ORNL/CP-101117

INTERMETALLIC-BASED HIGH-TEMPERATURE MATERIALS

Vinod K. Sikka
Metals and Ceramics Division
Oak Ridge National Laboratory
P.O. Box 2008
Oak Ridge, Tennessee 37831-6083

ABSTRACT

The intermetallic-based alloys for high-temperature applications are introduced. General characteristics of intermetallics are followed by identification of nickel and iron aluminides as the most practical alloys for commercial applications. An overview of the alloy compositions, melting processes, and mechanical properties for nickel and iron aluminides are presented. The current applications and commercial producers of nickel and iron aluminides are given. A brief description of the future prospects of intermetallic-based alloys is also given.

Keywords: Intermetallics, nickel aluminides, iron aluminides, Ni_3Al, Fe_3Al, FeAl, tensile properties, creep properties, castings, applications

INTRODUCTION

Materials of construction are limiting factors in many production processes. The important properties of concern for the application of materials at high temperatures as a minimum include the following:

Melting:	Melting point ≥ 1350°C with no incipient melting.
Mechanical properties:	Tensile, creep, fracture toughness, and fatigue.
Corrosion:	Oxidation, carburization, and sulfidation resistance.
Weldability:	Performed by gas tungsten arc , metal inert gas , submerged arc , or shielded metal arc .
Manufacturing:	Ease of manufacturing by standard processes.
Machinability:	Ease of machining by standard processes.

The most commonly used materials of construction include: (1) steels (carbon and alloy steels), (2) stainless steels (300 and 400 series), (3) nickel-based alloys, (4) titanium-based alloys, and (5) aluminum-based alloys. Each class of materials plays an important role in terms of their unique combination of properties.

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

Intermetallic compounds, which normally develop in steels and stainless steels during service and are intentionally introduced as a second phase in nickel-based alloys, are being developed as a new class of high-temperature structural materials. Many national and international symposia have been held that deal with the science and technology of intermetallic alloys. Although a very large number of intermetallic compounds have been investigated for academic reasons, only a handful are now approaching commercial feasibility. This paper will: (1) present a brief description of intermetallic compounds, (2) describe the development and mechanical properties of nickel- and iron-based intermetallic materials, (3) describe possible applications, and (4) discuss the future potential of these materials.

INTERMETALLIC COMPOUNDS

An intermetallic compounds[1] can be defined as an ordered alloy phases formed between two metallic elements,[2] where an alloy phase is ordered if two or more sublattices are required to describe its atomic structure.[3,4] The ordered structure exhibits superior elevated-temperature properties because of the long-range-ordered superlattice, which reduces dislocation mobility and diffusion processes at elevated temperatures.[5-8]

The shear moduli G versus melting temperature, T_m, for many intermetallic compounds[9] are shown in Figure 1. Although there is a great deal of scatter, the trend is clear that modulus increases dramatically with an increase in the melting point of the intermetallic compound. A plot of room-temperature hardness versus melting temperature[9] for pure metals and intermetallic compounds is shown in Figure 2. There is even more scatter in the data of hardness versus melting point than modulus versus T_m (Figure 1). However, the trend is clear that the hardness of the intermetallic compounds is higher and increases much more rapidly with melting temperature than pure metals.

Beside the modulus and hardness data in Figures 1 and 2, intermetallic compounds also show significantly higher work-hardening[10] rates than the commonly used commercial metals and alloys (see Table 1). The work-hardening rate of Ni_3Al is nearly three times that of stainless steel. Similarily, the work-hardening rate of FeAl is nearly four times that of aluminum and seven times that of carbon steels.

The brittle fracture or low-crack tolerance[10] of intermetallic compounds has been the primary barrier to their use. However, understanding of the causes for brittleness in intermetallics developed during the last decade has significantly enhanced their potential as structural materials in the monolithic form, as weld overlays, or as coatings by processes such as high-velocity oxyfuel (HVOF).

DEVELOPMENT AND COMMERCIALIZATION STATUS OF NICKEL AND IRON ALUMINIDES

The Ni-Al and Fe-Al phase diagrams show the existence of two intermetallic compounds in each system that are of practical interest: Ni_3Al, NiAl, Fe_3Al, and FeAl. Details of their physical characteristics are given in Table 2. Based on the crystal structure, Ni_3Al-based materials compete in mechanical properties with stainless steels and nickel-based alloys and NiAl, Fe_3Al and FeAl with carbon and alloy steels. Among the four intermetallics shown in Table 2, Ni_3Al is the most developed and in commercial use. The NiAl alloy is of great interest because of its high melting point (1640°C) and low cost which is due to its high aluminum content. However, NiAl is also the compound for which the least progress has been made in its ductilization for any practical applications. Fe_3Al and FeAl are both at stages of development where limited commercial applications are starting. The key development needs and current status of Ni_3Al, Fe_3Al, and FeAl are presented below. The NiAl developments will not be further discussed here.

Ni_3Al-Based Alloys

The major development[11,12] in Ni_3Al-based alloys has been the significant improvement in room-temperature ductility by small additions of boron (Figure 3). It is very important to note that the effectiveness of boron in ductilization occurs only for nickel-rich compositions (atomic ratio of Ni/Al>3). The base Ni_3Al composition with boron addition has been further modified to achieve a combination of strength, ductility, and processability across a broad range of temperature. As a result of various modifications, three compositions of Ni_3Al-based alloys are of practical interest (Table 3). The IC in the alloy designation stands for intermetallic compound. The effects of various alloying additions in Ni_3Al-based alloys have been discussed in previous publications.[13-15]

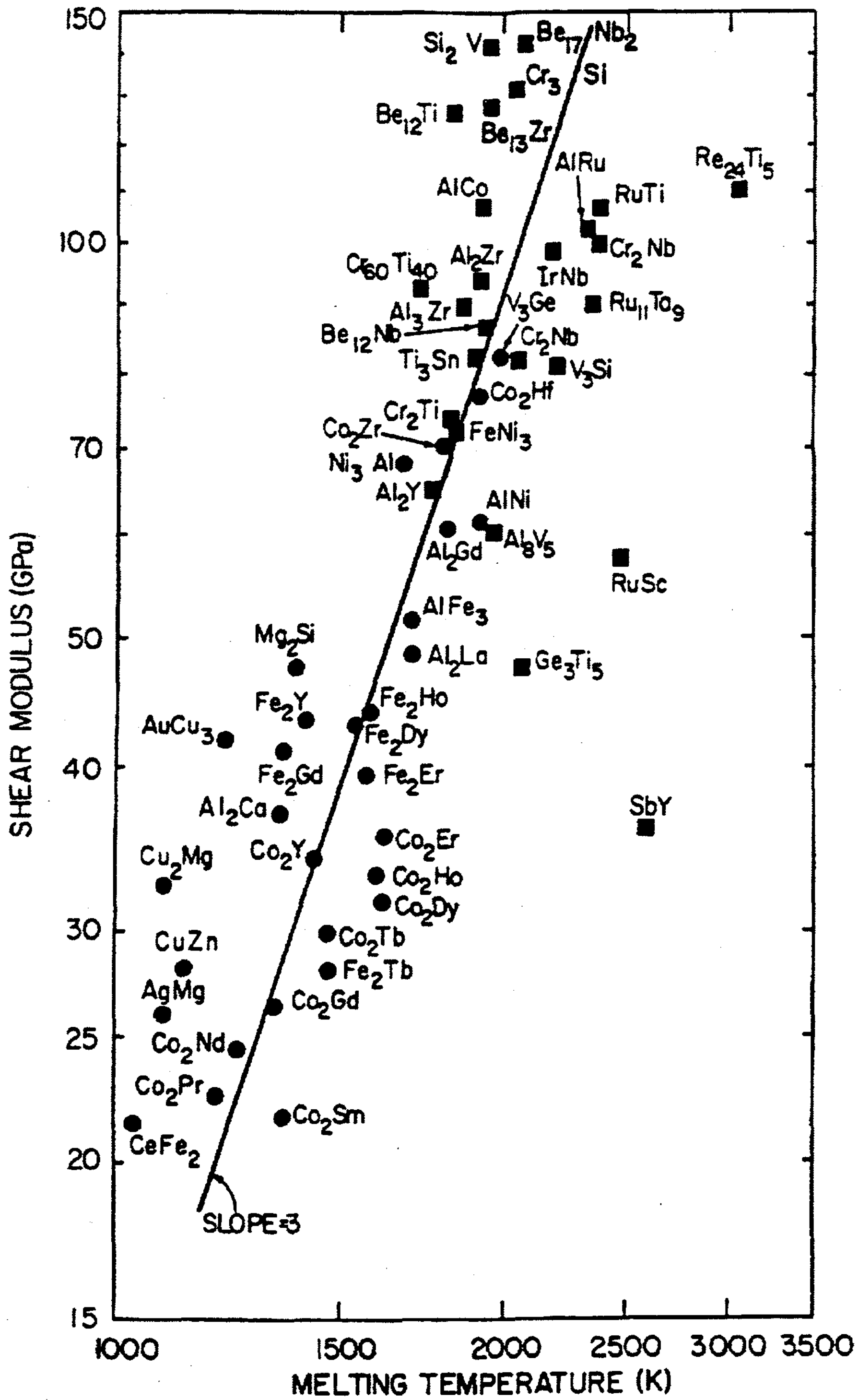

FIGURE 1 - Shear moduli at room temperature of intermetallic compounds as a function of their melting temperatures. Pre-existing data are shown as circles, and recent data are shown as squares.[9]

Among the three Ni_3Al-based alloys in Table 3, IC-221M is the most advanced in applications as a castable alloy.[15,16] The alloy is commercially melted by the Exo-Melt™ (EM) process developed at the Oak Ridge National Laboratory.[17] The EM process is a specialized furnace-loading scheme that efficiently uses the heat from the exothermic reaction of formation of Ni_3Al from its constituent elements. The EM process utilizes air-induction melting (AIM) for most applications, and has the major advantage of using the currently available equipment at most foundries. Other advantages of the EM process are that it requires nearly half the energy cost and melting time as oppose to conventional melting processes. The process is useable for both virgin and

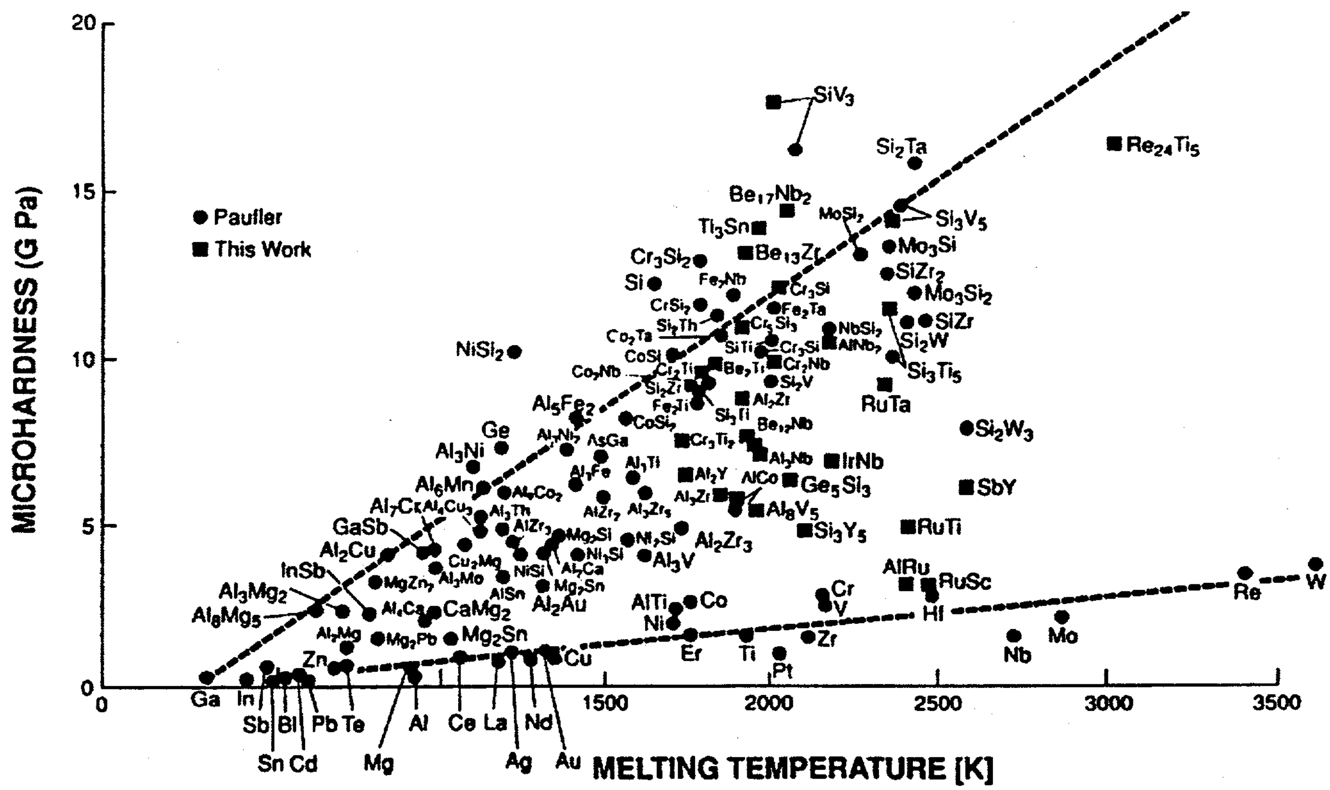

FIGURE 2 - Hardness at room temperature of metals and intermetallics compounds.[9]

revert stock. A comparison of the range of the actual chemical analysis of 94 virgin and revert heats with the nominal composition of IC-221M is shown in Table 4. It is clear from this table that the EM process yields chemistries in excellent agreement with target chemistries of the Ni_3Al-based alloy IC-221M. The EM process is currently being used on a commercial basis by four different foundries in the United States.

Tensile properties of the three nickel aluminides (IC-50, IC-218LZr, and IC-221M) are compared in Figures 4 through 6. Alloys IC-50 and IC-218LZr were tested in the wrought condition, and IC-221M in the cast condition. The IC-221M in the as-cast condition has the highest yield strength at all tested temperatures. The improvement in the yield strength of IC-221M is much more significant for temperatures exceeding 600°C. The ultimate tensile strength behaves similar to yield strength at temperatures above 600°C. However, at lower test temperatures, work hardening of the wrought alloys (IC-50 and IC-218LZr) results in significantly higher ultimate tensile strength values. As expected, the elongation values of the finer grained wrought alloys (IC-50 and IC-218LZr) are higher than the cast IC-221M at room temperature. However, in the intermediate temperature range of 650 to 750°C, the ductility drops to near zero for the chromium-free alloy, IC-50. This low ductility for the chromium-free Ni_3Al has been explained as an oxygen embrittlement phenomenon.[14] In spite of its very low ductility in the intermediate temperature range, the IC-50 alloy is of interest for certain specialized applications at temperatures up to 600°C in the preoxidized condition.

All three alloys (IC-50, IC-218LZr, and IC-221M) have been creep tested in the as-cast condition. Alloy IC-218LZr has also been tested in the wrought condition, produced by both ingot and powder metallurgy routes. The creep rupture data for the three alloys in the cast condition are plotted as a Larson-Miller parameter in Figure 7. Most of the creep tests were of 10- to 5000-h duration, and test temperatures varied from 800 to 1050°C. The IC-50 and IC-218LZr data were measured on material taken from 25-kg-size ingots, while the IC-221M data are for sand and centrifugal castings from 250- to 1500-kg-size heats. The data in Figure 7 show that the chromium-containing Ni_3Al-based alloys (IC-218LZr and IC-221M) have significantly higher strength than the single phase Ni_3Al-based alloy IC-50. Both alloys contain approximately 15% of the disordered γ phase. The 1.43% Mo seems to improve the short-term creep rupture strength of IC-221M. However, at longer times and higher test temperatures, the creep rupture strength of IC-221M is similar to IC-218LZr.

TABLE 1
WORK-HARDENING RATE[a] OF POLYCRYSTALS
(AT AXIAL STRAIN OF 0.1)[ref. 10]

Material	Work-hardening rate (normalized with respect to shear) modulus G
Commonly used metals and alloys	
Low-carbon steel	≈ G/50
Stainless steel	≈ G/40
Cu, Al, Ni	G/30-G/40
Intermetallic compounds	
Cu_3Al, Ni_3Mn, Ni_3Fe	G/23-G/38
$Al_{67}Ni_8Ti_{25}$	G/19
$Al_{66}Mn_6V_5Ti_{23}$	G/15
Al_3Sc	G/15
NiAl	G/15-G/38
Ni_3Al	G/12
Zr_3Al	G/10
FeAl[b]	G/7

[a]For the intermetallics generally obtained from compression tests at room temperature.
[b]Furnace-cooled after annealing.

TABLE 2
BASIC CHARACTERISTICS OF NICKEL- AND IRON-BASED ALUMINIDES

Compound	Crystal structure	Density g/cm³	Melting temperature (°C)	Fracture mode[a]
Ni_3Al	$L1_2$, fcc[b]	7.50	1400	IG[c]
NiAl	B2, bcc[d]	5.86	1640	IG[c] + TG[e]
Fe_3Al	DO_3, bcc[d]	6.72	1540	TG[e]
FeAl	B2, bcc[d]	5.56	1300	IG[c] + TG[e]

[a]At room temperature.
[b]fcc = face-centered cubic.
[c]IG = Intergranular.
[d]bcc = body-centered cubic.
[e]TG = transgranular.

The creep rupture properties of IC-218LZr are compared in Figure 8 for the wrought and cast conditions. It is noteworthy to mention that the grain size has a very significant effect on the creep rupture strength. The coarse grain cast structure showed the higher rupture strength. The grain size effect on the creep rupture properties of intermetallic-based alloys is similar to that observed in conventional metals and alloys.

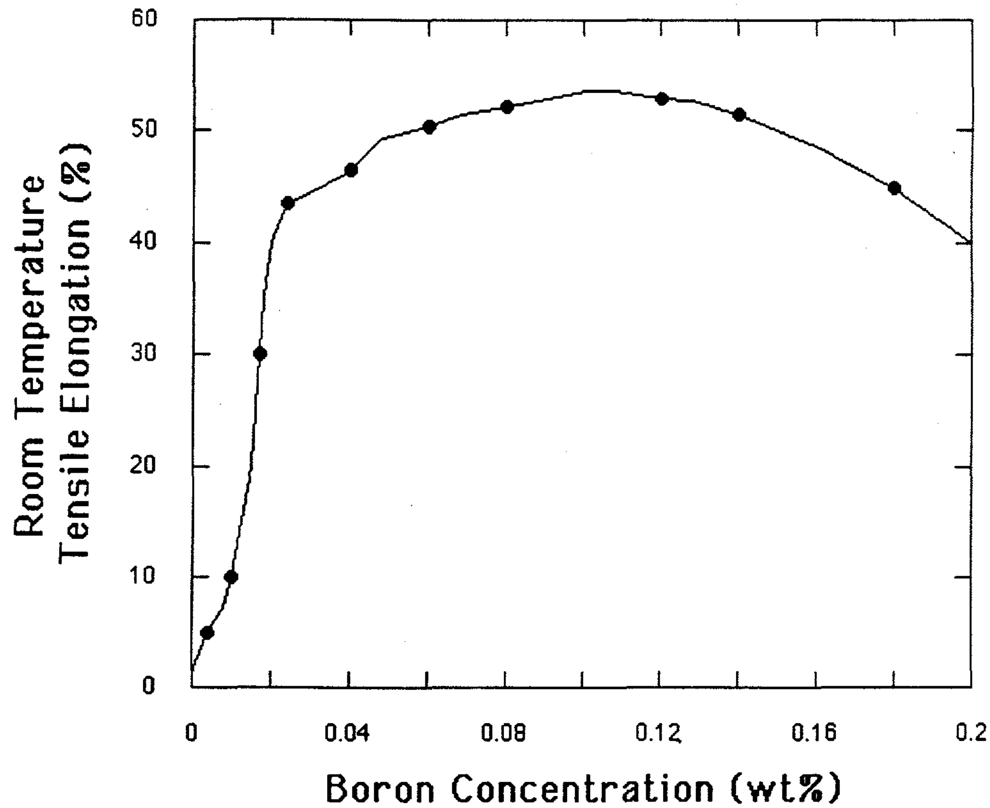

FIGURE 3 - Effect of boron addition on tensile elongation of Ni_3Al (24 at. % Al) tested at room temperature.

TABLE 3
COMPOSITION OF Ni_3Al-BASED ALLOYS

Element	Weight percent		
	IC-50[a]	IC-218LZr[b]	IC-221M[c]
Al	11.3	8.7	8.0
Cr	–	8.1	7.7
Mo	–	–	1.43
Zr	0.6	0.2	1.7
B	0.02	0.02	0.008
Ni	88.08	83.1	81.1

[a]Cold workable.
[b]Hot and cold workable.
[c]Castable alloy.

Included in Figures 4 through 7 are the data on cast stainless steel, HU, and wrought Alloy 625. These two alloys are included for comparison because they are most commonly used by industry in a variety of applications. It is clear from Figures 4 through 7 that the Ni_3Al-based alloys are stronger than the competitive alloys for the entire temperature range. However, it is noted that the ductility of Ni_3Al-based alloys makes them available in only very limited wrought conditions as opposed to highly ductile and formable Alloy 625. HU is a cast alloy and is also not available in the wrought condition.

TABLE 4
COMPARISON OF NOMINAL CHEMICAL ANALYSIS OF IC-221M WITH THE RANGE OBSERVED FOR HEATS MADE USING VIRGIN AND REVERT STOCK IN A PILOT COMMERCIAL MELT RUN OF 94 HEATS CARRIED OUT AT A COMMERCIAL FOUNDRY

Element	Nominal (wt %)	Virgin heats (wt %)[a]		Revert heats (wt %)[b,c]	
		Range	Average	Range	Average
Al	8.0	7.5-8.2	7.86	7.3-8.3	7.74
Cr	7.7	7.63-8.11	7.81	7.56-8.5	7.88
Mo	1.43	1.38-1.50	1.45	1.34-1.56	1.43
Zr	1.70	1.73-2.02	1.93	1.62-2.05	1.86
B	0.0080	0.004-0.008	0.0054	0.003-0.008	0.0054
C	–	0.012-0.032	0.022	0.01-0.05	0.024
Si	–	0.021-0.055	0.036	0.026-0.155	0.061
Fe	–	0.03-0.15	0.077	0.03-0.91	0.194
Ni	81.1	*d*	80.81	*d*	80.81

[a]Twenty-six virgin heats.
[b]Fifty percent virgin and fifty percent revert.
[c]Sixty-eight revert heats.
[d]Balance.

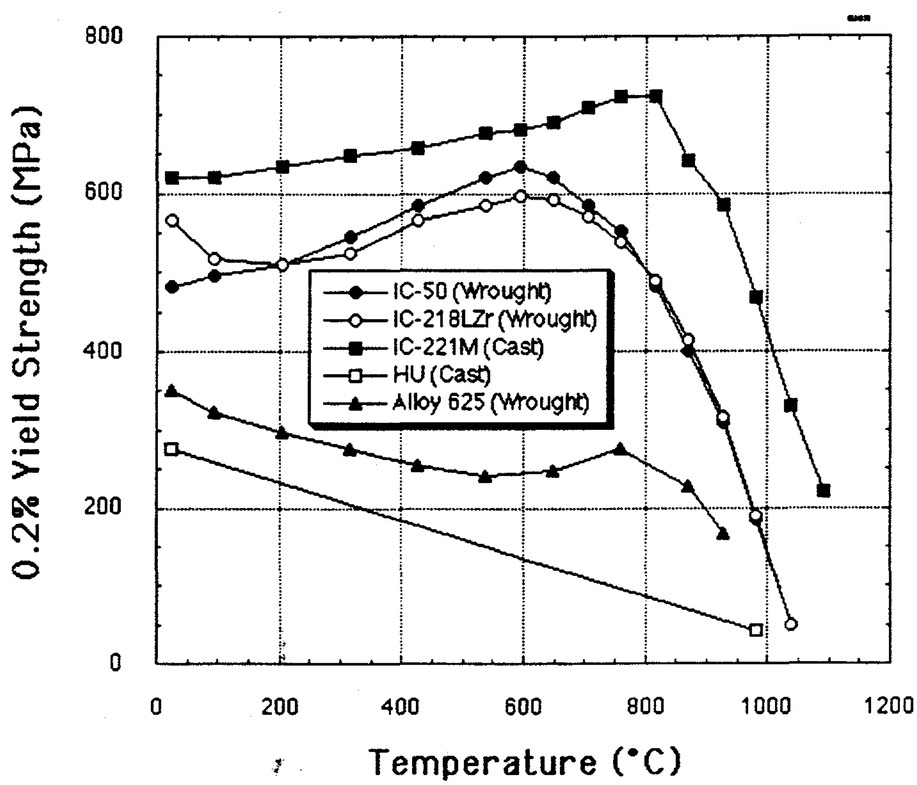

FIGURE 4 -The 0.2% yield strength as a function of test temperature for three nickel-aluminide alloys (IC-50, IC-218LZr, and IC-221M). The literature data for cast stainless steel, HU, and wrought nickel-based Alloy 625 are also included for comparison.

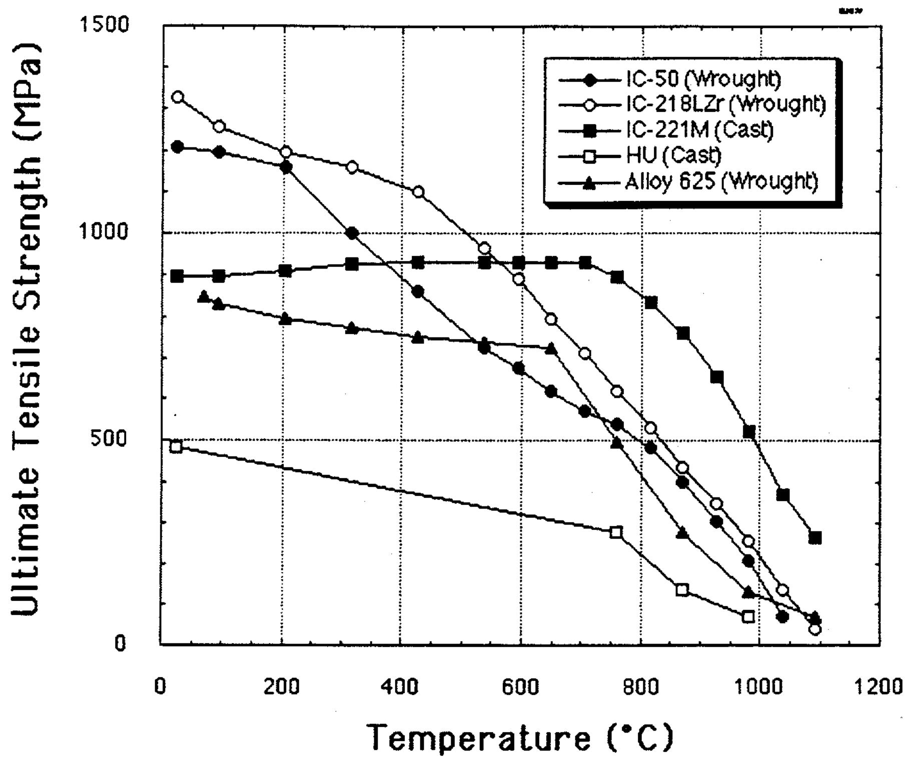

FIGURE 5 -The ultimate tensile strength as a function of test temperature for three nickel-aluminide alloys (IC-50, IC-218LZr, and IC-221M). The literature data for cast stainless steel, HU, and wrought nickel-based Alloy 625 are also included for comparison.

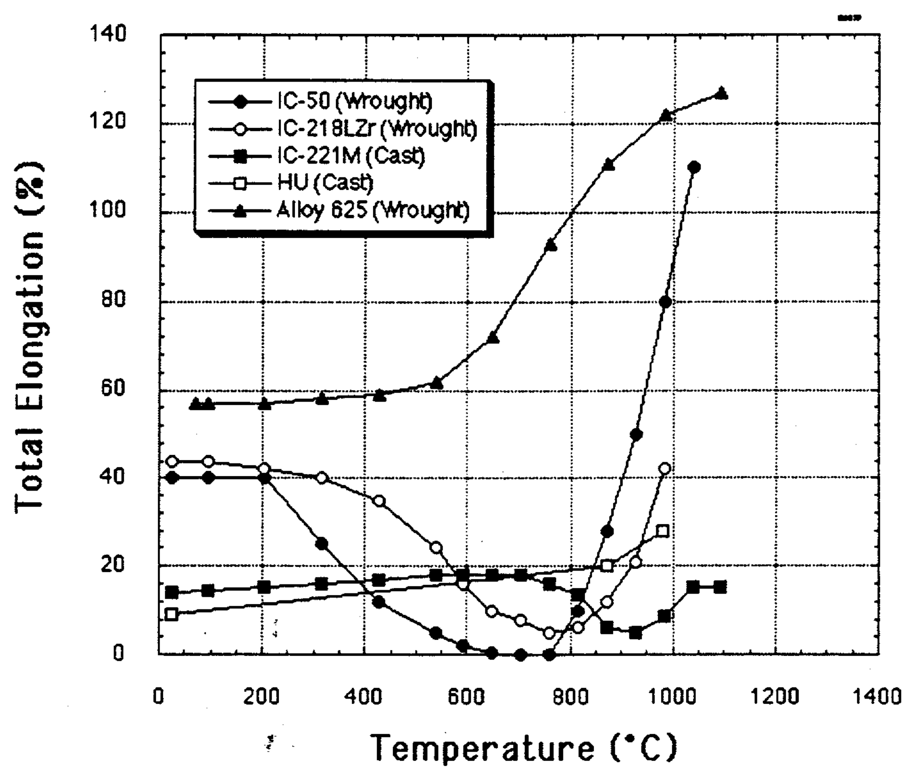

FIGURE 6 - Total elongation as a function of test temperature for three nickel-aluminide alloys (IC-50, IC-218LZr, and IC-221M). The literature data for cast stainless steel, HU, and wrought nickel-based Alloy 625 are also included for comparison.

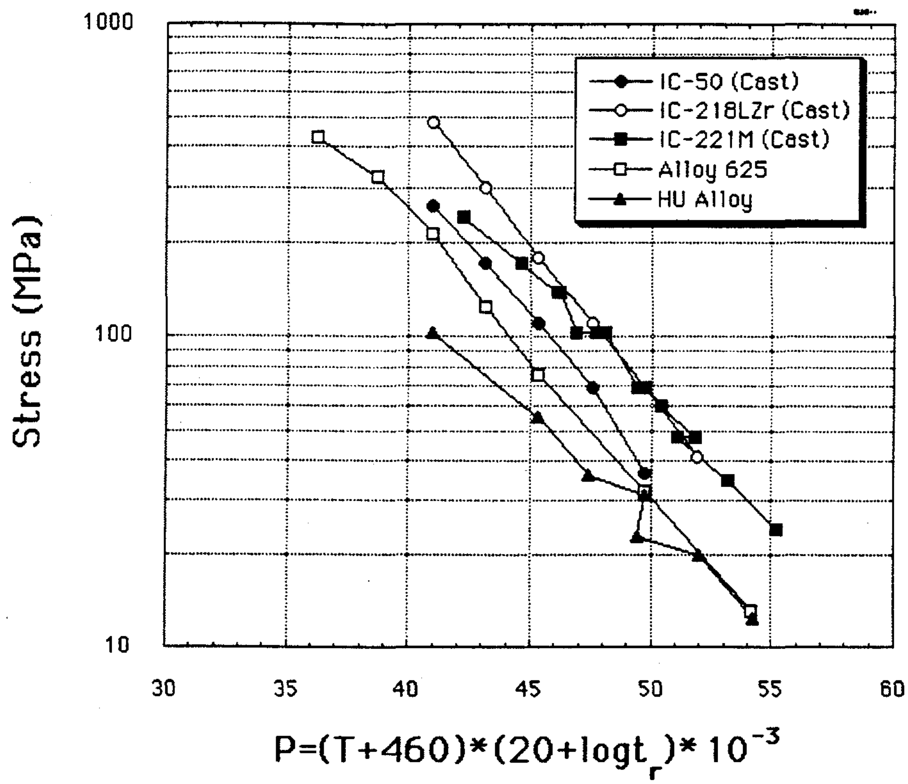

FIGURE 7 - Larson-Miller plot for creep rupture strength of cast Ni_3Al-based alloys (IC-50, IC-218LZr, and IC-221M). Literature data for cast stainless steel, HU, and wrought nickel-based Alloy 625 are also included for comparison.

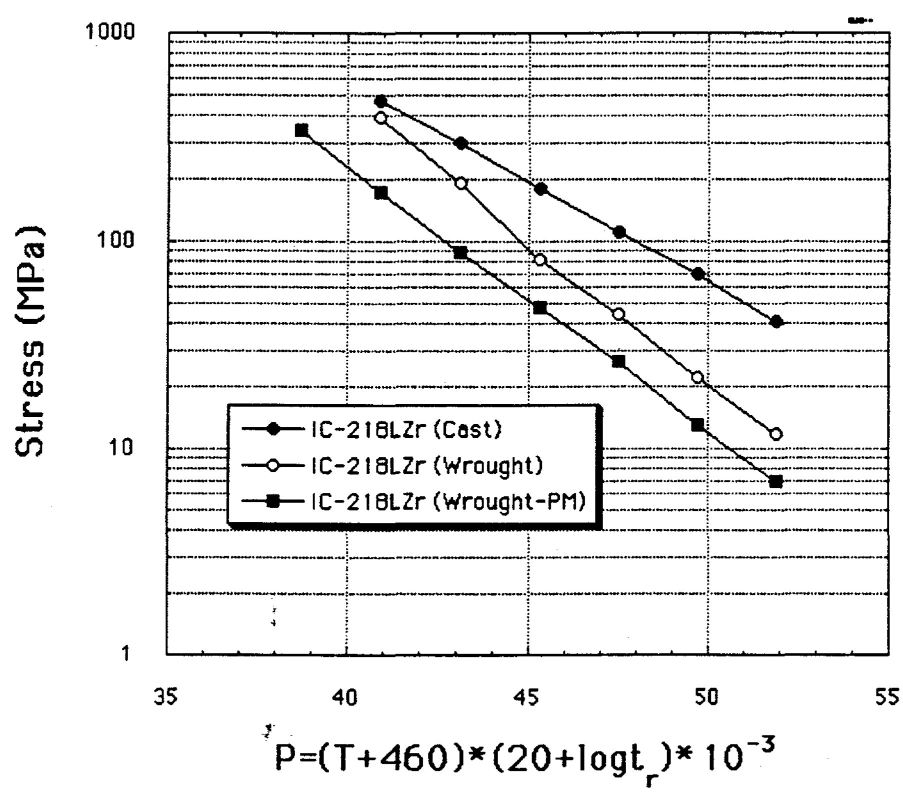

FIGURE 8 - Larson-Miller plot for creep rupture strength of IC-218LZr in cast and wrought conditions. The coarse grain cast structure has a very significant improvement in rupture strength than wrought product.

Fe_3Al- and FeAl-Based Alloys

Iron aluminides are attractive from the cost standpoint because their raw material constituents, iron and aluminum, are available in abundant quantities and are cheaper than most other alloying elements found in commercially used alloys. Both Fe_3Al and FeAl are oxidation and corrosion resistant because they form adherent protective (compact) Al_2O_3 scales at high temperature.[18] The iron aluminides are resistant to a wide range of high-temperature corrosive environments, including oxidation, carburization, sulfidation, and corrosion in molten nitrates and carbonate salts.[18-20] However, both Fe_3Al- and FeAl-based alloys have been plagued by poor mechanical properties at both ambient and elevated temperatures, as well as fabrication difficulties and inadequate weldability.

During 1985-1998 period, significant progress took place at ORNL in developing Fe_3Al- and FeAl-based alloys.[21-28] Among the most significant developments in iron aluminides was the identification of an environmental effect as the cause for their poor room-temperature ductility.[29] The environmental effect is related to the formation of hydrogen from the reduction of moisture in air by the aluminum in the iron aluminides. The moisture reduction reaction is given by:

$$2\,Al + 3\,H_2O \rightarrow Al_2O_3 + 6\,H\ . \tag{1}$$

It is the generation of this copious amount of atomic hydrogen that causes the embrittlement under applied stress conditions with significant loss of ambient temperature ductility. The moisture effect on the ductility of Fe_3Al is demonstrated in Table 5,[15] which shows that the ductility is highest in vacuum or in pure oxygen. However, the introduction of moisture into the evacuated chamber results in significant loss of ductility. The moisture effect was duplicated when tensile tests were conducted in air. Similar work on FeAl-based alloys is described in the literature.[15,29,30] The effects of other factors on the ductility of FeAl-based alloys have recently been reviewed by Baker and Munroe.[31]

TABLE 5
EFFECT OF TEST ENVIRONMENT ON ROOM-TEMPERATURE TENSILE PROPERTIES OF BINARY Fe_3Al (28 at. % Al)[a] [32]

Test environment	Elongation (%)	Strength (MPa)	
		0.2% Yield	Ultimate tensile
Air	3.7	279	514
Vacuum (10^{-4} Pa)	12.4	316	813
Oxygen[b]	11.7	298	888
H_2O Vapor[c]	2.1	322	439

[a]Specimens were annealed at 850°C for 1 h followed by a 5-d treatment at 500°C to stabilize DO_3 at room temperature. All of the tests were at a strain rate of $3.3 \times 10^{-3}\ s^{-1}$.

[b]Chamber was evacuated to 10^{-4} Pa, then oxygen was leaked in to a partial pressure of 6.7×10^{-4} Pa.

[c]Air saturated with water vapor was leaked into the vacuum chamber.

The effect of aluminum content on the room-temperature tensile ductility of Fe-Al alloys in air and vacuum is shown in Figure 9.[32] The difference in total elongation (TE) values between air and vacuum represents the environmental effect. The environmental effect (EE) is defined as

$$EE = [TE\ (vacuum) - TE\ (air)]/TE\ (vacuum) \times 100\ . \quad (2)$$

The EE is plotted as a function of aluminum content in Figure 10. It is clear from this figure that the environmental effect increases linearly with aluminum content and is least for the disordered alloy containing 16 at. % Al. The addition of 5% Cr is one method to essentially eliminate the environmental effect, as shown in Figure 9. This figure shows that the total elongation for the vacuum-tested Fe-Al alloys without chromium matches the total elongation in the air-tested alloy with 5% Cr.

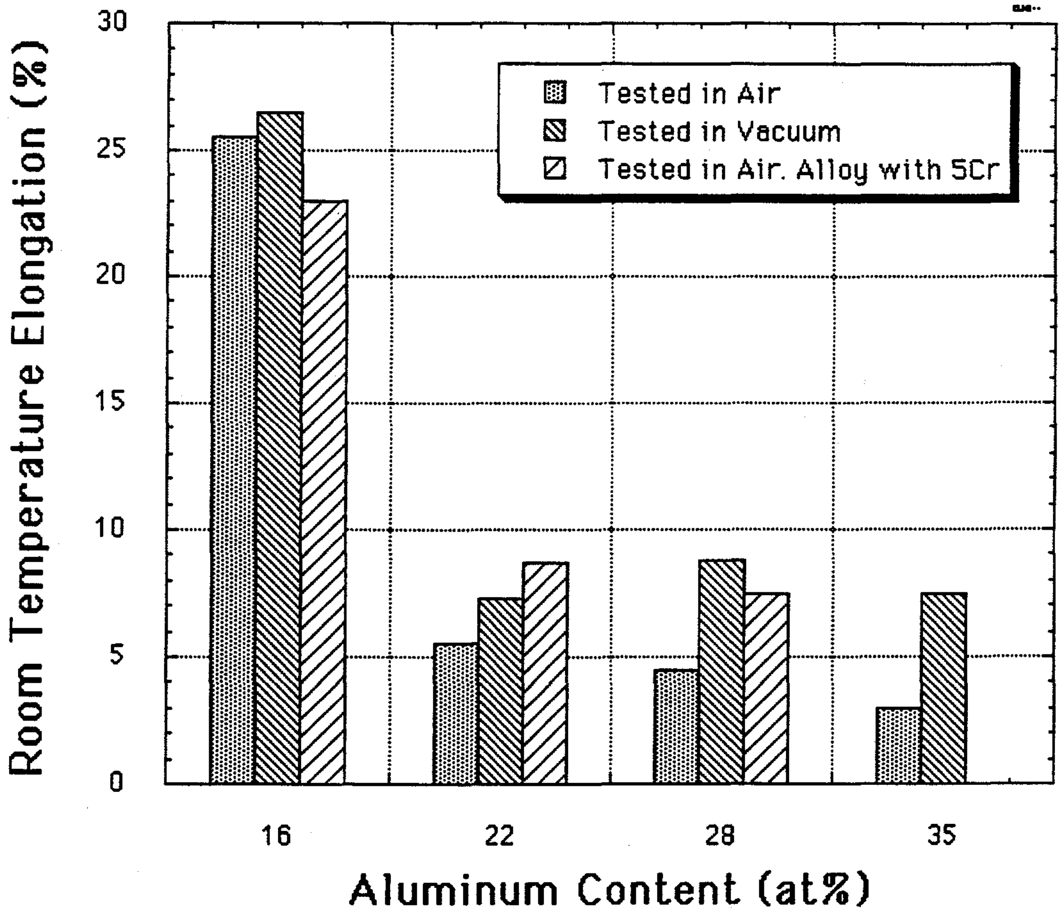

FIGURE 9 - Fe-Al alloys of four different aluminum contents. Data for alloys containing 5 at. % Cr in air are also included for comparison. The alloys containing 5 at. % Cr produce nearly the same ductility in air as the tests in vacuum, implying significant effect of chromium in reducing the environmental effect.

Based on basic studies of environmental effects and other strength and ductility considerations, three Fe_3Al- and four FeAl-based compositions are currently being pursued for the potential commercial application of iron aluminides (see Table 6). All of the Fe_3Al-based compositions (FAS, FAL, and FA-129) have been produced by AIM using the EM process and cast into round or slab ingots. The ingots were typically hot-worked at 1100°C and warm-worked at 650°C to sheet product used for mechanical property data. The average tensile properties of the Fe_3Al alloys are shown in Figures 11 through 13. These figures show that the leanest alloy (FAS) has the lowest strength properties, especially at temperatures over 600°C; the highly alloyed FA-129 has the highest. The lower ultimate tensile strength of FA-129 at room temperature, as opposed to 200°C, is caused by the environmental effect, which reduces work-hardening and ductility. However, at ≥ 200°C, where hydrogen can easily diffuse, the environmental effect is eliminated and normal flow stress behavior is followed. The creep data for Fe_3Al alloys in sheet form are shown in Figure 14.

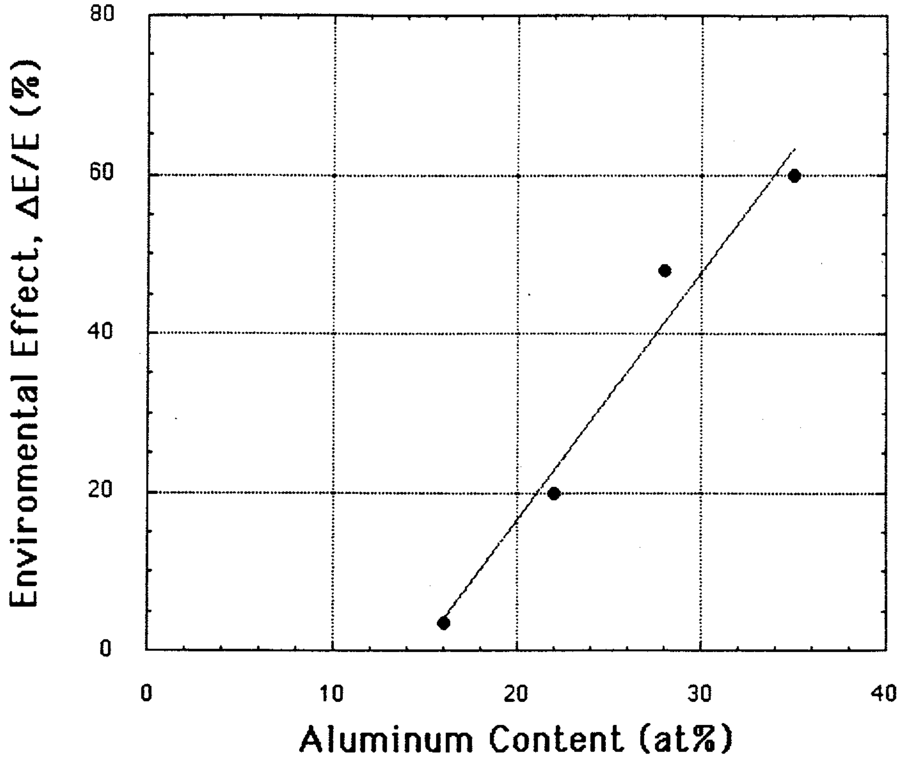

FIGURE 10 - Environmental effect (change in room-temperature elongation in air as compared to testing in vacuum) versus aluminum content for Fe-Al alloys. The environmental effect increases linearly with aluminum content.

TABLE 6
COMPOSITIONS OF Fe_3Al- AND FeAl-BASED ALLOYS

Element	Alloys (weight percent)							
	Fe_3Al-based			FeAl-based				
	FAS	FAL	FA-129	FA-385	FA-385M1	FA-385M2	FA-386M1	FA-386M2
C	–	–	0.05	0.03	0.03	0.03	0.10	0.10
Cr	2.2	5.5	5.5	–	–	–	–	–
Al	15.9	15.9	15.9	21.1	21.2	21.2	21.1	22.1
B	0.01	0.01	–	–	0.0025	0.0050	0.0050	0.0050
Mo	–	–	–	0.42	0.42	0.42	0.42	0.42
Zr	–	0.15	–	0.10	0.10	0.10	0.15	0.15
Nb	–	–	1.0	–	–	–	–	–
Ti	–	–	–	–	–	–	0.05	0.05
Fe	*a*	*a*	*a*	*a*	*a*	*a*	*a*	*a*
N	–	–	–	–	–	–	0.02	0.02

[a]Balance.

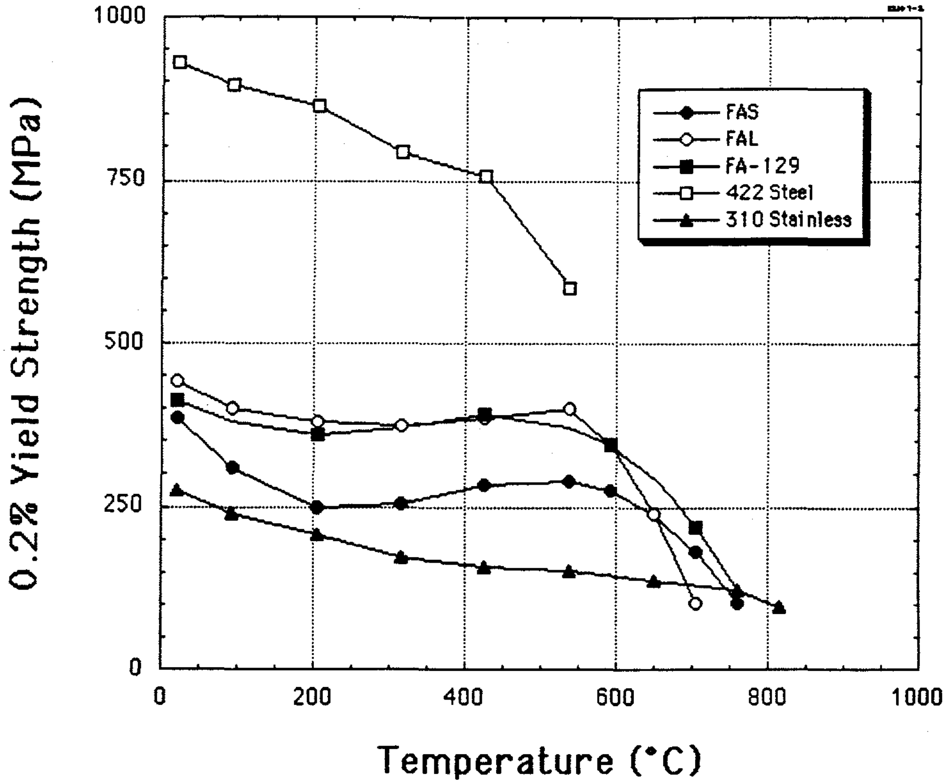

FIGURE 11 - Comparison of average 0.2% yield strength of wrought Fe_3Al-based alloys with that of wrought types 422 and 310 stainless steels.

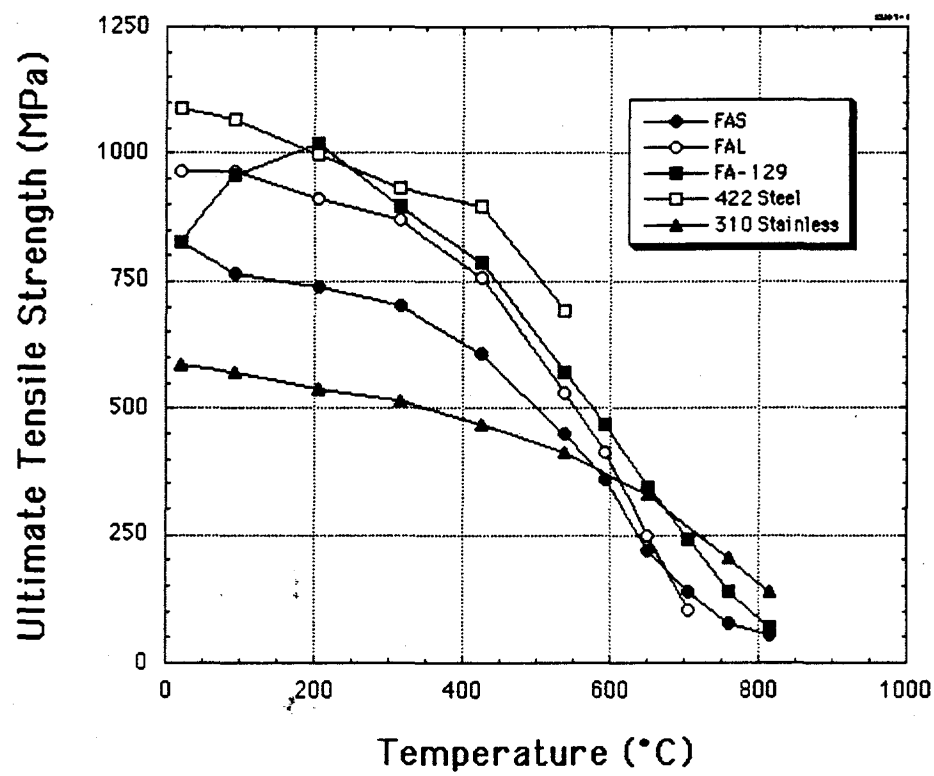

FIGURE 12 - Comparison of average ultimate tensile strength of wrought Fe_3Al-based alloys with that of wrought types 422 and 310 stainless steels.

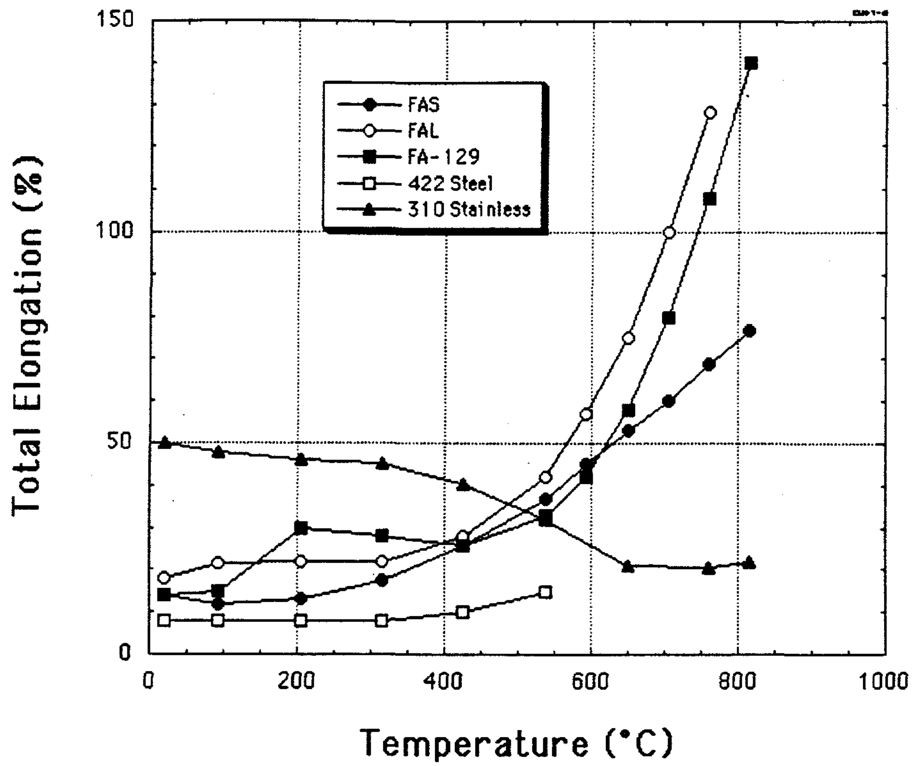

FIGURE 13 - Comparison of total elongation of wrought Fe_3Al-based alloys with that of wrought types 422 and 310 stainless steels.

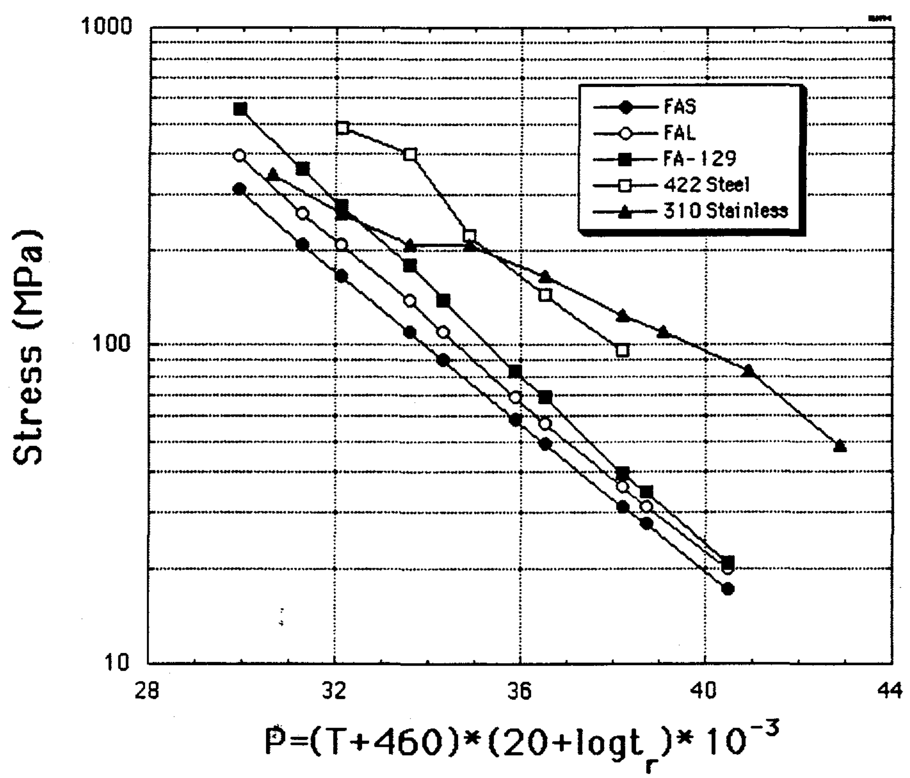

FIGURE 14 - Comparison of Larson-Miller parameters of average creep rupture strength of Fe_3Al-based alloys with that of wrought types 422 and 310 stainless steels.

Included also in Figures 11 through 14 are the comparative data on types 422 ferritic and 310 austenitic stainless steels. These comparisons show the tensile properties of Fe_3Al alloys are between the heat-treatable 422 and annealed 310 stainless steels. However, the creep rupture strength is shown to be below both stainless steels.

Tensile properties for FeAl-based alloys in the cast condition are plotted in Figures 15 through 17. The creep data for the cast and wrought (powder metallurgy processed) conditions are plotted in Figure 18. These figures also include the data on cast HU and wrought type 310 stainless steels and the Fe_3Al alloy FA-129. These graphs show: (1) there are only limited data available on FeAl alloys, and (2) the FeAl alloy in the cast condition has significantly higher yield strength values than Fe_3Al and stainless steel. The ultimate tensile strength values for FeAl alloys are lower than Fe_3Al, presumably because of its more sensitivity to environmental effect (see Figure 9); the FeAl also was tested in the cast, coarse-grained condition. At temperatures > 550°C, the ultimate tensile strength values of FeAl-based alloy FA-385M2 in the cast condition are higher than all competitive alloys. The total elongation values of FeAl-based alloys are lower than all other alloys up to a temperature of 550°C. Limited data in Figure 18 show the creep properties of FeAl to be higher than Fe_3Al alloys, and between 400 and 300 series stainless steels.

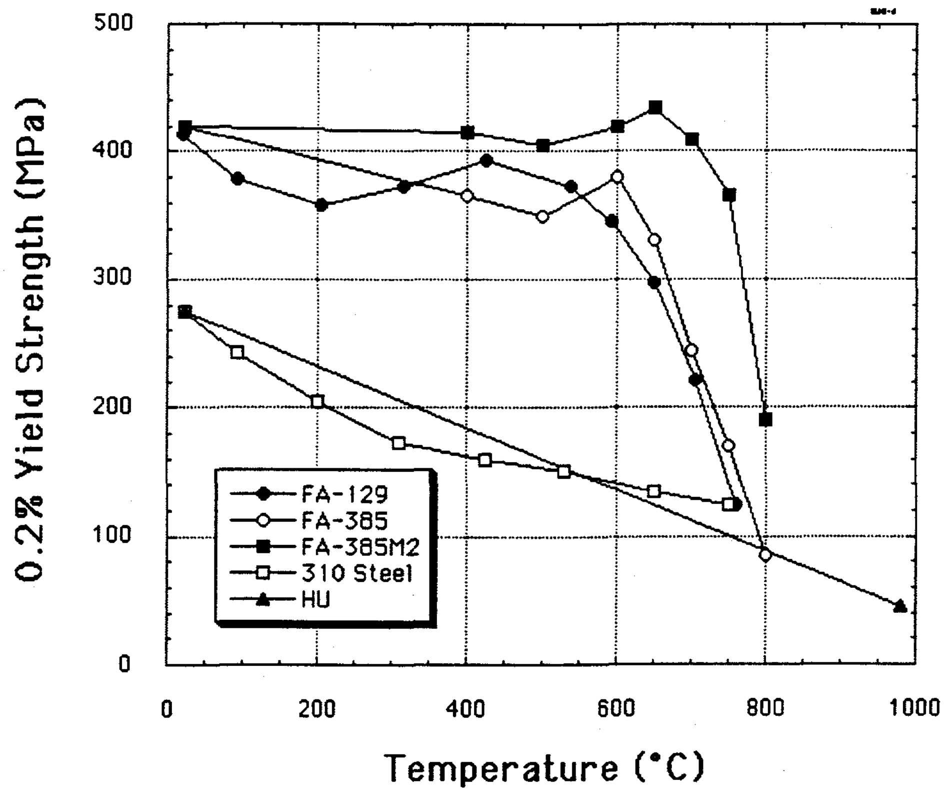

FIGURE 15 - Comparison of 0.2% yield strength of cast FeAl-based alloy with that of wrought type 310 and cast HU stainless steels. Data for wrought Fe_3Al alloy FA-129 is also included for comparison.

Besides the mechanical properties, the excellent corrosion properties of nickel and iron aluminides make them very attractive. The Ni_3Al-based alloys are especially resistant to oxidation and carburization and attack by chlorine at high temperatures.[16,19] The iron aluminides offer superior resistance to oxidation, and especially to sulfidation. The FeAl-based alloys also show excellent resistance to carburization and certain molten salts.[33,34] Data for the aqueous corrosion behavior of iron and nickel aluminides are also available.[34,35]

APPLICATIONS

The nickel and iron aluminides have niche applications based on their combination of mechanical and corrosion properties.[16] The specific applications of Ni_3Al- and iron-based alloys are briefly described.

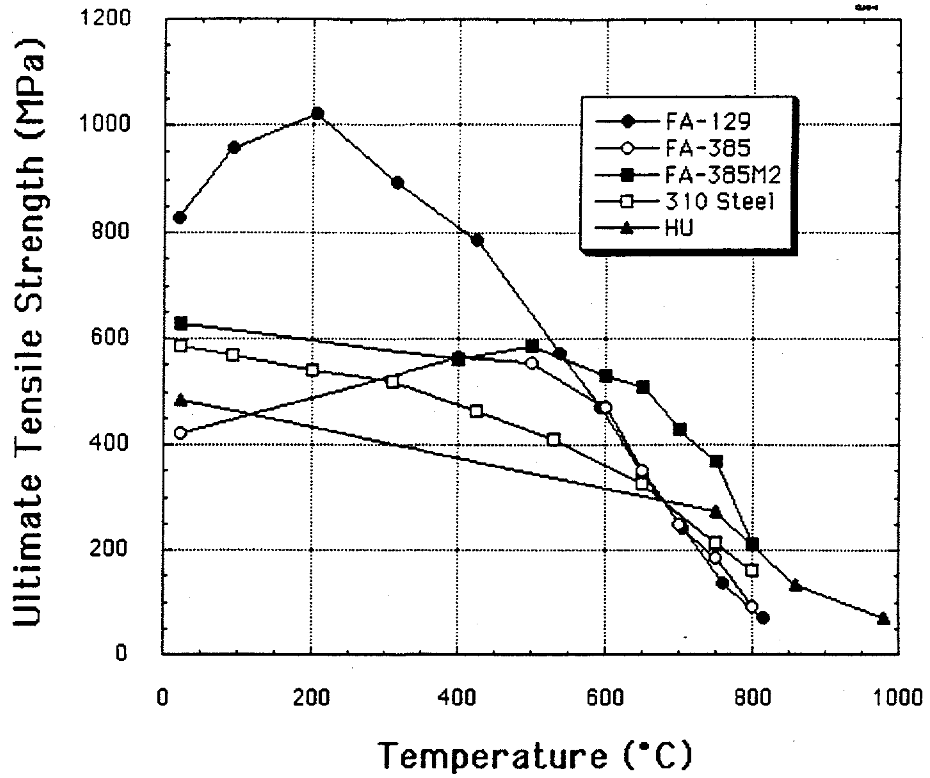

FIGURE 16 - Comparison of ultimate tensile strength of cast FeAl-based alloy with that of wrought type 310 and cast HU stainless steels. Data for wrought Fe_3Al alloy FA-129 is also included for comparison.

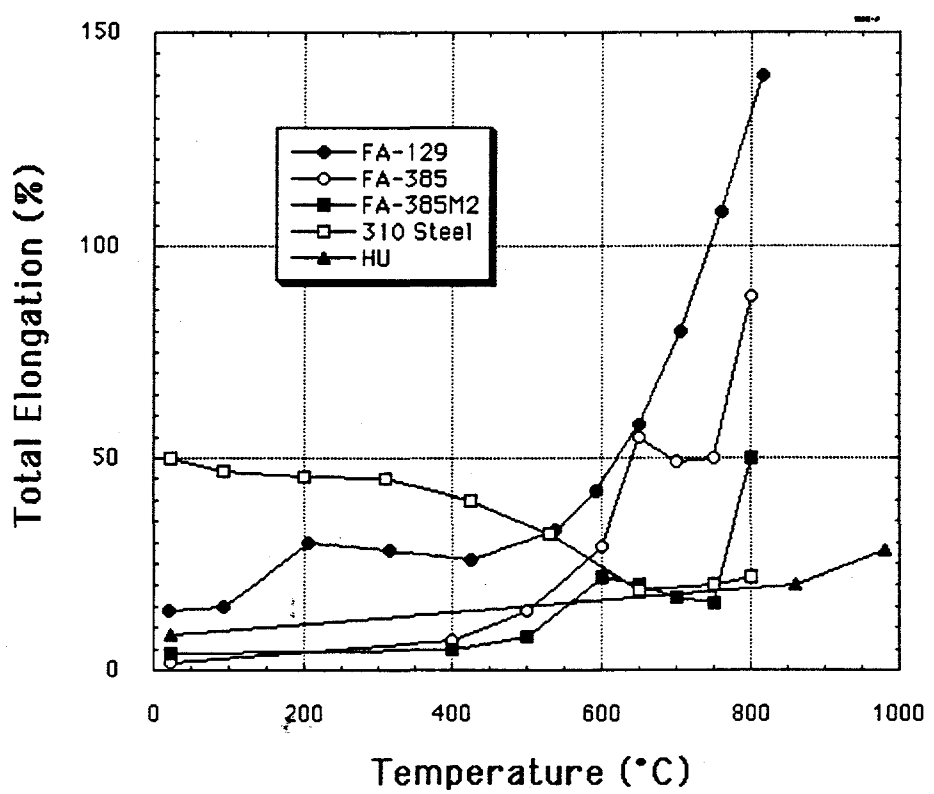

FIGURE 17 - Comparison of total elongation of cast FeAl-based alloy with that of wrought type 310 and cast HU stainless steels. Data for wrought Fe_3Al alloy FA-129 is also included for comparison.

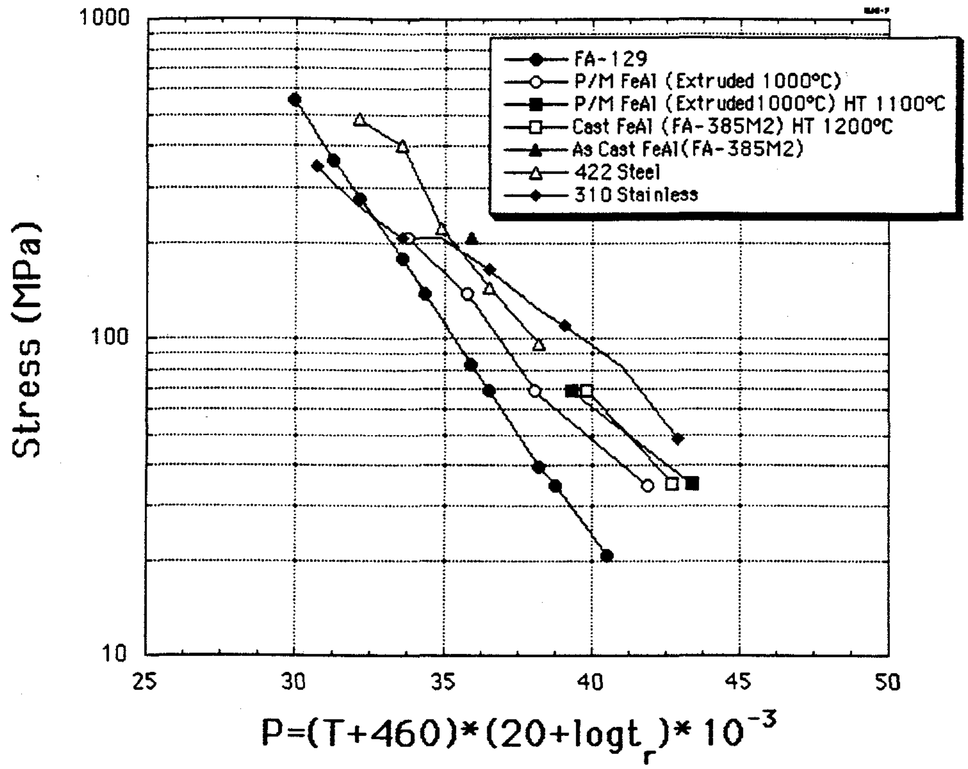

FIGURE 18 - Comparison of Larson-Miller parameter of creep rupture strength of wrought powder metallurgy and cast FeAl-based alloys with that of wrought type 310 and cast HU stainless steels. Data for wrought Fe_3Al alloy FA-129 is also included for comparison.

Ni_3Al-Based Alloy IC-221M

The cast nickel-aluminide alloy IC-221M has found application as trays and fixtures for carburizing furnaces (see Figure 19). Nickel-aluminide rolls have demonstrated excellent performance as transfer rolls in steel plate austenitizing furnaces. These rolls have been in service in the Bethlehem Steel Corporation, Burns Harbor furnace for over four years. Another very significant application of Ni_3Al is for tube hangers in

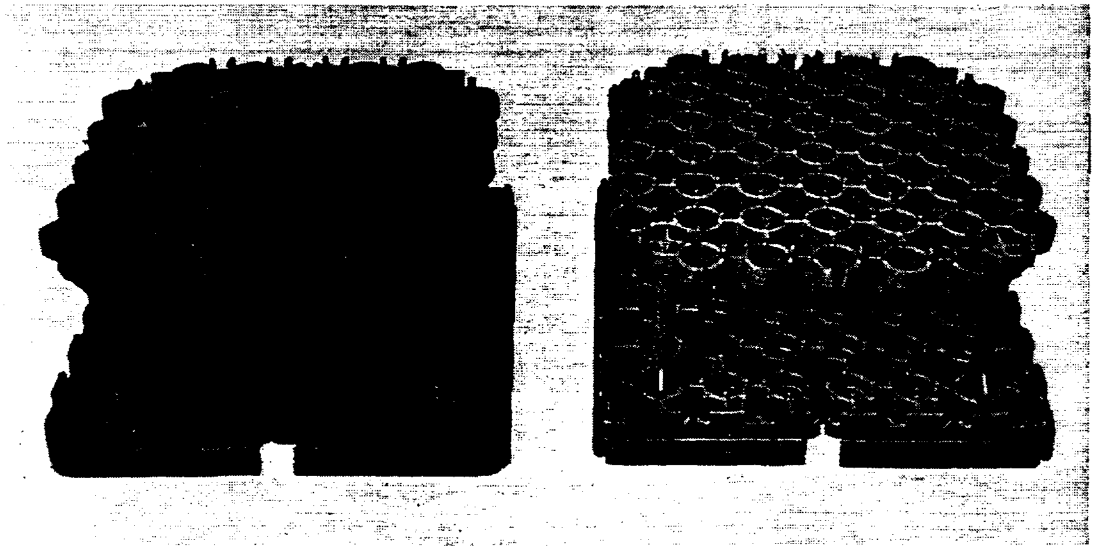

FIGURE 19 - Photograph of sand-cast trays and fixtures of IC-221M for continuous pusher carburizing furnaces.

the petrochemical industry. A cast tube hanger of IC-221M is shown in Figure 20. A newer application of IC-221M is as a radiant burner tube for heat-treating furnaces. In most cases, the applications of IC-221M are for material in the cast condition. However, there are possible applications as weld overlays and HVOF coatings.

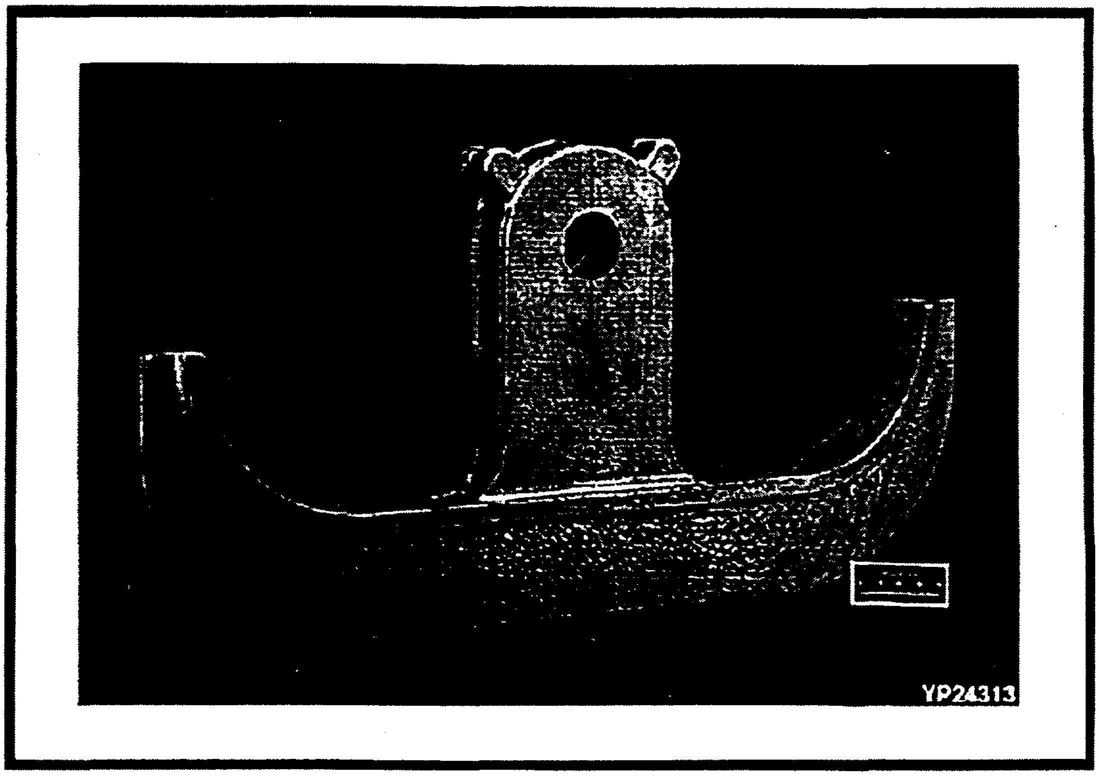

FIGURE 20 - Photograph of sand-cast tube hanger of IC-221M.

Fe_3Al and FeAl Alloys

The major application of Fe_3Al is currently for hot gas filters. These filters are manufactured by sintering powders using a proprietary process.[36] The other applications of Fe_3Al and FeAl are as weld-overlays in carburizing, sulfidizing, and molten salt applications. The FeAl-based alloy is currently being used in sheet form for microheaters .

LICENSEES

The following is a list of licensees and their products relative to intermetallic compounds invented at ORNL:

1. Alloy Engineering & Casting Co. (Champaign, Illinois) — This license deals with the production of sand castings and centrifugal-cast tubes of Ni_3Al-based alloys.

2. Alcon Industries (Cleveland, Ohio) — This license deals with the production of sand castings of Ni_3Al-based alloys.

3. Sandusky International (Sandusky, Ohio) — This license deals with the production of centrifugal castings of Ni_3Al-based alloys.

4. United Defense LP (Anniston, Alabama) — This license deals with the production of sand castings of Ni_3Al-based alloys.

5. Ametek Specialty Metals Products Division (Eighty Four, Pennsylvania) — This license is for the production of nickel- and iron-aluminide powders.

6. Stoody Company (Bowling Green, Kentucky) — This license is for the production of Ni_3Al weld wire.

7. Polymet Corporation (Cincinnati, Ohio) — This license is for nickel-aluminide wire.

8. Armco Research and Technology (Middletown, Ohio) — This license is for the production of nickel aluminides.

9. Hoskins Manufacturing Company (Hamburg, Michigan) — This license is for iron-aluminide wire, rod, and strip.

FUTURE OF INTERMETALLIC-BASED ALLOYS

Research into intermetallic-based alloys is currently a worldwide activity. Research is being pursued at universities, national laboratories, and industry, and the results are published in journals, books, and special symposia. Although extensive research has been conducted on a very broad range of intermetallics, the Ni_3Al-, Fe_3Al-, and FeAl-based alloys are closest to commercialization. The initial positive experience with Ni_3Al-based alloys is enhancing the awareness of many different industry sectors of these alloys. Based on inquiries to ORNL and to our licensees, the future of Ni_3Al-, Fe_3Al-, and FeAl-based alloys looks very favorable. Clearly, there is a great need for additional data development to further expand the applications of intermetallic-based alloys , and we at ORNL plan to continue developing such information.

SUMMARY AND CONCLUSIONS

This paper has introduced the subject of intermetallic compounds for structural applictions. Some specific differences in properties between the intermetallic and pure metals are pointed out. The Ni_3Al-, Fe_3Al-, and FeAl-based intermetallic alloys appear to be of the most practical significance in the near future. An overview is presented of the significant scientific developments that have resulted in the identification of alloy compositions for commercial applications. Mechanical properties (tensile and creep) of the alloys identified for commercial applications are presented. A brief description of the applications and the future of intermetallic alloys is also presented. Specific conclusions from this paper include:

1. The Ni_3Al-, Fe_3Al-, and FeAl-based intermetallic alloys appear to be closest to commercialization.

2. The Ni_3Al-based cast alloy IC-221M has the most extensive data base and operating experience in commercial applications.

3. The Fe_3Al-based alloy is in use as porous metal gas filters.

4. The FeAl-based alloy is in use as microheaters.

5. Many new applications of nickel and iron aluminides are currently being tested.

ACKNOWLEDGMENTS

The author thanks C. A. Blue and I. G. Wright for reviewing the paper, C. R. Howell for assisting with the graphics, and M. L. Atchley for preparing the manuscript.

Research for this work was sponsored by the U.S. Department of Energy, Assistant Secretary for Energy Efficiency and Renewable Energy, Office of Industrial Technologies, Advanced Industrial Materials Program, *and Office of Fossil Energy, Advanced Research and Technology Development Materials Program, [DOE/FE AA 15 10 10 0, Work Breakdown Structure Element ORNL-2(H)]* under contract DE-AC05-96OR22464 with Lockheed Martin Energy Research Corporation.

REFERENCES

1. R. W. Cahn, *Metals, Materials, and Processes*, **1** (1989) 1.

2. D. L. anton, D. M. Shah, D. N. Duhl, and A. F. Giamei, *JOM*, **41**(9) (1989) 12.

3. R. L. Fleischer, D. M. Dimiduk, and H. A. Lipsitt, *Annu. Rev. Mater. Sci.*, **19** (1989) 231.

4. R. L. Fleischer and A. I. Taub, *JOM*, **41**(9) (1989) 8.

5. N. S. Stoloff and R. G. Davies, *Prog. Mater. Sci.*, **13** (1966) 1.

6. J. H. Westbrook, ed., *Mechanical Properties of Intermetallic Compounds* (Wiley, New York, NY, 1960).

7. J. H. Westbrook, ed., *Intermetallic Compounds* (Wiley, New York, NY, 1967).

8. B. H. Kear, C. T. Sims, N. S. Stoloff, and J. H. Westbrook, eds., *Ordered Alloys — Structural Applictions and Physical Metallurgy* (Claitors Pub. Div., Baton Rouge, LA, 1970).

9. R. L. Fleischer, p. 157 in *Intermetallic Compounds — Structure and Mechanical Properties*, O. Izumi, ed., Proceedings of JIMIS-6 (Japan Institute of Metals, Tokyo, 1991).

10. E. M. Schulson, "Brittle Fracture and Toughening of Intermetallic Compounds," in *Intermetallics Physical Metallurgy and Processing of Intermetallic Compounds*, ed. N. S. Stoloff and V. K. Sikka (Van Nostrand Reinhold, New York, NY, 1994).

11. K. Aoki and O. Izumi, *Nippon Kinzoku Gakkaishi*,**43**, 1190 (1979).

12. C. T. Liu, C. L. White, and J. A. Horton, *Acta Metall.*, **33** (1985) 213.

13. M. Takeyama and C. T. Liu, *Mater. Sci. Eng.*, **A153** (1992) 538-47.

14. C. T. Liu and V. K. Sikka, *J. Met.*, **38** (1986) 19.

15. V. K. Sikka, *Oxidation and Corrosion of Intermetallic Alloys*, ed. G. Welsch and P. D. Desai (CINDAS/Purdue University: West LaFayette, IN, 1996) pp. 1-118.

16. V. K. Sikka, "Commercialization of Nickel and Iron Aluminides," *Proc. Intl. Symp. on Nickel and Iron Aluminides: Processing, Properties, and Applications*, (1997) 361-75.

17. V. K. Sikka, S. C. Deevi, and J. D. Vought, *Adv. Mater. Process.*, **147** (1995) 29-31.

18. P. F. Tortorelli and J. H. DeVan, *Oxidation and Corrosion of Intermetallic Alloys*, eds. G. Welsch and P. D. Desai (CINDAS/Purdue University: West Lafayette, IN,1996) pp. 266-321.

19. J. H. DeVan, *Oxidation Behavior of High-Temperature Intermetallics*, eds. T. Grobstein and J. Doychak (The Materials, Metals and Minerals Society: Warrendale, PA, 1989) pp. 107-115.

20. P. F. Tortorelli and P. S. Bishop, *Influence of Compositional Modifications on the Corrosion of Iron Aluminides by Molten Nitrate Salts*, Oak Ridge National Laboratory, ORNL/TM-11598 (January 1991).

21. C. G. McKamey, J. H. DeVan, P. F. Tortorelli, and V. K. Sikka, *J. Mater. Res.*, **6** (1991) 1779-1805.

22. N. S. Stoloff and C. T. Liu, *Intermetallics*, **2** (1994) 75-87.

23. C. G. McKamey, P. J. Maziasz, G. M. Goodwin, and T. Zacharia, *Matls. Sci. and Engin.*, **A174** (1994) 59-70.

24. C. T. Liu, V. K. Sikka, and C. G. McKamey, *Alloy Development of FeAl Aluminide Alloys for Structural Use in Corrosive Environments*, Oak Ridge National Laboratory, ORNL/TM-12199 (February 1993).

25. P. J. Maziasz, C. T. Liu, and G. M. Goodwin, *Heat-Resistant Materials II*, eds. K. Natesan, P. Ganesan, and G. Lai (ASM International: Materials Park, OH, 1995) pp. 555-566.

26. C. T. Liu, C. G. McKamey, P. F. Tortorelli, and S. A. David, "Corrosion Resistant Iron Aluminides Exhibiting Improved Mechanical Properties and corrosion Resistance," U.S. Patent 5,320,802, issued June 14, 1994.

27. P. J. Maziasz, G. M. Goodwin, and C. T. Liu, "High-Temperature Corrosion Resistant Iron Aluminide Alloys Exhibiting Improved Weldability," U.S. Patent 5,545,373, issued August 13, 1996.

28. V. K. Sikka, Processing of Intermetallic Aluminides," *Intermetallics - Physical Metallurgy and processing of Intermetallic Compounds*, eds. N. S. Stoloff and V. K. Sikka, Chapman and Hall, New York, NY, 1994.

29. C. T. Liu, e. H. Lee, and C. G. McKamey, *Scr. Metall.*, **23** (1989) 875.

30. P. J. Maziasz, G. M. Goodwin, D. J. Alexander, S. Viswanathan, *Proceedings of the International Symposium on Nickel and Iron Aluminies: Pocessing, Properties,a nd Applications*, eds. S. C. Deevi, V. K. Sikka, P. J. Maziasz, and R. W. Cahn (ASM Intenational: Materials Park, OH, 1997) pp. 157-176.

31. I. Baker and P. R. Munroe, *International Materials Reviews*, **42**(5) (1997) 181-220.

32. V. K. Sikka, S. Viswanathan, and C. G. McKamey, *Structural Intermetallics*, ed. R. Darolia, J. J. Lewandowski, C. T. Liu, P. L. Martin, D. B. Miracle, and M. V. Nathal (The Minerals, Metals & Materials Society, Warrendale, PA, 1993) pp. 483-91.

33. K. Natesan and P. F. Tortorelli, *Proceedings of the International Symposium on Nickel and Iron Aluminies: Pocessing, Properties,a nd Applications*, eds. S. C. Deevi, V. K. Sikka, P. J. Maziasz, and R. W. Cahn (ASM Intenational: Materials Park, OH, 1997) pp. 265-280.

34. R. A. Buchanan, J. G. Kim, R. E. Ricker, and L. A. Heldt, *Oxidation and Corrosion of Intermetallic* Alloys, eds. G. Welsch and P. D. Desai (CINDAS/Pardue University: West LaFayette, IN, 1996) pp. 351-419.

35. R. E. Ricker, *Proceedings of the International Symposium on Nickel and Iron Aluminies: Pocessing, Properties,a nd Applications*, eds. S. C. Deevi, V. K. Sikka, P. J. Maziasz, and R. W. Cahn (ASM Intenational: Materials Park, OH, 1997) pp. 253-263.

36. J. Hurley, S. Brosious, and M. Johnson, "Iron Aluminide Hot Gas Filters," paper presented at the Advanced Coal-Fired Power Systems 1996 Review Meeting, Morgantown Energy Technology Center, July 18, 1996.