



THE AS-QUENCHED MICROSTRUCTURES OF Fe-9Al-30Mn-1.2C-xSi ALLOYS

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Introduction

The microstructures and the mechanical properties of the austenitic Fe-Al-Mn-C alloys have been studied by many workers[1-13]. On the basis of their studies, it is found that when an alloy with a chemical composition in the range of Fe-(8-11) wt pct Al-(28-35) wt pct Mn-(0.8-1.3) wt pct C was solution heat-treated and then quenched, the microstructure of the alloy was single -phase austenite[1,4-13]. After being aged at temperatures ranging from 500°C to 750°C for moderate times, fine (Fe,Mn)₃AlC_x carbides started to precipitate coherently within the austenite matrix[8-13]. The (Fe,Mn)₃AlC_x carbide has an ordered L'1₂-type structure[24]. Owing to the precipitation of fine (Fe,Mn)₃AlC_x carbides within the austenite matrix, the strength of the alloy was remarkably increased without significant loss in ductility. In addition, in order to improve the corrosion resistance and high-temperature oxidation resistance as well as strength, silicon has been added to the Fe-Al-Mn-C alloys[2,14-21]. In their studies, it is generally concluded that the Si addition could effectively improve these properties. It was also predicated that the silicon addition appeared to enhance the formation of ferrite (α) or ordered B2 phases[19-21]. Recently, we have made transmission electron microscopy observations on the phase transformations of an Fe-8 wt pct Al-29 wt pct Mn-0.9 wt pct C alloy containing 1.5 wt pct Si[22]. In the previous study, we have shown that the as-quenched microstructure of the alloy was a mixture of austenite and ferrite phases, and extremely fine D0₃ particles were formed within the ferrite matrix. This result is quite different from that observed by other workers in the Fe-Al-Mn-C and Fe-Al-Mn-C-Si alloys. Extending this work, it is interesting to study successively the effects of silicon content on the as-quenched microstructures of the Fe-Al-Mn-C alloy. Therefore, the purpose of this work is an attempt to study the as-quenched microstructures of the Fe-9Al-30Mn-1.2C alloy with 0, 0.5, 1.0, 1.5 and 2.5 silicon contents, respectively.

Experimental Procedures

The present investigated alloys were prepared in an air induction furnace by using 99.5 pct iron, 99.7 pct aluminum, 99.9 pct manganese, ferrosilicon and pure carbon powder. The chemical compositions

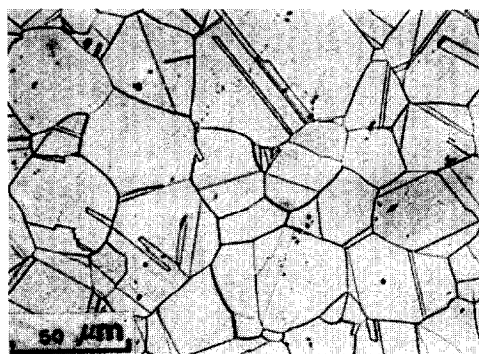
TABLE I
Chemical Compositions of the Investigated Alloys

Alloy	Chemical Composition (wt pct)				
	Fe	Al	Mn	C	Si
A	59.8	9.0	30.0	1.2	—
B	59.3	9.0	30.0	1.2	0.5
C	58.8	9.0	30.0	1.2	1.0
D	58.3	9.0	30.0	1.2	1.5
E	57.3	9.0	30.0	1.2	2.5

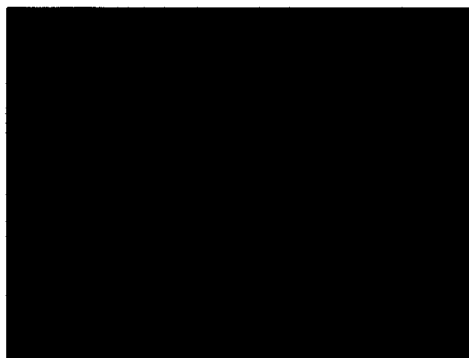
of the alloys are listed in Table I. After being homogenized at 1250°C for 12 hours under a protective argon atmosphere, the ingots were hot forged and then cold rolled to a final thickness of 2.0 mm. The sheets were subsequently solution heat-treated at 1050°C for 2 hours and rapidly quenched into room-temperature water. The microstructures of the alloys were examined by means of optical microscopy and transmission electron microscopy. Electron microscopy specimens were prepared by means of a double jet electropolisher with an electrolyte of 30 pct acetic acid, 60 pct ethanol and 10 pct perchloric acid. The polishing temperature was kept in the range from -10°C to 10°C, and the current density was kept in the range from 1.5 to 2.0 x 10⁴ A/m². Electron microscopy was performed on a JEOL 2000FX scanning transmission electron microscope (STEM) operating at 200 kV. Elemental distributions were examined using a LINK-AN 10000 energy-dispersive X-ray spectrometer (EDS). Quantitative analyses of elemental concentrations for Fe, Al, Mn and Si were made with the aid of a ZAF-corrected program on the LINK system (where Z = backscatter coefficient; A = absorption coefficient; F = fluorescence coefficient).

Results and Discussion

Figure 1(a) shows an optical micrograph of the as-quenched alloy A, revealing austenite grains with annealing twins. Figure 1(b), a selected-area diffraction pattern (SADP), clearly exhibits that only the austenite reflection spots could be observed and no spots of the precipitates could be detected. This result is consistent with that observed by other workers in the austenitic Fe-Al-Mn-C alloys[1-13]. However, along with the addition of 0.5 wt pct Si in the Fe-9Al-30Mn-1.2C alloy, a high density of extremely fine precipitates could be found within the austenite matrix. A typical example is shown in



1(a)



1(b)

Figure 1. (a) An optical micrograph, (b) a SADP taken from the austenite matrix of the as-quenched alloy A.

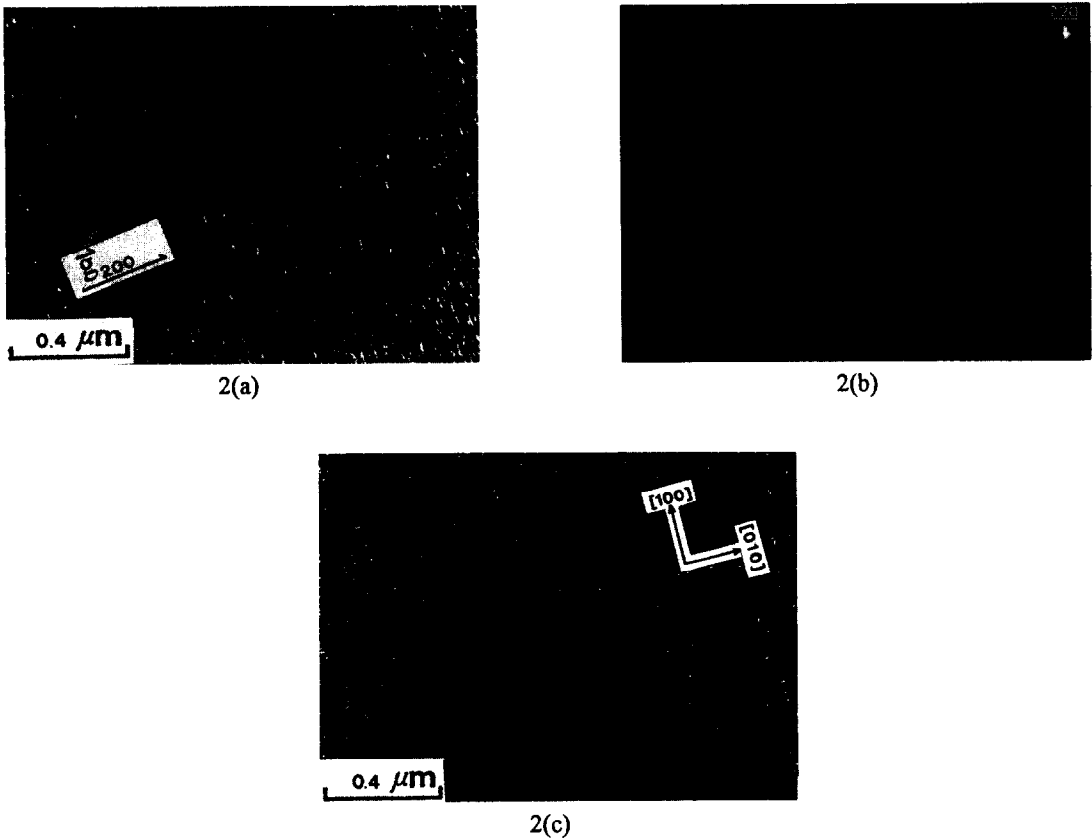


Figure 2. Electron micrographs of the as-quenched alloy B. (a) BF taken with the reflecting vector $\bar{g} = 200$ in $[001]$ zone, and (b) a SADP taken from an area covering the $L'1_2$ precipitates and their surrounding austenite matrix. The foil normal is $[001]$ (hkl = austenite; hkl = $L'1_2$ precipitate) (c) a 100 DF of the $L'1_2$ precipitates.

Figure 2. Figure 2(a) is a bright-field (BF) electron micrograph of the as-quenched alloy B, revealing a structural modulation within the austenite matrix. Figure 2(b), a SADP, indicates that in addition to the reflection spots corresponding to the austenite phase, the diffraction pattern also consists of small superlattice spots of 100, 110, 120, etc. From these superlattice spots and the fact that the superlattice 100 and 120 spots are much stronger than the 110 spots, it is deduced that the extremely fine precipitates have an ordered $L'1_2$ -type structure[23-25]. In Figure 2(b), it is also seen that satellites lying along $\langle 100 \rangle$ reciprocal lattice directions about the (200) and (220) reflections could be observed. The existence of the satellites indicates that the extremely fine $L'1_2$ precipitates may be produced during quenching by spinodal decomposition[8]. Figure 2(c), a dark-field (DF) electron micrograph, clearly reveals the presence of the $L'1_2$ precipitates. This result is quite different from that observed by other workers in the Fe-Al-Mn-C alloy[4-13]. In their studies, the $L'1_2$ precipitates could only be found in the aged alloys. Figures 3(a) and (b) are a SADP and a DF electron micrographs of the as-quenched alloy C (1.0 wt pct Si), clearly exhibiting that the intensity of the superlattice spots becomes more pronounced and the amount of the $L'1_2$ precipitates increases with increasing Si content. Both optical micrography and transmission electron micrography examinations indicated that the as-quenched microstructures of the Fe-9Al-30Mn-1.2C-xSi alloys with $0 \leq x \leq 1$ were essentially austenite phase

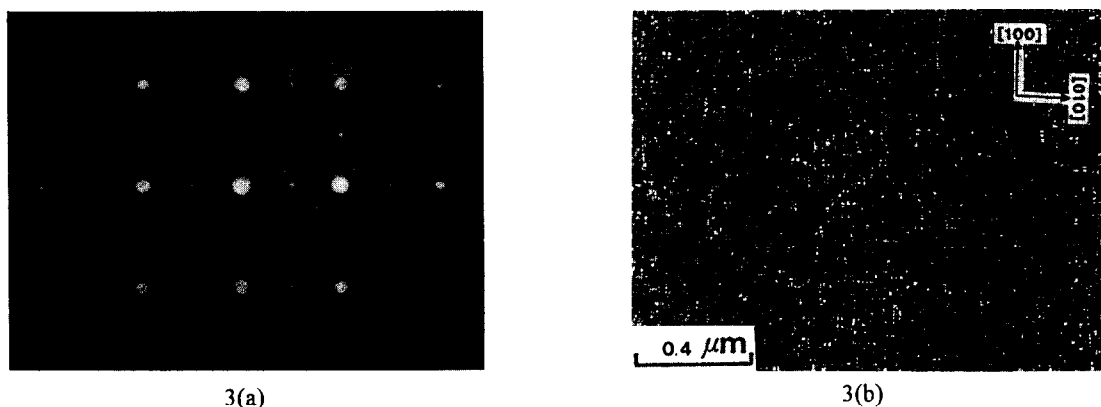
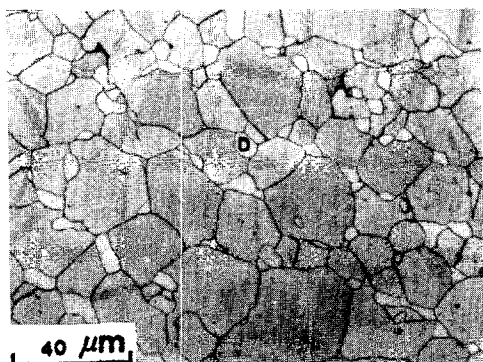


Figure 3. Electron micrographs of the as-quenched alloy C. (a) a SADP taken from a mixed region covering the austenite matrix and $L'1_2$ precipitates. The foil normal is $[001]$ (hkl = austenite; hkl = $L'1_2$ precipitate), and (b) a 100 DF of the $L'1_2$ precipitates.

with or without $L'1_2$ precipitates within the austenite matrix. However, when the Si content was increased to 1.5 wt pct, some discrete grains started to appear along the austenite grain boundaries and twin boundaries; besides, the austenite phase containing fine $L'1_2$ precipitates. A typical microstructure is shown in Figure 4. Figure 4(a) is an optical micrograph of the as-quenched alloy D. Figures 4(b) and (c) are two SADPs taken from an area which corresponds to a discrete grain (i.e., marked as "D" in Figure 4(a)), exhibiting the superlattice reflection spots of the ordered $D0_3$ phase. However, the $D0_3$ reciprocal lattice contains all the B2 and disordered α reflections[26]. Therefore, in order to examine whether the B2 or disordered α phase coexists with the $D0_3$ phase, DF electron microscopy was performed using different superlattice reflections. Figure 4(d), $1\bar{1}1$ DF, clearly reveals the presence of the $D0_3$ domains. Figure 4(e), 200 DF taken from the same area as Figure 4(d), shows that a high density of disordered α phase (dark contrast) could be observed within the domains. This indicates that in the as-quenched condition, the microstructure of the discrete grain is a mixture of (α + $D0_3$) phases. The amount of the (α + $D0_3$) phases increases with increasing the Si content, as demonstrated in Figure 5.

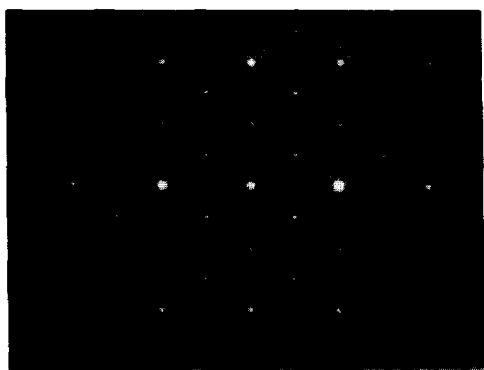
Based on the above observations, two important experimental results are discussed below: (I) That along with the addition of Si in the Fe-9Al-30Mn-1.2C alloy fine $L'1_2$ precipitates could be formed within the austenite matrix during quenching is a remarkable feature in the present study. This result is different from that observed by other workers in the austenitic Fe-(8-11) wt pct Al-(28-35) wt pct Mn-(0.8-1.3) wt pct C alloys, in which they found that the as-quenched microstructures were single-phase austenite, and $L'1_2$ precipitates could only be observed in the aged alloys. Besides the addition of Si, the chemical composition of the present alloy is similar to that examined by other workers. It seems to imply that the addition of silicon in the Fe-Al-Mn-C alloy may favor the formation of fine $L'1_2$ precipitates within the austenite matrix during quenching. However, the reason why the silicon addition could lead this result is unclear. (II) A second important feature of the present study is that the $D0_3$ phase could be observed in the Fe-9Al-30Mn-1.2C-xSi alloys with $x = 1.5$ or 2.0. This result is contrary to that reported by other workers in the Fe-Al-Mn-C-Si alloys, in which they claimed that the Si addition in the Fe-Al-Mn-C alloys appeared to enhance the formation of α or B2 phases[19-21]. The following two reasons may account for the apparent discrepancy. (1) In their studies, the α or B2 phase had been determined principally by either optical microscopy or scanning electron microscopy. No transmission electron microscopy micrographs had been provided in their literatures. (2) Figures 6(a)



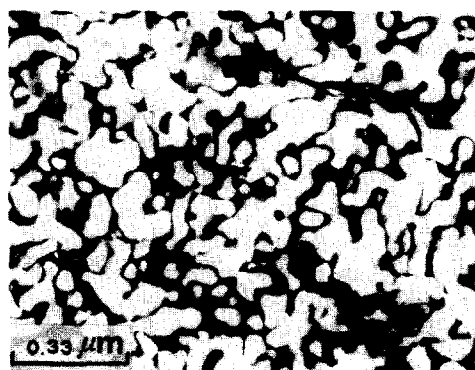
4(a)



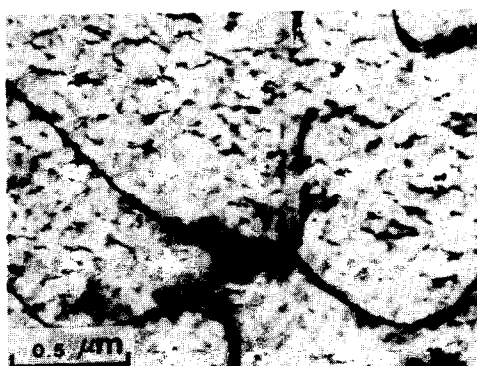
4(b)



4(c)



4(d)



4 (e)

Figure 4. (a) An optical micrograph, (b)-(e) electron micrographs of the as-quenched alloy D. (b)-(c) two SADPs taken from an area of a discrete grain (i.e., marked as "D" in Fig. 4(a)) (hkl = ferrite; hkl = $D0_3$ phase), (d) $1\bar{1}1$ and (e) $200 D0_3$ DF images, respectively.



Figure 5. An optical micrograph of the as-quenched alloy E.

and (b) represent two typical EDS spectra taken from austenite and ($\alpha + D0_3$) region in the as-quenched alloy D, respectively, where the iron, aluminum, manganese and silicon peaks were examined by conventional EDS analysis. The average atomic percentages of alloying elements examined by analyzing at least 10 different EDS spectra of each region are listed in Table 2. It is seen in Figure 6 and Table 2 that the silicon concentration in the ($\alpha + D0_3$) region is higher than that in the austenite matrix. Furthermore, it is well-known that the silicon addition in Fe-Al and Fe-Al-Mn alloys could pronouncedly enhance the formation of the $D0_3$ phase[27-29]. Therefore, it is reasonable to believe that a significant amount of silicon addition in the Fe-Al-Mn-C alloy should be favorable for the formation of the $D0_3$ phase instead of the α or B2 phase reported by other workers.

Finally, it is worthwhile to note that in a previous study, we have shown that the as-quenched microstructure of the Fe-8Al-29Mn-0.9C-1.5Si alloy was a mixture of austenite and ($\alpha + D0_3$) phases; no precipitates could be observed within the austenite matrix in the as-quenched alloy[22]. By comparing

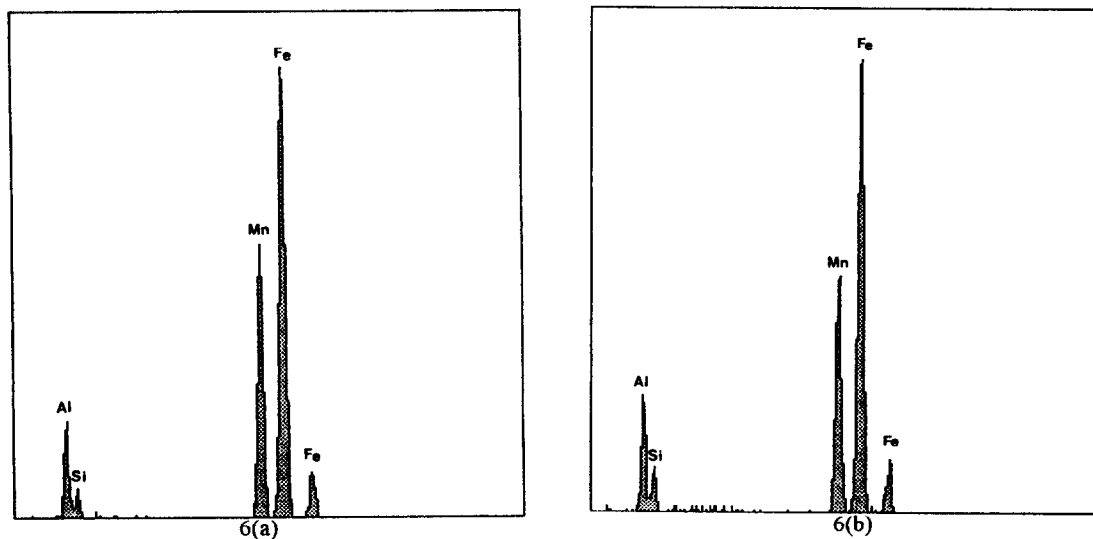


Figure 6. Two typical EDS spectra obtained from (a) an austenite grain, and (b) a ($\alpha + D0_3$) region in the as-quenched alloy D.

TABLE 2
Chemical Compositions of the Phases Presented in the As-Quenched Alloy D

Phase	Chemical Composition (wt pct)			
	Fe	Al	Mn	Si
austenite	58.88	8.50	31.20	1.42
($\alpha + \text{D}_0_3$)	58.70	9.40	28.70	3.20

the previous study and the present work, it seems to imply that the amount of both carbon and silicon contents may play an important role in the formation of the $L'1_2$ precipitates within the austenite matrix during quenching.

In summary, the as-quenched microstructure of the Fe-9Al-30Mn-1.2C alloy was single-phase austenite. Along with the addition of Si in the alloy, fine $L'1_2$ precipitates could be formed within the austenite matrix during quenching. In addition, when the silicon content was more than 1.5 wt pct, the ($\alpha + \text{D}_0_3$) phases could be detected in the as-quenched Fe-9Al-30Mn-1.2C-xSi alloys.

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