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LOW-ALUMINUM-CONTENT IRON-ALUMINUM ALLOYS*

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ABSTRACT

The low room-temperature ductility of Fe₃Al-based alloys is associated with their environmental embrittlement. Reducing the aluminum level from 28 to 16 at. % has been found to be an effective method in essentially eliminating the environmental-embrittlement effect and increasing the room-temperature ductility value to over 25%. This paper will present data on alloy compositions, melting, casting and processing methods, and mechanical properties. Plans for future work on these alloys will also be described.

INTRODUCTION

The Fe-Al alloys have been of great interest because of their excellent resistance to oxidizing, carburizing, and sulfidizing environments. A significant world wide effort¹ is under way in the development of Fe₃Al and FeAl-based alloys. A major deterrent to their commercial use has been their limited room-temperature ductility and high-temperature strength. It has now been well documented²⁻⁴ that the environmental effect associated with hydrogen embrittlement is the major cause of poor room-temperature ductility of ordered structures based on Fe₃Al and FeAl alloys. During the last year, it has been demonstrated^{5,6} that one method of reducing the environmental effect is to reduce the aluminum to get the Fe-Al alloy in the disordered structure phase field. The 16 at. % Al was found to be suitable to essentially eliminate the environmental effect. The purpose of this paper is to describe: (1) the alloy composition for engineering applications based on Fe-16 at. % Al, (2) the melting and processing of such alloys, (3) the mechanical properties, and (4) the applications.

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DISCUSSION OF CURRENT ACTIVITIES

Alloy Compositions

The Fe-16 at. % Al binary alloy was further modified for engineering applications. The chromium addition was made to improve aqueous corrosion resistance, molybdenum for pitting resistance, and zirconium and carbon for grain refinement. The final composition was designated as FAP (see Table 1). A modification of FAP with 0.06 at. % Y (designated as FAPY) was developed for additional oxidation resistance at high temperatures.

Table 1. Compositions of iron-aluminum alloys.

Element	Alloy (atomic percent)	
	FAP	FAPY
Al	16.12	16.12
Cr	5.44	5.44
Zr	0.11	0.11
C	0.13	0.13
Mo	1.07	1.07
Y	--	0.06
Fe	77.13	77.07

Melting and Processing

The FAP and FAPY alloys can be prepared by air-induction melting. The use of an argon cover significantly reduces any loss of elements such as aluminum and zirconium. The aluminum-containing-iron alloy can be susceptible to gas porosity, which can be minimized by: (1) using dry-melt charge and (2) purging molten metal with argon gas prior to pouring in the molds.

The FAP and FAPY alloys can be sand or investment cast into shapes. However, additional work is needed to identify the optimum pouring temperatures, mold temperatures, and cooling conditions.

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The ingots can be processed by a variety of processes including: (1) extrusion, (2) forging, (3) rolling, (4) swaging, and (5) drawing. The acceptable extrusion and forging temperatures are 1000 to 1100°C. The hot rolling at 800 and 650°C works extremely well. However, the alloys can also be cold-worked by swaging, rolling, and drawing with intermediate annealing treatments at 800°C. The heat treatment can be carried out in air, and the product can be air cooled. The processing techniques used in the laboratory still need to be tested in commercial production situations.

Mechanical Properties

From the 0.76-mm-thick sheet produced by a combination of hot forging (50%), hot rolling (30%), and warm or cold rolling (70%), 12.7-mm-gauge length tensile specimens were punched. These specimens were given a final anneal at 800°C for 1 h followed by air cooling prior to testing. Some specimens were also given treatments other than 800°C. The sand castings were tested by machining 6.35-mm-diam and 19.05-mm-gauge length threaded bars. Some specimens were tested in the as-cast condition and some after a treatment at 800°C for 1 h followed by air cooling. Most of the tensile tests were conducted at a strain rate of $3.33 \times 10^{-3} \text{ s}^{-1}$. In one study, tensile tests were conducted at room temperature over a strain rate range of 10^0 to $6 \times 10^{-7} \text{ s}^{-1}$. A limited number of creep and Charpy-impact tests were also conducted.

Cast Versus Wrought Properties

Tensile properties of alloy FAPY (see Fig. 1), cast by Cast Masters (Bowling Green, Ohio), were determined in the cast condition and after processing a part of it into the 0.76-mm-thick sheet. Data from the same heat in the two conditions are compared in Fig. 2. Comparing the as-cast versus the wrought materials, these figures show the classic behavior of lower strength properties in the coarse-grained cast condition at low temperature and higher strength properties above a certain temperature (typically, $0.5 T_m$ for body-centered cubic structures). The $0.5-T_m$ temperature for the FAPY alloy is 600°C, which is close to the cross-over temperature observed in Figs. 2(a) and (b).

The fine-grained structure in the wrought condition results in significantly higher ductility values at room temperature [see Figs. 2(c) and (d)]. The total elongation and reduction of area values in the wrought condition are 25 and 40% as opposed to 1.5 and

<1%, respectively, for the cast condition. The cast condition showed over 10% elongation and reduction of area values for test temperatures of $\geq 200^{\circ}\text{C}$. However, no significant change occurred for the wrought condition. The reasons for the much larger

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Fig. 1. A step block and a machine component of iron-aluminum alloy FAPY cast at Cast Masters (Bowling Green, Ohio). The alloy was air-induction melted with an argon cover.

difference in ductility of wrought and cast conditions at room temperature are not understood at present. The ductile-to-brittle transition temperature (DBTT) for the FAPY alloy is $\geq 150^{\circ}\text{C}$ in the wrought condition. For the cast condition, it would be even higher. Thus, at room temperature, the alloy is being tested in the brittle range. In addition to coarse grain size, any casting defects will significantly lower the ductility. However, when tested at or above 200°C , the alloy is in the ductile range and, thus, casting defects become less important. The coarser grain structure of the cast condition, as opposed to the wrought condition, results in its lower ductility.

Fig. 2. Comparison of tensile properties in cast and wrought conditions of alloy FAPY taken from the step casting shown in Fig. 1. The air-cooled wrought specimens and the slow-cooled cast specimens were annealed for 1 h at 800°C prior to testing: (a) 0.2% yield strength, (b) ultimate tensile strength, (c) total elongation, and (d) reduction of area.

Strain-Rate Effects

The sheet produced from the casting prepared by Cast Masters (see Fig. 1) was also used for determining the strain-rate effects on room-temperature properties. Data from these tests are shown in Figs. 3(a) and (b). Both yield and ultimate tensile strength curves follow the same trend. Except for the highest strain rate of 1 s^{-1} , the

Fig. 3. Tensile properties at room temperature as a function of strain rate for alloy FAPY in wrought condition. The specimens were annealed for 1 h at 800°C followed by air cooling prior to testing: (a) 0.2% yield and ultimate tensile strength and (b) total elongation and reduction of area.

strength values were essentially independent of strain rate. The ductility values, especially total elongation, remained $\geq 20\%$ over the entire strain-rate range used. The reduction of area values were over 30% for all strain rates except at the slowest strain rate of $6 \times 10^{-7} \text{ s}^{-1}$, where it became approximately 25%. The strain-rate effect, especially of decreasing ductility with lower strain rates, is typically associated with environmental effects.⁷ For example, the ordered alloy Fe_3Al (ref. 8) shows a large decrease in ductility with decreasing strain rate. The results in Fig. 3(b) show that the FAPY alloy is not sensitive to environmental effect as opposed to Fe_3Al -based alloys.

Alloying Element Effects

Efforts were made to further modify the base FAP composition for further improving either the room-temperature ductility or the high-temperature strength. Effects of two element additions are described below:

Titanium

A systematic addition of titanium to the base FAP composition was carried out to identify the solid-solution effects. Subsequently, the addition of titanium will be made

in conjunction with carbon and nitrogen. The effects of titanium addition of up to 1 wt % on room-temperature tensile properties are presented in Fig. 4, which shows that the addition of titanium increased the strength and resulted in a decrease in ductility. A 20% elongation could be retained with a substantially higher value of yield and ultimate tensile strength for an addition of 1 wt % Ti.

Fig. 4. Bar charts of room-temperature tensile properties as affected by titanium addition to FAP alloy. All of the specimens were annealed for 1 h at 800°C followed by air cooling prior to testing: (a) 0.2% yield strength, (b) ultimate tensile strength, (c) total elongation, and (d) reduction of area.

The 1 wt % Ti alloy was further tested up to 700°C for determining its usefulness in retaining high-temperature strength (see Fig. 5). Figure 5 shows that the strengthening effect of 1 wt % Ti addition to the FAP alloy is very significant up to 600°C and significant even at 700°C. A substantial increase in yield strength in the temperature range of 400 to 600°C for 1 wt % Ti alloy is unique and needs microstructural work for its understanding. The high-temperature ductility values of titanium-containing alloys were comparable to the FAP alloy. Microstructural work is

Fig. 5. Comparison of tensile properties of FAP and FAP with 1 wt % Ti as a function of test temperature. Specimens of both alloys were annealed for 1 h at 800°C followed by air cooling prior to testing: (a) 0.2% yield strength, (b) ultimate tensile strength, (c) total elongation, and (d) reduction of area.

needed to determine the cause of strength improvement by the titanium addition. However, the 1 wt % Ti-containing alloy will be further investigated in an attempt to improve the room-temperature cast ductility through precipitation of either titanium carbides or titanium nitrides.

Nitrogen

Nitrogen additions are often used to improve the strength of ferritic and austenitic steels. In a small study, the effects of 0.05 and 0.10 wt % addition of nitrogen to the base FAPY composition were examined. The results of this study are presented in Fig. 6, which shows that nitrogen additions alone of up to 0.1 wt % have minimal effect on room-temperature strength or ductility. However, nitrogen combined with titanium may produce interesting benefits in strength through the precipitation of titanium nitrides. Titanium-nitride precipitation during solidification may also produce beneficial grain-refining effects and improve room-temperature ductility of castings.

Applications

Several possible applications of the Fe-16 at. % Al-based alloys FAP and FAPY are given in Table 2. Efforts are under way to commercialize some of the applications through various technology transfer mechanisms.

SUMMARY AND CONCLUSIONS

The development of an alloy based on Fe-16 at. % Al was described. The Fe-16 at. % Al was used as a base because it was not sensitive to environmental effects, unlike Fe₃Al-based compositions. The Fe-16 at. % Al alloy containing 5 at. % Cr for aqueous corrosion resistance, 1 at. % Mo for pitting or crevice corrosion resistance, and zirconium and carbon additions for grain refinement was designated as FAP. The same composition with 0.1 at. % Y for high-temperature oxidation resistance was designated as FAPY. Both alloys were melted and processed into 0.76-mm-thick sheet for mechanical properties evaluation. The FAPY alloy was also tested in the as-cast condition. The effects of strain rate and the addition of nitrogen and titanium, on the tensile properties were also evaluated. The following conclusions are possible from the work to date:

Fig. 6. Bar charts showing the effect of nitrogen addition on the room-temperature tensile properties of the FAPY alloy. All of the alloys were annealed for 1 h at 800°C followed by air cooling prior to testing: (a) 0.2% yield strength, (b) ultimate tensile strength, (c) total elongation, and (d) reduction of area.

1. The Fe-16 at. % Al-based alloys FAP and FAPY yielded room-temperature ductility values of over 20% in the wrought condition. The ductility values were not affected by a broad variation of strain rates. This implies that the FAP and FAPY alloys were not sensitive to environmental effects related to hydrogen embrittlement at room temperature.
2. Although the room-temperature ductility in the fine-grained wrought condition is over 20%, the values in the as-cast condition are still approximately 1%. The cast

Table 2. Potential applications of low-aluminum-content iron-aluminum alloys

Application	Component system
Heating elements	Toasters, stoves, ovens, cigarette lighters, and dryers
Wrapping wire	Insulation wrapping for investment-casting molds
Regenerator disks	Automotive gas-turbine engines
Furnace furniture	Components for gas-fired hot-forging furnaces
Tooling	Dies for superplastic forming of titanium-based alloys
Shields	Coal-fired power plants to protect the superheater and reheater tubes
Automotive	Exhaust manifolds, catalytic converters, and exhaust support hangers
Molten metals	Sensor sheathing material for molten aluminum, zirconium, and cadmium
Others	Components needing high-temperature sulfidation and oxidation resistance

ductility values, however, increase to over 10% at test temperatures of $\geq 200^{\circ}\text{C}$.

3. Titanium addition up to 1 wt % was found to produce a significant increase in strength at temperatures up to 700°C , and still maintained approximately 20% elongation at room temperature.
4. Nitrogen addition up to 0.1 wt % produced minimal changes in room-temperature strength or ductility of the FAPY alloy, but further improvement in room-temperature ductility in the as-cast condition may be attained by combining nitrogen and titanium additions in the same alloy.
5. The FAP and FAPY alloys offer sufficient room-temperature ductility and oxidation resistance to make these alloys acceptable for many applications.

FUTURE WORK

Future work will focus on three key areas: (1) room-temperature ductility improvement in the as-cast condition, (2) lowering of the DBTT below room temperature, and (3) improvement in high-temperature strength. Improvements in all three areas will likely be based on compositional adjustments, process control, and thermomechanical

processing. Other activities needed in the future are: (1) development of physical and mechanical property data bases, (2) welding procedures and weldments for property development, (3) corrosion properties, (4) prototyping, and (5) scaleup. The future plan will also have a strong interaction with industry.

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