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PROCESSING AND APPLICATIONS OF IRON ALUMINIDES*

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Abstract

Iron aluminides are well known for their resistance to high-temperature sulfidizing and oxidizing environments. In order to take advantage of their excellent corrosion resistance, several methods for their processing have been identified. Issues with melting and processing are discussed in detail. The effects of grain size and melting practice on low-temperature ductility are also presented. Many applications for iron aluminides are described.

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Introduction

Iron aluminides are well known for their excellent resistance to high-temperature sulfidizing and oxidizing environments. Major issues with the applications of iron aluminides have been their poor room-temperature ductility and low high-temperature strength (1). An environmental effect has been identified (2-5) as the major cause for poor room-temperature ductility of iron aluminides. Several approaches have been suggested (6,7) in order to eliminate or reduce the environmental effects. Among the approaches cited, alloying with chromium has been found to be the most effective. Several compositions of iron aluminides containing chromium and the minor additions of other elements have been identified (7) for a broad range of applications (see Table 1). All of the compositions except that designated as FAPY are ordered Fe_3Al-base alloys. The FAPY alloy is a disordered α alloy. The purpose of this paper is to examine various methods of producing iron aluminides and describe their applications.

Processing of Iron Aluminides

Many possible routes for the production of iron aluminides are presented in Figure 1. Among these, the melting route is the most economical. However, the selection of melting routes for iron aluminides is associated with many issues (see Table 2). The use of a wet charge or moisture around the melting crucible can result in the generation of large amounts of hydrogen from the reaction:

$$2\,Al + 3H_2O = Al_2O_3 + 6\,H\,. \qquad (1)$$

The molten iron aluminide can dissolve large amounts of hydrogen (8). The dissolved hydrogen cannot escape during solidification and produces large voids (see Figure 2). Such voids are extremely deleterious to the ingot or casting quality and properties. During air melting, the hydrogen-related porosity can be eliminated (8) by using a dry charge or blowing the molten metal with argon gas. The duration of argon blowing will depend on the size of the melt and can be determined by conducting hydrogen-gas analyses during melting. The vacuum-melting processes, such as vacuum induction or vacuum-arc remelting, produce ingots free of gas porosity. However, vacuum processes add to the cost of the alloy.

The formation of Fe_3Al from a combination of elemental iron and aluminum is exothermic (9) (see Figure 3). The conventional method of melting iron and adding aluminum to it causes the rise of molten-bath temperature by several hundred degrees. Such a rise in temperature causes melt oxidation, longer holding times prior to pouring, and a potential for missing the target chemistry because of alloying element oxidation. A furnace loading of melt stock, as shown in Figure 4, can take advantage of heat generated from the formation of Fe_3Al and FeAl, and allows bringing the melt to the pouring temperature in a gradual manner with minimum oxidation. This method is routinely used in our laboratory and has been successfully applied commercially for the melting of 2500-kg heats of nickel aluminide at Sandusky International (Sandusky, Ohio). In addition to proper furnace loading, an argon gas cover during the air melting can further minimize the melt oxidation (see Figure 4). The transfer of molten alloy from the crucible to the casting molds using the "tea kettle" pouring method further reduces the oxide entrapment in the ingot or casting. The "tea kettle" approach essentially permits the pouring of clean metal from underneath the oxide slag.

The selection of a suitable crucible for the melting of iron aluminides is important for two reasons: (1) to minimize the impurity pickup from the crucible material, and (2) to get a long crucible life. The magnesium-oxide crucible is the common choice for melting commercial materials. The free energy data in Figure 5 show that aluminum can reduce magnesium oxide at temperatures close to the melting point of iron aluminides. Such a reduction process results in the pickup of magnesium (10) in the alloy, as opposed to melting in an Al_2O_3 crucible (see Table 3). Of course, the reduction of magnesium oxide by aluminum also results in crucible erosion.

Table I. Compositions of Iron Aluminides[a] Chosen at the Oak Ridge National Laboratory for Commercialization

Element	FAS[b]		FAL[c]		FA-129[d]		FAPY[e]	
	Alloy (%)							
	Weight	Atomic	Weight	Atomic	Weight	Atomic	Weight	Atomic
Al	15.9	28.08	15.9	28.03	15.9	28.08	8.46	16.12
Cr	2.20	2.02	5.5	5.03	5.5	5.04	5.50	5.44
B	0.01	0.04	0.01	0.04	---	---	---	---
Zr	---	---	0.15	0.08	---	---	0.20	0.11
Nb	---	---	---	---	1.0	0.51	---	---
C	---	---	---	---	0.05	0.20	0.03	0.13
Mo	---	---	---	---	---	---	2.00	1.07
Y	---	---	---	---	---	---	0.10	0.06
Fe	81.89	69.86	78.44	66.81	77.55	66.17	63.71	77.07

[a]FAS, FAL, and FA-129 are the Fe_3Al-base alloys. FAPY is a disordered α alloy.
[b]Sulfidation-resistant alloy.
[c]High room-temperature tensile ductility.
[d]High-temperature strength with good room-temperature ductility.
[e]Very high room-temperature ductility.

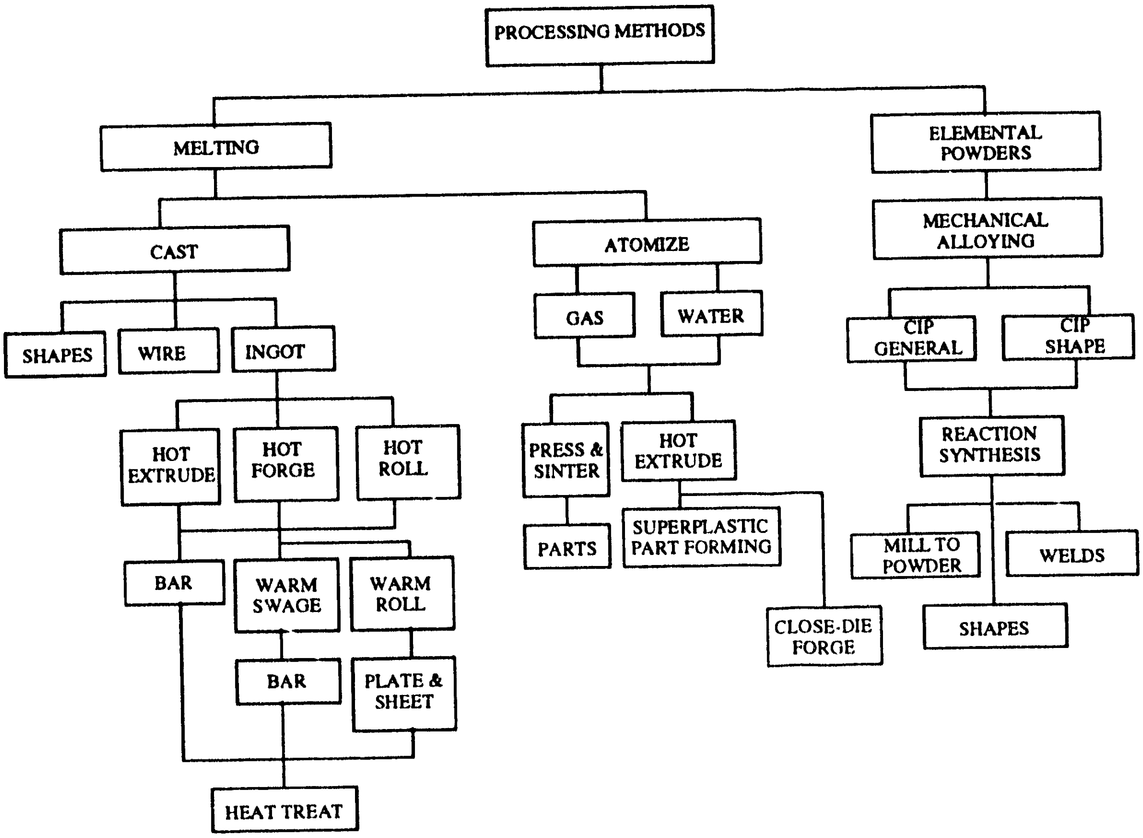

Figure 1 - Possible methods for the production of iron aluminides.

The commercial melting of conventional alloys uses aluminum additions as a deoxidizer to the melt prior to its pouring into ingot or casting molds. Only a small amount of aluminum in the aluminides oxidizes to form an Al_2O_3 film, which protects the molten metal underneath from further oxidation. The Al_2O_3 film also prevents any pickup of nitrogen from air. The low levels of oxygen and nitrogen in iron aluminides melted by several different methods are shown in Table 4. The formation of protective Al_2O_3 on top of the molten metal also produces excellent recovery of various other alloying elements (see Table 5).

There are several issues related to the processing or use of castings of iron aluminides (see Table 6). The iron-aluminide compositions in Table 1 tend to produce large grain sizes during sand and ingot casting (see Figure 6). The large grain size has dramatic influence on ductility of both Fe_3Al-base and α alloys (see Figures 7 and 8). Such low-ductility values make cold processing of cast structures impossible. In the case of Fe_3Al-base alloys, it restricts even some of normal foundry handling operations at room temperature. To improve the cast ductility, it is imperative that the grain size be reduced. One example of grain refinement by the inoculation process is shown in Figure 9. For the same cast grain size, the temperature for improvement in ductility can be lowered by going from air to vacuum melting (see Figure 10). The data in Figure 10 show the improvement in overall ductility and the lowering of temperature at which ductility is improved for the α alloy, FAPY.

The ductility data of the disordered FAPY alloy in Figures 8 and 10 suggest that the cast structure of FAPY can be worked at a much lower temperature than required for the ordered alloys, or much larger reductions can be taken at the same working temperature. For example, the 25-mm-thick cast slab of FAPY could be reduced 50% per pass at 1050°C without concern for the decrease in slab surface temperature in contact with the rolls. This observation is based on data in Figure 10 which show that FAPY's cast ductility drops significantly only at temperatures $\leq$200°C. On the other hand, the cast Fe_3Al alloy requires heating after each pass to maintain the surface temperature above 650°C in order to avoid surface cracking by a decrease in temperature from roll chilling.

Table II. Issues Related to Melting During the Production of Iron Aluminides

Item	Issue	Consequence	Possible Solutions
• Charge	Wet or moist	Gas porosity	(1) Dry charge, and (2) Blow the melt using argon
• Furnace loading	Improper loading	Overheating and wrong chemistry	Use suggested loading to take advantage of the exotherm
• Furnace lining or crucible	Magnesium oxide may get reduced by aluminum	Magnesium pickup may cause hot shortness	Use rammed Al_2O_3 crucible; magnesium oxide is OK in vacuum
• Molten metal	Oxidation	Oxide entrapment in casting and ingots	(1) Vacuum melt, (2) air melt with argon cover, (3) teakettle pour, (4) use filters
• Impurity	Carbon and silicon	Ductility reduction	Keep carbon ≤0.05 wt %, silicon ≤0.1 wt %; need further study for other elements

Figure 2 - Gross porosity observed in a 230-kg air-melted ingot of iron aluminide.

The significantly higher ductility of the disordered alloy as compared to the ordered alloy for comparable grain sizes at temperatures ≤200°C (see Figures 7 and 8) also permits its cold working by a variety of processes. In fact, FAPY has been cold rolled to thin foil, cold swaged to a variety of bar sizes, and cold drawn to rod and wire. The recrystallization temperature of FAPY alloy is 800°C, and this temperature is used for intermediate anneals during cold-working operations.

Applications of Iron Aluminides

Iron aluminides compete with the 300 and 400 Series stainless steels and some nickel-base alloys. Specific advantages include: (1) excellent sulfidation resistance, (2) oxidation resistance, (3) lower density, (4) good wear resistance, (5) cavitation-erosion resistance, and (6) potentially lower cost. Based on these advantages, several applications have been identified for the Fe_3Al-base alloys which include the following:

1. Sintered porous gas-metal filters: In this application, the filters are used to remove particulate matter from the gas produced in the coal-gasification process and other processes where the gas contains a high sulfur content. Advantage is taken of the superior sulfidation resistance of iron-aluminide alloys as opposed to any other currently available material. The filters are prepared by sintering powders to a desired level of porosity.

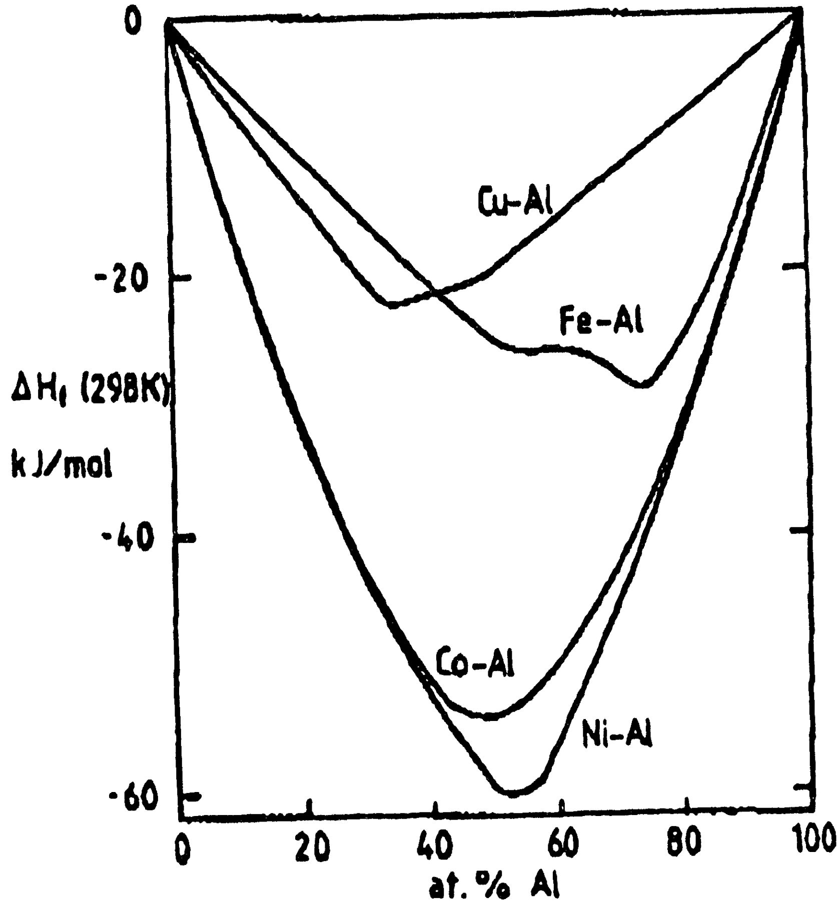

Figure 3 - Extent of exothermic reaction in aluminum binary systems with transition metals including: iron, cobalt, nickel, and copper.

2. Heating elements: This application uses the iron-aluminide alloy wire for heating elements in toasters, ovens, and dryers. Advantage is taken of the high resistivity, which remains constant up to 1000°C, and the excellent oxidation resistance. The fabrication of wire has been hampered by limited ductility at room temperature. However, the hot-rolled bar is currently feasible as furnace heating elements.

3. Furnace fixtures: This application takes advantage of the excellent oxidation resistance of iron-aluminide alloys for components such as retorts, rollers, beams, etc. The furnace fixtures are expected to be manufactured by various casting processes.

4. Catalytic converter substrate: This application takes advantage of the excellent oxidation resistance of iron aluminides. The 0.050-mm-thick foil for this application is prepared primarily by warm rolling followed by cold rolling in the last few passes.

5. Regenerator disks: In this application, iron aluminide is used as a heat exchanger in a gas turbine engine. Advantage is taken of the excellent oxidation and sulfidation resistance. The foil requirements for this application are similar to those for the catalytic converter substrates.

6. Components for molten salt applications: Iron-aluminide alloys have excellent compatibility with oxidizing and carbonate salts. Processes dealing with molten salts have the potential of using iron aluminides for their containment, transfer, or even rotating components. The components for this application will be manufactured by a combination of the casting process, hot-working ingots, and welding.

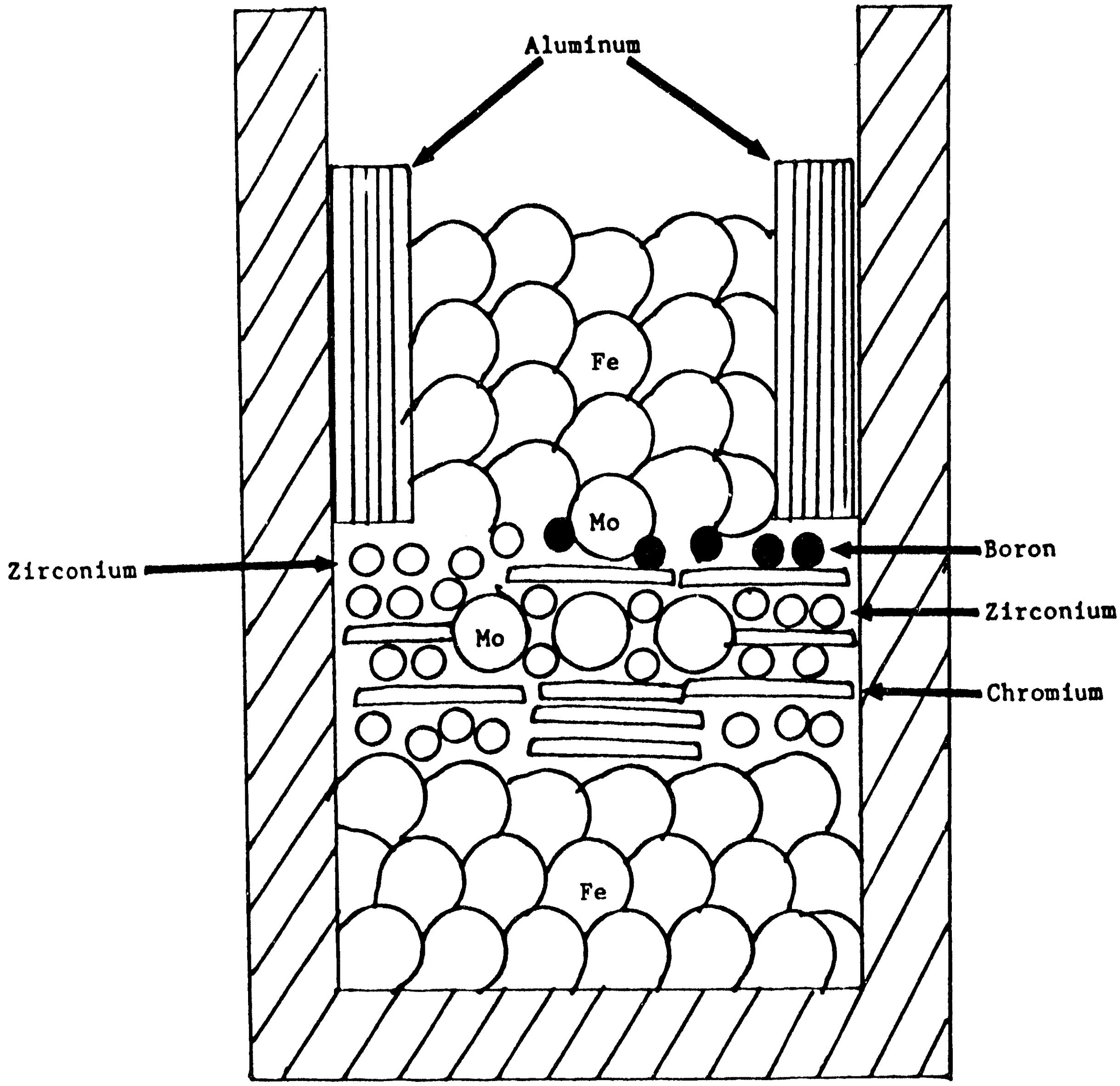

Figure 4 - Furnace-loading sequence to take advantage of heat of formation of Fe_3Al during the melting of iron-aluminide alloys.

7. Shielding: This application uses iron aluminide as a shielding to prevent the excessive oxidation of tubes in power plants and incinerators. The shields are typically 3 to 4 mm thick and are shaped like tubes. These shields are typically manufactured by bending the warm-rolled sheet of the desired thickness.

Summary and Conclusions

A schematic showing various processing methods possible for iron aluminides has been presented. Both melting and powder metallurgy methods are possible. Important issues during melting and processing of iron aluminides are brought out including the influence of melting practice and grain size on room-temperature ductility. Many applications of iron aluminides are also identified. Specific conclusions from this study include:

1. The proposed method of loading the melt charge into the furnace takes advantage of the exotherm in formation of the aluminide from the elements and results in substantial savings of energy and melt time, and results in a melt of controlled chemistry.

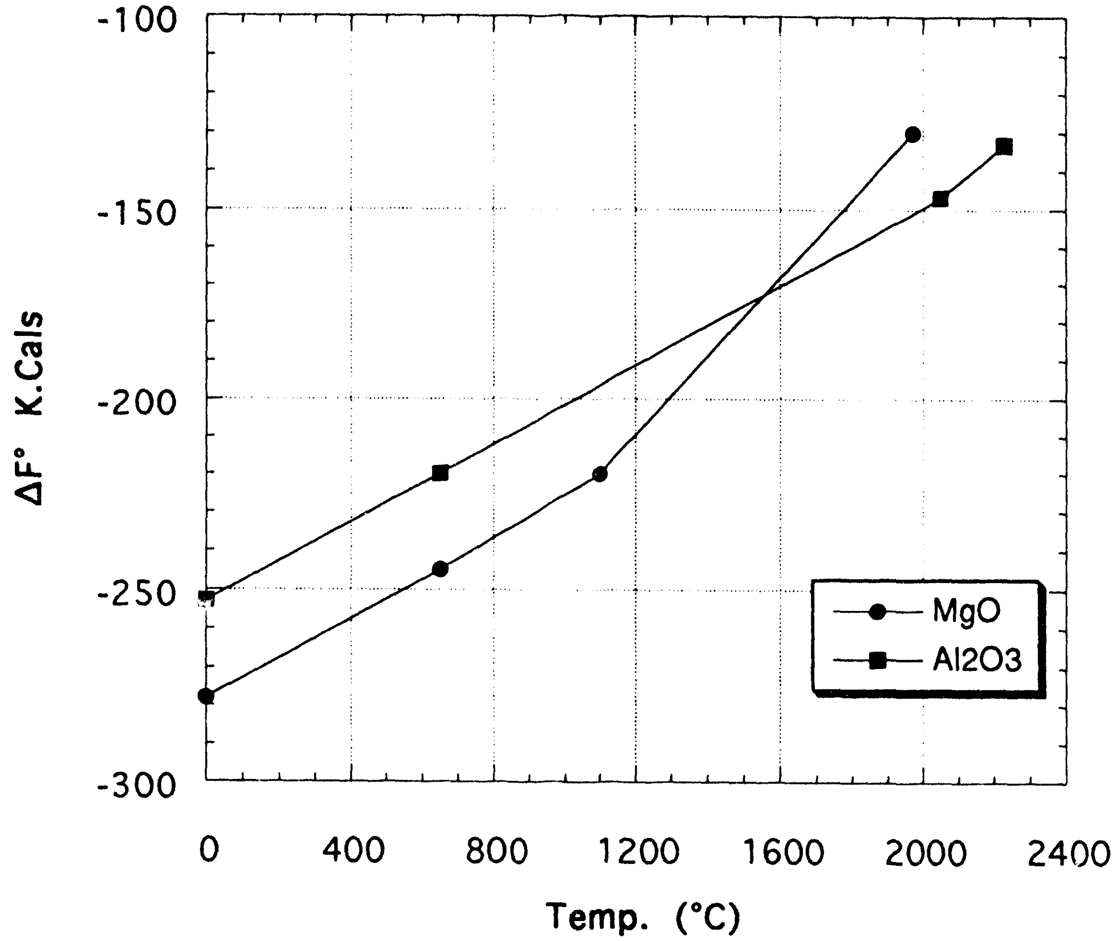

Figure 5 - Comparison of standard free energy of formation as a function of temperature to reveal stability of MgO and Al_2O_3.

2. The gas porosity in air-melted iron aluminides can be reduced by the use of dry charge and argon blowing of the melt. Vacuum melting can also provide porosity-free castings.

3. Grain-size control is extremely important in improving the room-temperature ductility of iron aluminides. Vacuum melting with grain refinement produces additional improvement in room-temperature ductility as compared to air melting.

4. The disordered alloy containing 16 at. % Al is cold workable for foil and wire production as opposed to Fe_3Al-base alloys.

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Table III. Comparison of Specifications and Analyses of Vacuum-Induction Heats of Alloy FA-129 Melted in MgO and Al_2O_3 Crucibles at Special Metals Corporation

Element	ORNL Specification (wt %)		Check Analysis (wt %)			
			74% MgO, 24% Al_2O_3 Crucible (100 kg/heat)		Al_2O_3 Crucible (80 kg/heat)	
			Heat		Heat	
	Target	Range or limit	D5-3965	D5-3966	D5-3968	D5-3969
C	0.05	0.04 to .06	0.049	0.054	0.047	0.053
Mn	---	0.02 max	0.01	<0.01	<0.01	<0.01
P	---	0.005 max	NA[a]	NA[a]	NA[a]	NA[a]
S	---	0.005 max	0.001	0.0008	0.0016	0.0012
Si	---	0.20 max	<0.001	<0.01	<0.01	0.01
Ni	---	0.20 max	0.01	<0.01	<0.01	<0.01
B	---	0.005 max	<0.001	<0.001	<0.001	<0.001
Mg	---	0.0010 max	0.002	0.002	0.001	0.001
N	---	0.0050 max	0.0002	0.0001	0.0001	0.0001
O	---	0.0050 max	0.0016	0.0007	0.0015	0.0008
Al	15.9	15.5 to 16.5	16.33	16.30	16.29	16.42
Cr	5.5	5.0 to 6.0	5.28	5.31	5.31	5.34
Nb	1.0	0.9 to 1.1	0.98	1.00	0.99	1.00
Fe	*b*	*b*	*b*	*b*	*b*	*b*

[a]NA = Not applicable.
[b]Balance.

Table IV. Effect of Melting Practice on Range of Oxygen and Nitrogen Content Observed in Fe_3Al-Base Alloys

Melting Practice	Weight Percent	
	Oxygen	Nitrogen
Air induction	0.0017 to 0.0040	0.0005 to 0.0008
Vacuum induction	<0.0007 to 0.0020	0.0001 to 0.0010
Vacuum-arc remelting	0.0010	0.0003
Electroslag remelting	<0.0010 to 0.0014	0.0002

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Table V. Recovery of Various Elements During Air-Induction Melting of 7-kg Iron-Aluminide Heats

Element	Alloy 1		Alloy 2		Alloy 3		Alloy 4	
	Target (wt %)	Recovery (%)	Target (wt %)	Recovery (%)	Target (wt %)	Recovery (%)	Target (wt %)	Recovery (%)
C	---	---	---	---	0.04	250.00[a]	---	---
Cr	2.157	98.75	5.46	91.03	5.46	95.24	2.194	95.72
Mo	0.995	100.00	---	---	---	---	---	---
Nb	1.542	100.00	---	---	0.21	100.00	---	---
Al	15.672	98.86	15.88	96.73	15.88	97.54	15.932	96.67
B	0.011	81.82	0.01	80.00	---	---	0.011	27.27
Zr	0.189	100.00	0.19	100.00	---	---	---	---
Fe	*b*	---	*b*	---	*b*	---	*b*	---

[a]Recovery of greater than 100% indicates pickup of carbon from external sources. For example, a graphite rod was used for stirring the liquid metal, and a small fraction of the graphite was probably dissolved in the metal.

[b]Balance (100 minus total of all other elements).

Table VI. Issues Related to Processing During the Production of Iron Aluminides

Item	Issue	Consequence	Possible Solutions
Casting properties	Large grain size and porosity	Low ductility and strength	Use of inoculation for grain-size control Hot-isostatic pressing (HIP) for porosity closure, but HIP temperature may increase grain size
Casting quality	Oxide entrapment	Poor surface finish and properties	Proper mold design Teakettle pour Melt filtration prior to pouring
Cold processing	Too low ductility	Cracking and, thus, not possible	Warm processing at 200° ≥ T ≤ 700°C
Cutting	Abrasive versus band	Cracking	Abrasive cutting must use water-soluble oil Band saw cutting preferred Electrodischarge machining (EDM) not good because it charges hydrogen into metal

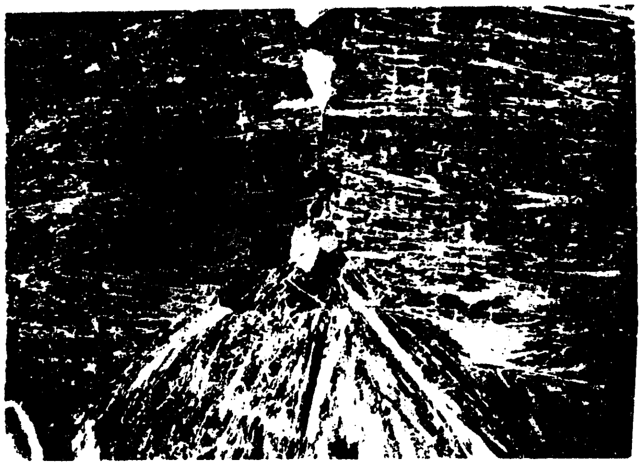

Figure 6 - Coarse grain structure in an as-cast ingot of FAPY alloy.

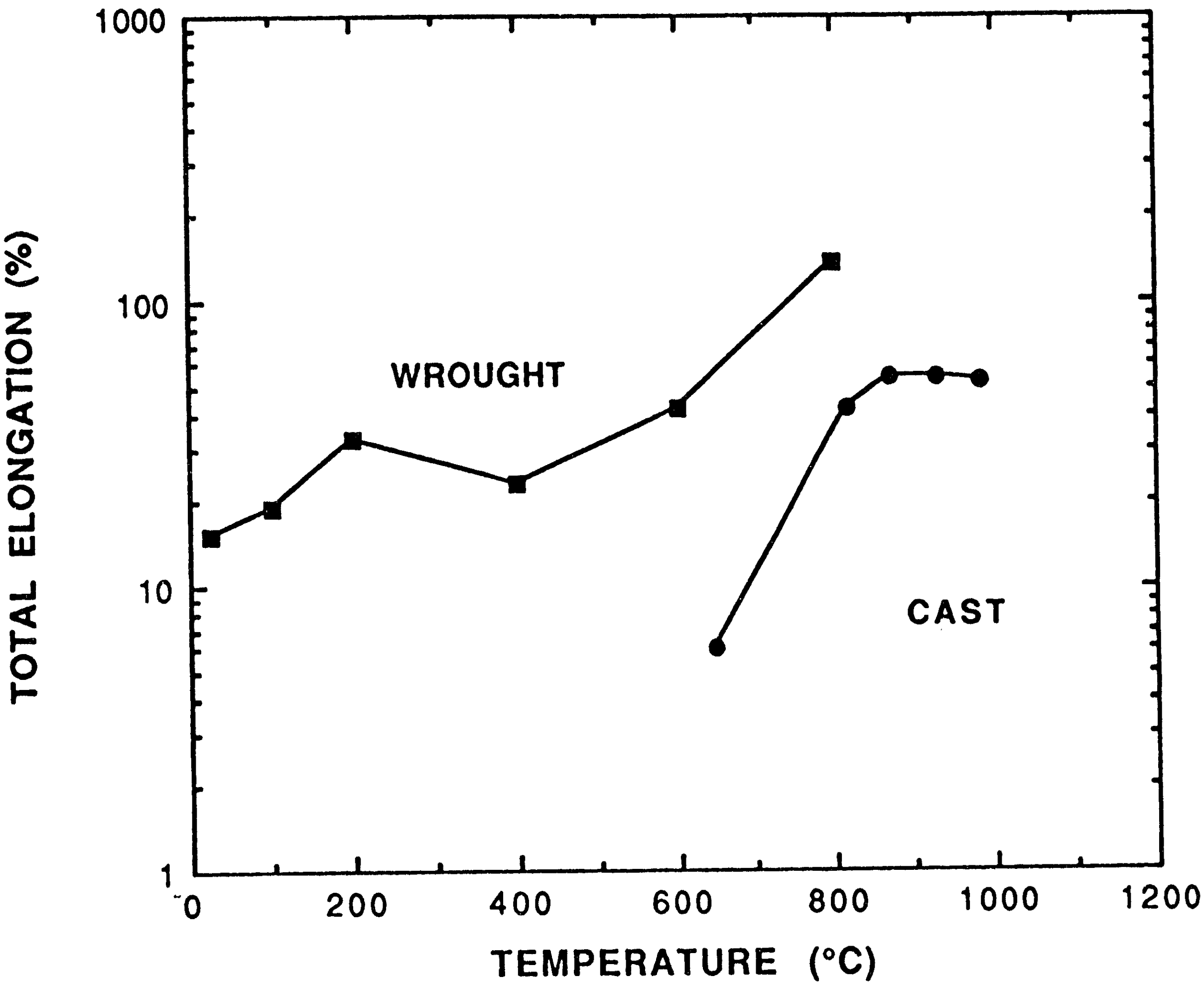

Figure 7 - Comparison of cast and wrought tensile elongation of iron-aluminide alloy FA-129.

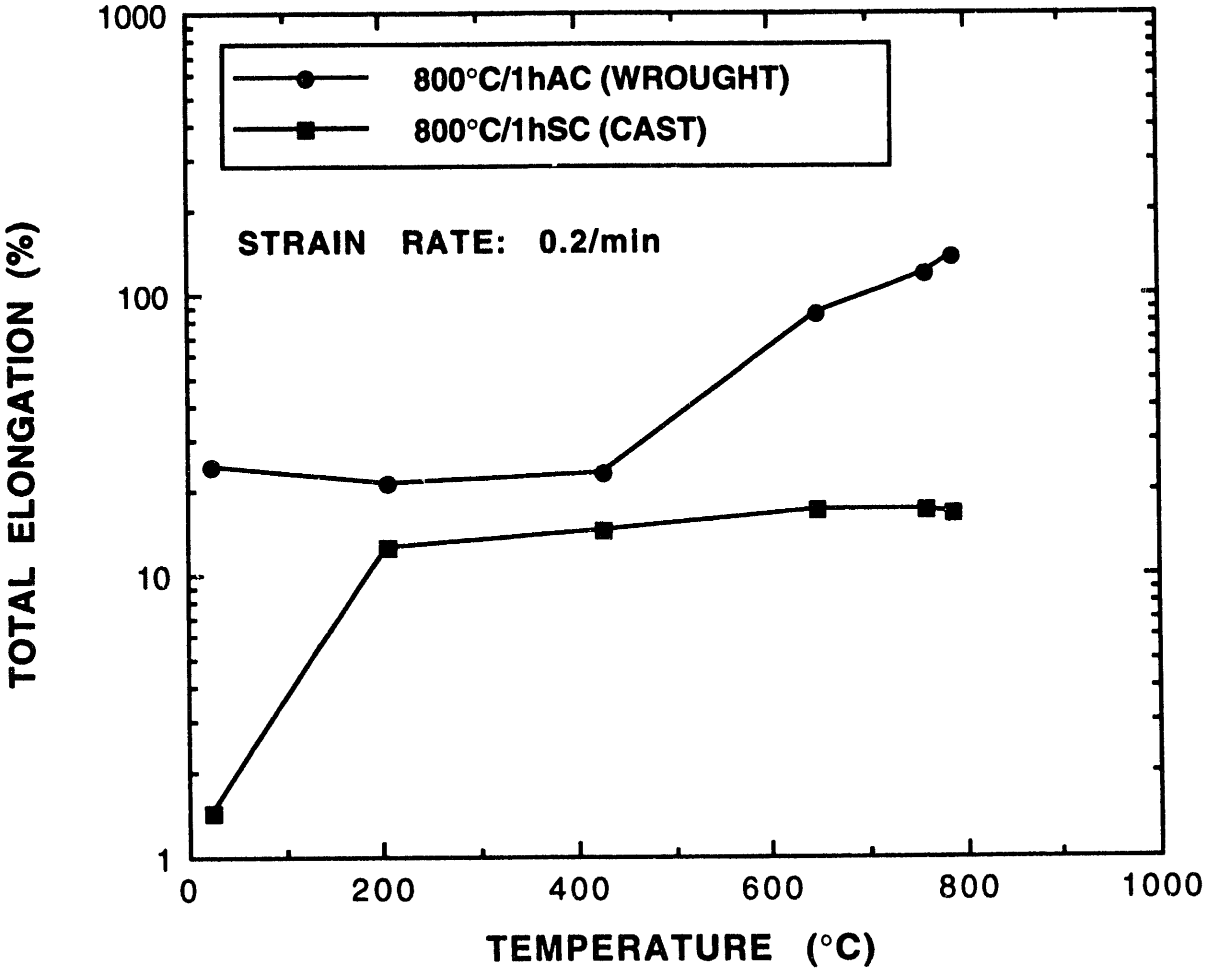

Figure 8 - Effect of processing on total elongation of commercially air-melted FAPY. AC denotes air cool and SC denotes slow cool.

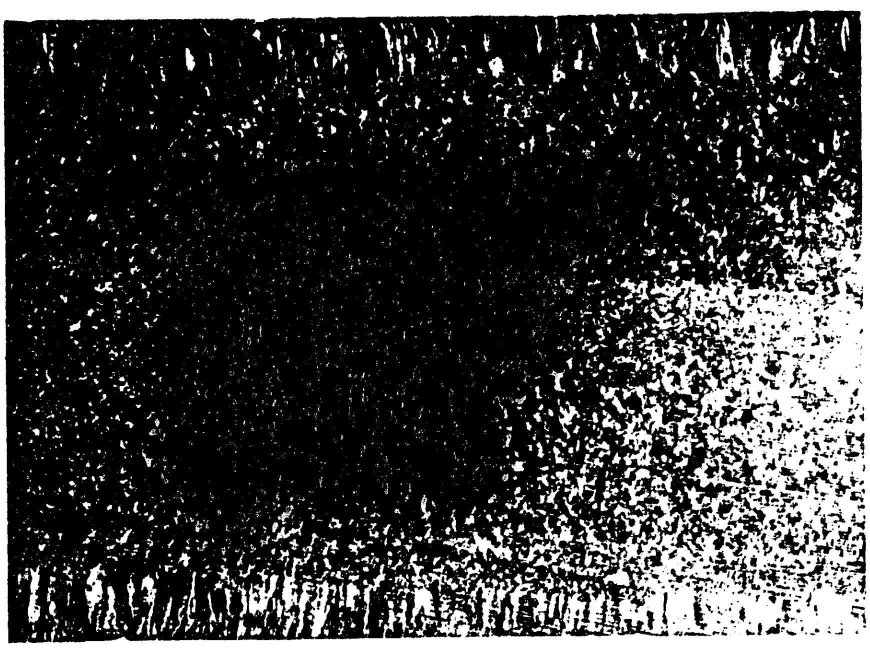

Figure 9 - Grain refinement of FAPY alloy by inoculation process.

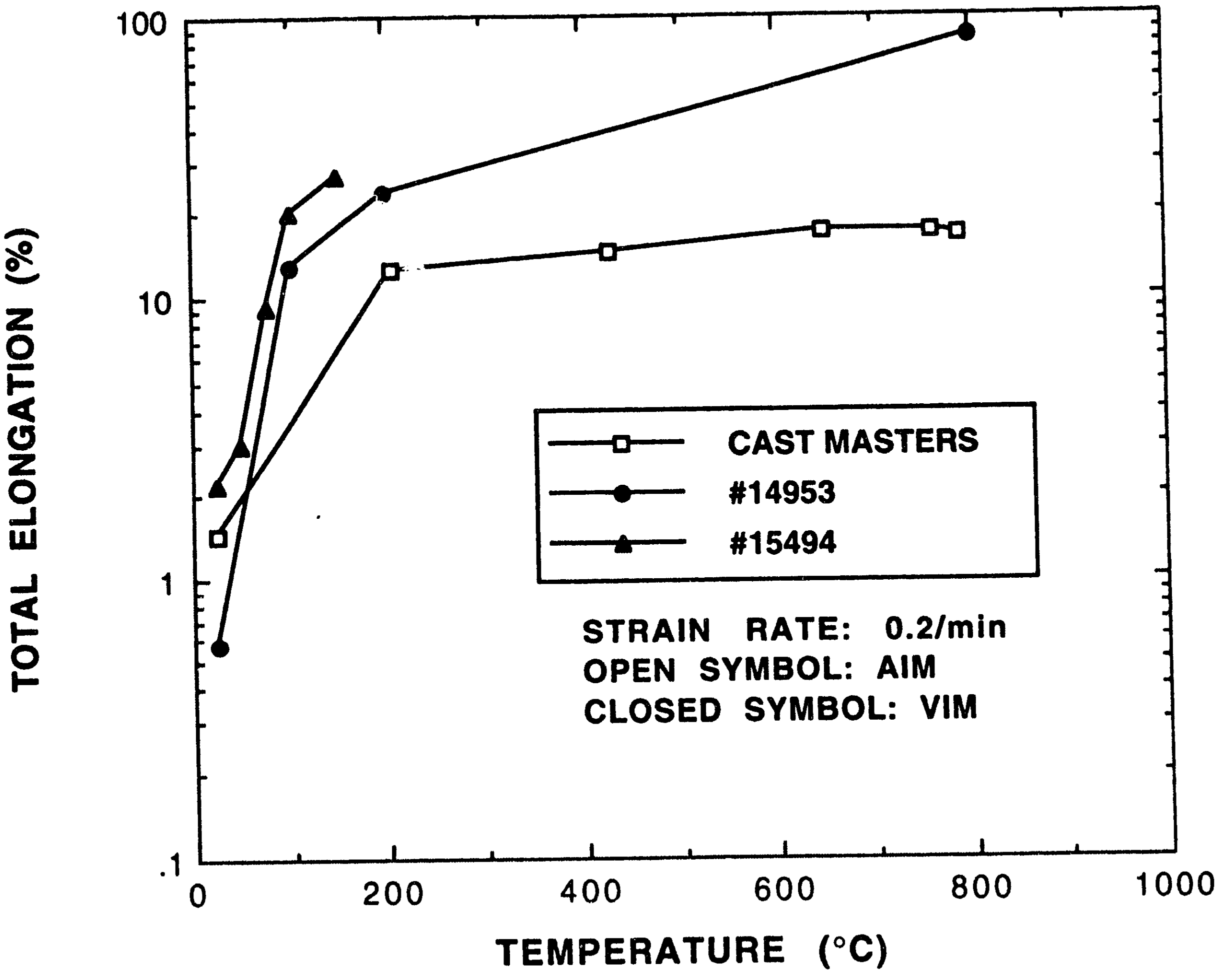

Figure 10 - Effect of melting practice on ductility of FAPY in the as-cast condition.

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