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Effect of Aging and Cold Rolling on the Microstructure and Mechanical Properties of a New Fe-Mn-Al-Cr-C Duplex Alloy

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The microstructural changes that occur during aging and cold rolling of a new Fe-Mn-Al-Cr-C duplex alloy have been investigated. Two treatments were developed to produce either a good combination of tensile strength and ductility (σ_u = 800 MPa, σ_y = 525 MPa, and A = 46%) or a high strength (σ_u = 1340 MPa, σ_y = 1200 MPa, and A = 15%) with a ductile type of fracture after aging at 320 °C. Aging between 550 °C and 700 °C led to a significant decrease in strength and ductility due to the precipitation of the brittle βMn phase. However, aging above 750 °C showed a considerable increase in strength and ductility due to the precipitation of very fine grains of ferrite within the austenite phase.

Keywords aging, cold rolling, duplex alloy, stainless steel

1. Introduction

Fe-Mn-Al alloys are developed as a possible substitute for Cr-Ni stainless steel[1–3] because of their low cost, light weight, and high strength. In the chemical design of the new Fe-Mn-Al-Cr-C duplex alloy, three major considerations were taken into account: partial substitution of Cr by Al and Si; substitution of Ni by Mn; elevated temperature strength; and microstructural stabilization. In order to increase the elevated temperature strength and thermally stabilize the austenite, small additions of Mo and B were added. In the Fe-28% Mn-7% Al system, the duplex microstructure can be developed by lowering the carbon content to less than about 0.4 wt.%.

The age hardening in Fe-Mn-Al-C austenitic alloys occurs in the course of continious precipitation of $(FeMn)_3$ AlC carbide[4] from the supersaturated austenite matrix. $(FeMn)_3$ AlC carbides were found to precipitate not only within the austenite matrix, but also on the grain boundaries in the form of coarser particles at aging temperatures varying from 450 to 650 °C. Besides the precipitation of $(FeMn)_3$ AlC carbides, β_{Mn} precipitates could also be observed to form on the grain boundaries through $\gamma \rightarrow \alpha + \beta_{Mn}$ reactions.[4] The β_{Mn} phases exist in the Fe-Mn-Al system[5] at high concentrations of Mn. In the Fe-Mn-Al-Cr alloy[6] aged at 560 °C, a large amount of β_{Mn} precipitates having a Widmanstätten morphology were formed within the ferrite phase.

In this present study, the effect of aging and cold rolling on the microstructure and mechanical properties of a new Fe-Mn-Al-Cr-C duplex alloy have been investigated.

2. Experimental Procedures

The chemical composition of the new Fe-Mn-Al-Cr-C duplex alloy in wt.% is as follows: Fe-28Mn-1.22Ni-7Al-1.2Si-5Cr-0.5V-0.4C-0.01N-0.1Mo-0.006B. The heat was melted, cast, homogenized, and hot rolled to 5 mm thickness; then, it was solution treated at 1150 °C and water quenched. The as-quenched plates were aged at temperature ranging from 320 to 920 °C (treatment A), cold rolled up to 75% deformation at room temperature, and then aged at temperature ranging from 320 to 920 °C (treatment B). The samples for LM observations were ground and polished and then etched in 2% nital. Mechanical properties were measured using a Vickers diamond pyramid hardness tester and an MTS mechanical testing machine. The yield strength σ_y, tensile strength σ_u, and elongation at fracture A were measured at room temperature and at 320 °C. Information on the precipitates formed during aging were obtained by x-ray diffraction analysis using Cu K_α radiation.

3. Results and Discussion

3.1 Treatment A: Solution Treatment/Water Quench/Aging

The microstructure of the new Fe-Mn-Al-Cr-C duplex alloy after casting and thermomechanical processing, solution treating at 1150 °C for 30 min, and water quenching is composed of two phases: the austenite and the ferrite (Fig. 1a). The degree of supersaturation developed in the ferrite phase by water quenching from 1150 °C was quite high. Thus, aging in the low-temperature range resulted in strengthening, mainly of the ferrite phase α, by the precipitation of fine $(FeMn)_3$AlC carbides.

Figure 1(b) to (f) present the effect of the aging temperature on the microstructure of the solution-treated specimens. The sequence of micrographs show the following. 1(b) (520 °C, t = 100 h), fine precipitation within the ferrite phase. 1(c) (620, t = 4 h), well-developed precipitates within the ferrite phase and the precipitation of β_{Mn} phase at the α/α grain boundary having a typical Widmanstätten morphology. Since β_{Mn} precipitation significantly denudes the matrix of Mn, there is simultaneous rearrangement of the austenite lattice to ferrite. Low energy α/α grain boundaries are beginning to predominate at 620 °C instead of oriented curved high-energy grain boundaries. The

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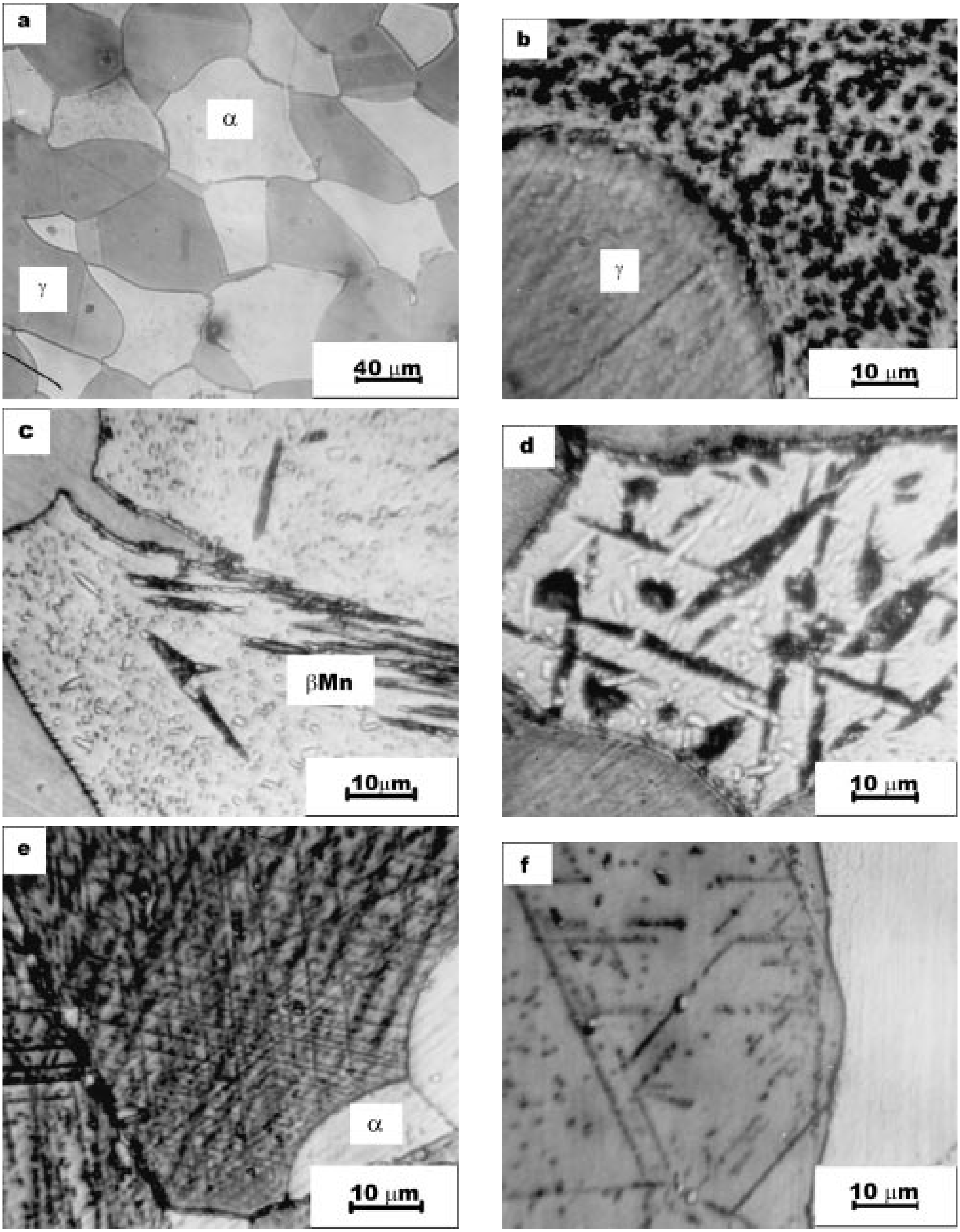

Fig. 1 Effect of aging temperature and time on the microstructure of treatment A: (**a**) solution treatment, (**b**) aging at 520 °C (100 h), (**c**) aging at 620 °C (4 h), (**d**) aging at 620 °C (100 h), (**e**) aging at 820 °C (24 h), and (**f**) aging at 920 °C (24 h)

Table 1 Phase transformation of the Fe-Mn-Al-Cr-C duplex alloy

Aging T (°C)	Phase transformation		Observation
500 °C	Treatment A	$\alpha \rightarrow \alpha + (FeMn)_3AlC$	Within the α phase No precipitation within the γ phase
	Treatment B	$\alpha \rightarrow \alpha + (FeMn)AlC$	Within the α phase No precipitation within the γ phase
600 °C	Treatment A	$\gamma \rightarrow \alpha + \beta_{Mn}$	At the α/α interfaces β_{Mn}: Widmanstätten morphology At the α/γ interfaces
		$\gamma \rightarrow \beta_{Mn} + \alpha$	β_{Mn}: blocky morphology
	Treatment B	β_{Mn} precipitation	
800 °C	Treatment A	$\gamma \rightarrow \gamma + MnC$	MnC: fibrous morphology Absence of β_{Mn}
	Treatment B	$\gamma \rightarrow \gamma + \alpha_{II}$	Fine α_{II} grains within γ phase Absence of β_{Mn}

result of this trend is the development of a well-defined lath-shaped βMn phase through the $\gamma \rightarrow \alpha + \beta$Mn reactions. 1(d) (620 °C, $t = 100$ h) coarsening of the precipitates within the ferrite phase and precipitation of beta-Mn phase at the ferrite/austenite interface. 1(e) (820 °C, $t = 24$ h) beginning of fibrous Mn carbides precipitation within the austenite phase through a $\gamma \rightarrow \alpha +$ MnC reactions. The precipitation of fine fibrous Mn carbides within the austenite phase is due to the high mobility and high solubility of Mn within the austenite phase at elevated temperature. 1(f) (920 °C, $t = 24$ h) dissolution of precipitates within the ferrite phase.

The metallographic data presented in Fig. 1 and x-ray diffraction analysis data of overaged conditions are consistent with the existence of the following precipitates: $(FeMn)_3AlC$ and β_{Mn}. The different phase transformations that occurred during aging of the Fe-Mn-Al-Cr-C duplex alloy are summarized in Table 1. The sharp decrease in ductility observed between 550 and 650 °C (Fig. 2) appears to be associated with the precipitation of the very brittle β_{Mn} phase at the α/α and the α/γ interfaces. A good combination of strength and ductility at room temperature was achieved after aging up to 24 h at 320 and 820 °C. This is attributed to the duplex structures with very strong bonding between the austenite and the ferrite phases and to the absence of the βMn phase at 320 and 820 °C. The tensile properties obtained at 320 °C ($\sigma_u = 630$ MPa, $\sigma_y = 350$ MPa, and $A = 50\%$) indicate that the Fe-Mn-Al-Cr-C duplex alloy has a high thermal stability at 320 °C.

3.2 Treatment B: Solution Treatment/Water Quench/Cold Roll/Aging

The microstructure of the Fe-Mn-Al-Cr-C duplex alloy cold rolled at room temperature is shown in Fig. 3(a). It was observed that, at this deformation temperature (room temperature), the austenite deformed by the formation of deformation twins. This was possible for the following reasons: first, Mn lowered considerably the stacking fault energy[7] of the Fe-Mn-Al-Cr-C duplex alloy; and, second, the calculated M_d temperature was below room temperature. Figure 3(b) to (f) present the effect of the aging temperature on the microstructures of the cold-rolled Fe-Mn-Al-Cr duplex alloy, showing the following: 3(b) (420 °C, $t = 100$ h) very fine precipitation within the ferrite phase; 3(c) (520 °C, $t = 100$ h) significant homogeneous and

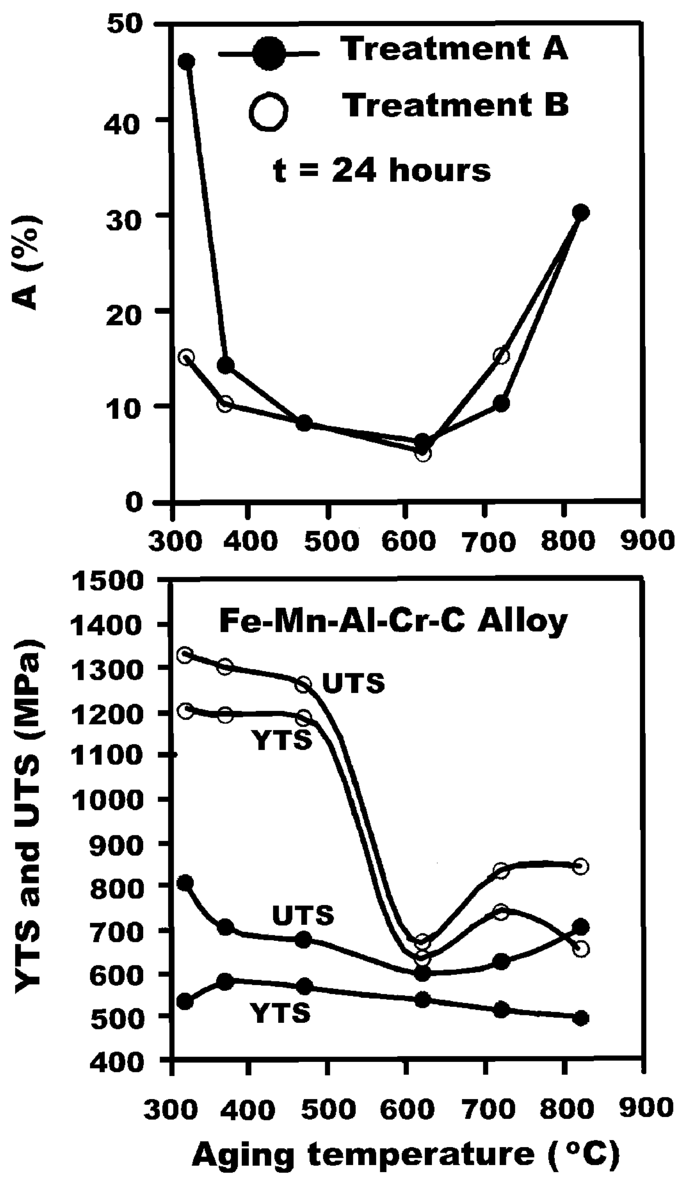

Fig. 2 Effect of prior aging temperature on the room-temperature mechanical properties

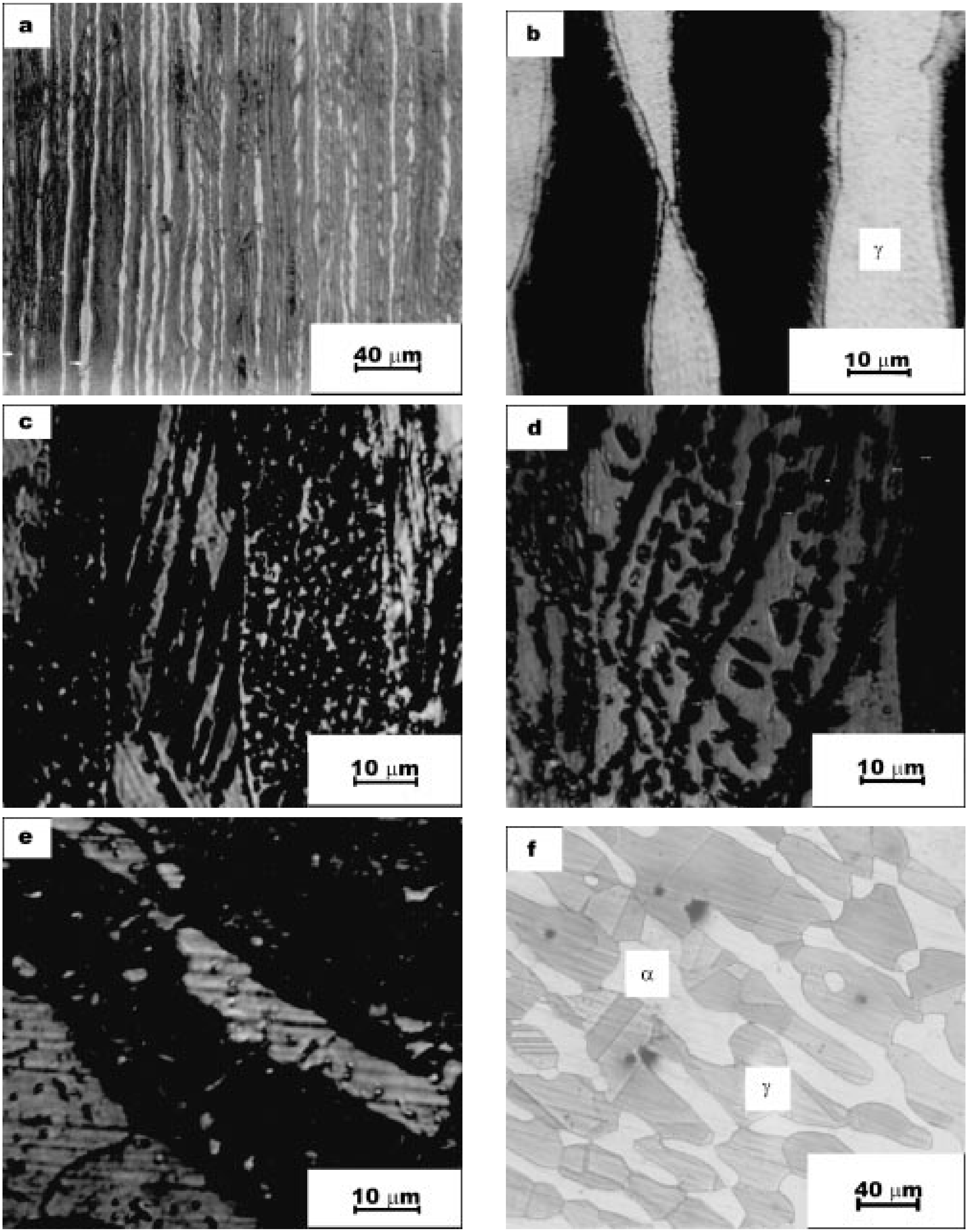

Fig. 3 Effect of aging temperature and time on the microstructure of treatment B: (**a**) cold rolled, (**b**) aging at 420 °C (100 h), (**c**) aging at 520 °C (100 h), (**d**) aging at 620 °C (24 h), (**e**) aging at 820 °C (24 h), and (**f**) aging at 950 °C (24 h)

heterogeneous precipitation in the deformation twins within the austenite phase and in slip bands within the ferrite phase; 3(d) (620 °C, $t = 24$ h) coarsening of precipitates in ferrite and at grain boundaries; and 3(e) (820 °C, $t = 24$ h) precipitation of secondary ferrite within the austenite phase. The sharp decrease in strength and ductility observed at 620 °C of the cold-rolled and aged duplex alloy (Fig. 2) is attributed to the formation of the brittle β_{Mn} phase at the α/γ interfaces. The introduction of deformation before aging did not change the second stage of decomposition (precipitation of β_{Mn}), and the lowest tensile properties were observed around the aging temperature of 600 °C for treatments A and B (Fig. 2).

Aging the cold-rolled Fe-Mn-Al-Cr-C duplex alloy at 850 °C for 30 min led to the formation of a secondary ferrite within the austenite phase through a $\gamma \rightarrow (\alpha_{II} + \gamma)$ reaction (Fig. 3e). This secondary ferrite has a different composition than the ferrite of the duplex structure due to the nature of its formation. The transformation of thermomechanically processed austenite to ferrite is very complex and is determined by the composition of the austenite and its stability to plastic deformation and temperature, the morphology of the austenite after deformation (laminated microstructure as shown in Fig. 3a), which will control the ferrite nucleation rate through grain boundaries and deformation twins. Aging the deformed specimen above 950 °C led to a complete recrystallization of the deformed microstructure, as shown in Fig. 3(f). An extraordinary increase simultaneously in ductility and strength was observed at temperature above 750 °C (Fig. 2). This is explained by the precipitation of very fine secondary ferrite within the austenite phase and the absence of β_{Mn} phase. The addition of B and Mo to the Fe-Mn-Al system has enhanced the microstructural stability and strengthened the ferrite/ferrite and the ferrite/austenite interfaces at temperature above 750 °C.

4. Conclusions

The effects of aging and cold rolling on the microstructure and the mechanical properties of the Fe-Mn-Al-Cr-C duplex alloy have been investigated. The mains conclusions are as follows.

Treatment A: solution treatment/water quench/cold roll/age:

- Good combination of strength and ductility was obtained at room temperature after aging at 320 °C ($\sigma_u = 800$ MPa, $\sigma_y = 525$ MPa, and $A = 46\%$) and 820 °C ($\sigma_u = 700$ MPa, $\sigma_y = 490$ MPa, and $A = 30\%$).
- Aging between between 550 and 700 °C led to a significant decrease in ductility and strength due to the precipitation of the brittle β_{Mn} phase at the interfaces. Aging in the temperature range 700 to 900 °C resulted in the precipitation of fine fibrous Mn carbide within the austenite phase.
- No β_{Mn} phase was observed to occur on aging at 820 °C up to an aging time of 100 h. The Fe-Mn-Al-Cr-C duplex alloy has the potential to be used safely at 320 and 820 °C.

Treatment B: Solution treatment/water quench/cold roll/age:

- Aging at 320 °C led to a very high strength at room temperature with a ductile type of fracture ($\sigma_u = 1340$ MPa, $\sigma_y = 1200$ MPa, and $A = 15\%$).
- Decrease in tensile properties was observed between 550 and 700 °C due to the β_{Mn} phase.
- Aging the cold-rolled microstructure at 820 °C resulted in an increase in tensile properties at room temperature ($\sigma_u = 840$ MPa, $\sigma_y = 640$ MPa, and $A = 30\%$). This increase in the tensile properties is attributed to the microstructural stability of the duplex alloy, the abscence of any brittle phases at the interfaces, and the precipitation of the secondary ferrite within the austenite phase.

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