement of $a/6\,\langle 112\rangle$ Shockley partial dislocations. Thus the formation of ε martensite is primarily observed in the alloys with low stacking fault energies. The stacking faults located inside the austenite matrix create nuclei for the ε martensite formation and obviously the increased density of dislocation type lattice imperfections play an important role during the formation of ε martensite in predeformed austenitic samples [2, 10]. The existence of dislocations creates two competing effects in the austenite structure, namely, stimulation of ε martensite formation due to the formation of favourable nucleation sites and inhibition of growth by the faulted austenite substructure. It seems that the latter effect is generally dominant during the austenite to ε martensite transformations in Fe-Mn based alloys and the ε martensite formation is suppressed with increasing amount of plastic deformation. The increased density of dislocations can easily obstruct the movement of Shockley partial dislocations and the larger activation energies are required to start the transformation in deformed samples. Thus the M_s temperature is decreased to compensate the energy difference caused by the applied plastic deformations. However, the role of dislocations on the ε martensite formation has been studied in great detail in Fe-Mn based alloys and it was concluded that the existence of third alloying element greatly changes the formation characteristics of ε martensite by altering the behaviour of dislocation movements and restricting the permanent slip formation [3, 11]. Therefore the composition of a particular alloy should be an important factor. It can be concluded after the present study that despite the addition of Mo as the third alloying element, obtained results on the influence of austenite predeformation upon the M_s temperature and volume fraction of ε martensite formation show a general agreement with those of Fe-Mn binary alloys. The observed difference in the ε martensite volume fractions of Fe-Mn and Fe-Mn-Mo alloys in predeformed austenitic samples at room temperature can be explained in terms of the different characteristics of the dislocation movements and it seems that the ε martensite formation is more suppressed in deformed austenitic samples of Fe-Mn-Mo alloys most probably due to the inhibition of growth.

4. Conclusions

Present results revealed the formation of ε type martensitic structures in the austenite samples of Fe-14.3%Mn-3.7%Mo alloy. The M_s temperature was changed with the deformation of the austenite matrix prior to the transformations and decreased as the amount of this deformation was raised. Predeformation of the austenite matrix also influenced the volume fraction of ε martensite formed during the transformations and it was found to increase sharply for the samples tested at different temperatures between the M_s and 0 °C.

Although the ε martensite formation increased the strength of austenite, the contribution was relatively smaller and not enough to describe it as an hard phase.

The obtained results show a fair agreement with those of the Fe-Mn alloys reported earlier and the contribution of Mo as the third alloying element did not create big differences on the examined properties of the ε martensite formation. However there was a considerable difference on the amount of ε martensites formed at room temperature and this was considered to be caused due to the different nature of dislocations in deformed Fe-Mn-Mo austenites.

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