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The effects of chromium addition and heat treatment on the microstructure and tensile properties of Fe-24Al (at.%)

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Abstract

Fe-24Al (at.%) base alloys containing 0-6 at.% Cr were elaborated by melting and casting under argon atmosphere. The ingots obtained were initially homogenized at 1000 °C for 5 h in air, then hot rolled at temperatures in the range 1000-800 °C. The hot rolled strips obtained were submitted to two heat treatments: 800 °C for 1 h, and 800 °C for 1 h plus 500 °C for 9 days. Tensile test specimens were machined from the hot rolled and heat treated strips. Samples for transmission electron microscopy and X-ray diffraction were taken from the as-rolled and annealed material for microstructural characterization. The best combination of ductility and yield strength is obtained for the alloy Fe-24Al-2Cr (at.%) heat treated at 800 °C for 1 h. The material heat treated at 800 °C for 1 h presents a partially recrystallized microstructure containing the α (disordered) and B2 (ordered FeAl) phases. The additional heat treatment at 500 °C for 9 days leads to a microstructure containing both α and DO_3 (ordered Fe_3Al) phases with degradation of the mechanical properties.

Keywords: Chromium; Iron; Aluminium; Heat treatment; Tensile properties; Microstructure

1. Introduction

Iron aluminides based on Fe_3Al are ordered intermetallic alloys that offer excellent oxidation resistance, good sulfidation resistance, high mechanical strength and lower materials cost than many conventional alloys, making them candidates for structural applications in corrosive environments up to temperatures of 600 °C [1,2]. However, the low ductility at ambient temperature and the sharp decrease in mechanical strength above 600 °C impose severe restrictions for the practical use of these aluminides. These limitations have motivated most of the recent investigations on Fe_3Al based alloys to focus on improving the ductility [3-11].

McKamey and coworkers [5-8] investigated the effects of composition of Fe_3Al based alloys on the yield strength and elongation to fracture measured in tensile tests performed at room temperature. These authors observed increased alloy ductility from 1% to 5% with a decrease in the yield strength from 800 to 350 MPa when the amount of Al was increased from 24 to 30 at.%. They also verified that the ductility of the Fe-28Al (at.%) alloy can be significantly improved by the addition of up to 6 at.% chromium, with a slight decrease in the yield strength [12,13].

The lower aluminum content Fe-24Al (at.%) alloy is known to exhibit good corrosion resistance and higher mechanical strength than Fe-28Al (at.%) and it seems reasonable also to look for ductility improvements for this composition. In this investigation we evaluated the room temperature tensile properties of the binary alloy Fe-24Al (at.%) and ternary alloys Fe-24Al-2Cr, Fe-24Al-4Cr and Fe-24Al-6Cr (at.%) after various heat treatments. The results indicate that the ductility of these alloys can be greatly improved by chromium additions and heat treatments without any drastic variation in the mechanical strength.

2. Experimental details

Binary Fe-24Al and ternary Fe-24Al-(2-6)Cr (at.%) alloys were prepared by melting in an electric resistance furnace followed by casting under argon atmosphere, using commercially pure aluminum and iron. The alloy ingots were initially homogenized at 1000 °C for 5 h in air then hot rolled at 1000-800 °C

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to 0.8 mm thick sheet (condition I). Tensile test specimens with gage dimension $31.0 \times 6.0 \times 0.8$ mm^3 were machined using a Tensilgrind apparatus, and heat treated under two different conditions: condition II, 1 h at 800 °C in air followed by water quenching; condition III, 1 h at 800 °C and 9 days at 500 °C in air, followed by water quenching. The alloy Fe-24Al-2Cr (at.%) was also heat treated for 1 h at temperatures in the range 750-900 °C with various cooling media; water, oil and iced brine solution.

All these heat treatments resulted in partially or fully recrystallized microstructure depending on the temperature and alloy composition utilized. Tensile tests were performed on a universal mechanical testing machine in air using a strain rate of 10^{-4} s^{-1}. A minimum of two specimens were tensile tested for each heat treatment condition. Transmission electron microscopy (TEM) and X-ray diffraction (XRD) were used to characterize the microstructure of the as-worked and heat-treated specimens. The fracture surface of tensile tested specimens was analyzed in a scanning electron microscope (SEM).

3. Results

Table 1 shows the tensile test results for the alloys Fe-24Al, Fe-24Al-2Cr, Fe-24Al-4Cr and Fe-24Al-6Cr in the as-rolled and two heat treatment conditions investigated. The best compromise of strength and ductility was obtained for the alloy Fe-24Al-2Cr hot rolled and heat treated at 800 °C for 1 h. For this particular composition the 1 h heat treatment temperature was then varied from 750 to 900 °C, water quenching the samples, and its effects on the mechanical properties were investigated. The variations in the elongation to fracture and 0.2% yield stress as a function of heat treatment temperature are shown in Figs. 1 and 2 respectively.

Fig. 1 shows that the highest ductility is obtained in this alloy for the 1 h at 800 °C heat treatment. Fig. 2 shows that the yield strength is reduced from 840 MPa in the as-rolled condition, to values between 658 and 616 MPa when the heat treatment temperature is increased from 750 to 900 °C.

In a series of experiments the effect of the cooling rate at the end of the heat treatment was tested for the alloy Fe-24Al-2Cr using water, oil and iced brine solution cooling media. The results obtained, $\sigma_y = 658$

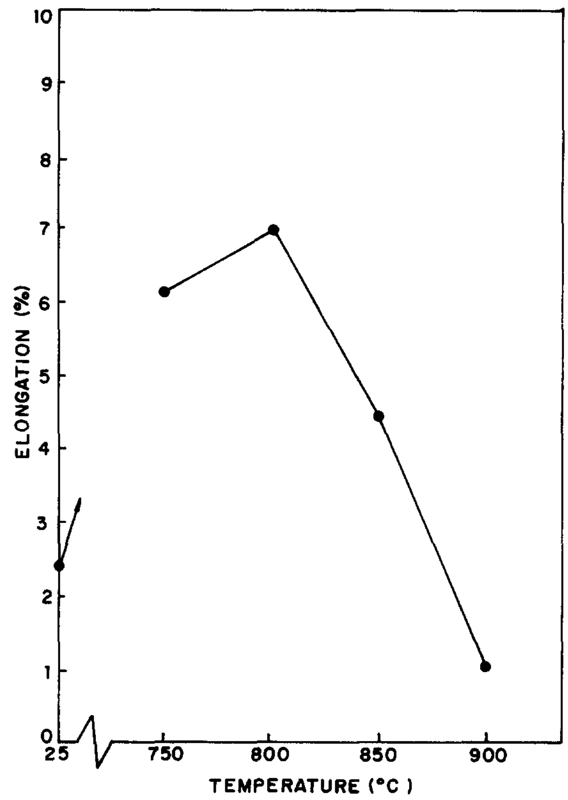

Fig. 1. Room temperature elongation vs. heat treatment temperature (1 h) for the Fe-24Al-2Cr (at.%) alloy.

Table 1
Effect of heat treatment on tensile properties of Fe-24Al and Fe-24Al-(2-6)Cr (at.%) tested in air at room temperature

Heat Treatment Condition	Fe-24Al		Fe-24Al-2Cr		Fe-24Al-4Cr		Fe-24Al-6Cr	
	Elongation (%)	Yield (MPa)	Elongation (%)	Yield (MPa)	Elongation (%)	Yield (MPa)	Elongation (%)	Yield (MPa)
I, Hot rolled, 800-1000 °C	2.4	832	2.4	840	1.6	853	1.1	945
II, Hot rolled + 800 °C 1 h, WQ	6.2	646	7.0	641	3.3	525	5.2	550
III, hot rolled + 800 °C, 1 h + 500 °C 9 d, WQ	3.8	386	4.6	368	2.2	302	0.8	304

WQ, water quenched.

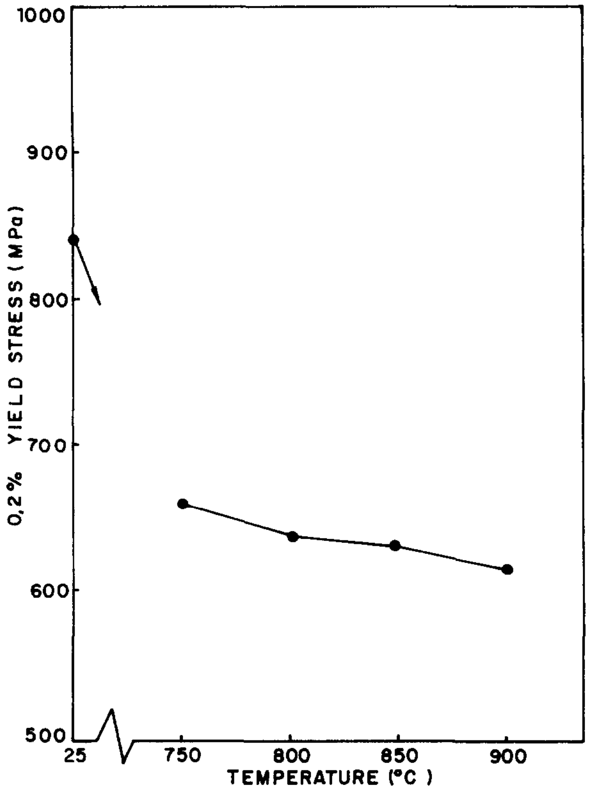

Fig. 2. Room temperature yield stress vs. heat treatment temperature (1 h) for the Fe-24Al-2Cr (at.%) alloy.

MPa for oil, $\sigma_y = 641$ MPa for water, and $\sigma_y = 623$ MPa for iced brine solution, indicate that the yield strength is not strongly affected by the cooling rates used. However, the elongation values mesaured for the specimens quenched in water, oil and iced brine solution, $\varepsilon_f = 7.8\%$, $\varepsilon_f = 6.8\%$ and $\varepsilon_f = 9.0\%$ respectively, indicate slightly improved ductility when the cooling rate is increased.

XRD performed on heat treated samples showed that condition II leads to an α (disordered Fe-Al solid solution) plus B2 (ordered FeAl) structure, and condition III to α plus DO_3 (ordered Fe_3Al). The amounts of each phase were not determined since a certain degree of texture impairs the analysis. TEM analysis revealed, for specimens heat treated according to condition II, the presence of a partially recrystallized microstructure containing grains and subgrains of α and B2 phases, as well as disordered regions with a high dislocation density. This is illusrated in Fig. 3 for the Fe-24Al composition. The additional heat treatment associated with condition III does not alter appreciably the initial partially recrystallized situation and the microstructure of these specimens is composed of DO_3 ordered areas in a continuous α matrix, as illustrated in Fig. 4 for Fe-24Al-2Cr.

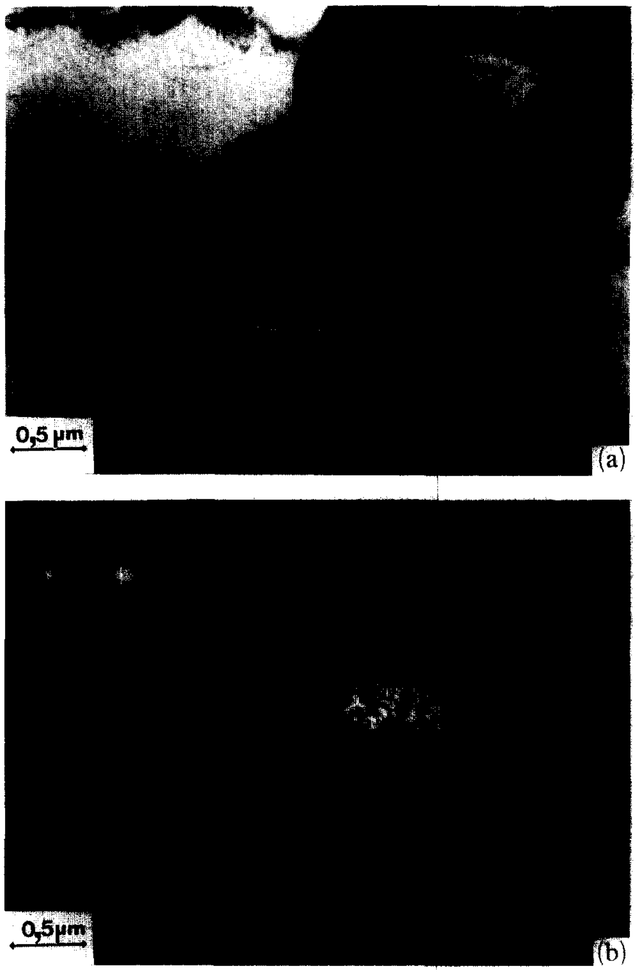

Fig. 3. TEM imges of Fe-24Al (at.%) alloy heat treated at 800 °C for 1 h and water quenched; (a) bright field, (b) (100) B2, dark field.

The SEM fractograph in Fig. 5 shows the typical morphology of the fracture surface of tensile tested specimens. In general, the fracture mode in all alloy compositions is transgranular cleavage in nature for all heat treatment conditions investigated. In some specimens a mixed fracture mode was observed with small contribution (5%-10%) of intergranular failure. However, we could not find any correlation between the intergranular fracture mode contribution and the alloy composition or heat treatment conditions.

4. Discussion

Previous studies on Fe_3Al based aluminides [6,7] have shown that the room temperature ductility of these alloys decreases to values close to 1% when the aluminum content is reduced to 24 at.%. An explanation for this behavior, though not proposed before,

Fig. 4. TEM images of Fe–24Al–2Cr (at.%) alloy heat treated at 800 °C for 1 h and at 500 °C for 9 days and water quenched: (a) bright field, (b) (111) DO_3, dark field.

cannot be in principle related solely to hydrogen environmental embrittlement [14,15] since less aluminum is available in this particular alloy composition to participate in the reaction $2Al + 3H_2 \rightarrow Al_2O_3^+ + 6e^-$. Our results for Fe–24Al show that it is possible to increase the elongation to fracture in tensile tests to values of the order of 8%, keeping the yield strength level around 650 MPa, by an appropriate choice of chromium addition and heat treatment.

An explanation for this improved ductility with high mechanical strength in Fe–24Al alloy would probably be related to the amount of disordered phase (α phase) present in the alloy after heat treatment at 800 °C for 1 h. The slight increase in ductility after quenching in iced brine solution favors this idea since more drastic cooling would retain a higher amount of α phase at room temperature. However, the effects of grain size, texture, and the amount of chromium on the ductility cannot be excluded.

The 500 °C annealing for 9 days led to general degradation of the mechanical properties of Fe–24Al based alloys. The microstructure after this heat treatment is characterized by the presence of the DO_3 and α (disordered solid solution) phases as revealed by XRD and TEM.

Fig. 5. SEM fractograph of Fe–24Al–2Cr (at.%) (condition I).

The investigations of McKamey and coworkers showed that the best ductility in Fe–28Al (at.%) containing chromium was obtained after warm rolling (approximately 600 °C) which introduced a partially recrystallized structure. In this study, improved ductility of Fe–24Al was reached by hot rolling (800–1000 °C) followed by a heat treatment at 800 °C for 1 h which leads to a partially recrystallized microstructure containing the $\alpha + B2$ phases. The results showed that by controlling the amount of recrystallization, by cold working and heat treatment, it is possible to improve the mechanical properties of Fe_3Al aluminides.

5. Conclusion

The present investigation clearly shows that it is possible to obtain improved ductility in Fe–24%Al alloys through the addition of up to 2 at.% chromium and the choice of appropriate heat treatment. The reason for this ductility enhancement is not, at present, completely clear, but there are some indications that this aspect could be related to the presence of some amount of disordered phase. Studies are under way to elucidate this point.

Acknowledgments

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