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OVERVIEW OF THE DEVELOPMENT OF FeAl INTERMETALLIC ALLOYS

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ABSTRACT

B2-phase FeAl ordered intermetallic alloys based on an Fe-36 at.% Al composition are being developed to optimize a combination of properties that includes high-temperature strength, room-temperature ductility, and weldability. Micro-alloying with boron and proper processing are very important for FeAl properties optimization. These alloys also have the good to outstanding resistance to oxidation, sulfidation, and corrosion in molten salts or chlorides at elevated temperatures, characteristic of FeAl with 30-40 at.% Al. Ingot- and powder-metallurgy (IM and PM, respectively) processing both produce good properties, including strength above 400 MPa up to about 750°C. Technology development to produce FeAl components for industry testing is in progress. In parallel, weld-overlay cladding and powder coating technologies are also being developed to take immediate advantage of the high-temperature corrosion/oxidation and erosion/wear resistance of FeAl.

INTRODUCTION

IRON- AND NICKEL-ALUMINIDE INTERMETALLICS generally have outstanding oxidation/corrosion resistance (>1000-1100°C) because they form a thin, stable, adherent Al_2O_3 film [1-3]. However, the thermodynamic forces driving this reaction can also cause environmental/hydrogen embrittlement at room temperature due to moisture in the air [4-6]. There are metallurgical solutions to this problem, and with proper alloying (particularly boron addition) and processing to control microstructure, ductilities in the range of 5-40% or more can seen in Fe_3Al, Ni_3Al or FeAl alloys. The considerable effort at the Oak Ridge National Laboratory (ORNL) on the development and commercialization of Fe_3Al-type iron-aluminide alloys has been well documented and reviewed [3,7-11]. Related work on FeAl alloys began later at ORNL and was not published until patents were filed [12-14]. The purpose of this paper is to overview ORNL work on developing FeAl alloys, with emphasis on the current status and on potential industrial applications. Key results will be highlighted, with experimental details to be found elsewhere.

INITIAL FeAl ALLOY DEVELOPMENT

FeAl is attractive because it maintains its excellent oxidation and corrosion resistance to higher temperatures than Fe_3Al, and has a much higher ordered-B2 to disordered-α phase transition temperature (>1100°C compared to 800-900°C for Fe_3Al alloys). However, FeAl alloys tended to be more brittle and more difficult to fabricate than lower aluminum alloys, and to be weak above 600°C. FeAl development at ORNL was initiated in 1989-1990 to provide a new structural material resistant to highly-oxidizing molten nitrate salts at 650°C [15]. Base binary FeAl alloy compositions ranging from 28-43 at.% Al showed that alloys with 35-40 at.% had good high-temperature ductility (Fig. 1a), but that alloys with ≥35 at.% Al had the best resistance to molten salt corrosion at 650°C (Fig. 1b). Examination of the fracture mode indicated that FeAl alloys with <40 at.% Al showed transgranular failure, while alloys with >40 at.% Al exhibited mainly grain boundary failure. Therefore, Fe-36 at.% Al was chosen as the base FeAl alloy for alloy development to improve the room-temperature ductility and high-temperature strength [13]. These FeAl alloys also showed oxidation resistance to >1100°C and sulfidation resistance, at least at 800°C, that was far superior to FeCrNi and FeCrAl alloys, and similar to Fe-28 at.% Al (Fig. 1c).

The first phase of FeAl alloy development explored additions of Cr, Ni, Co, Mn, Ti, Zr, V, Mo, B and C to a base alloy of Fe-36 at.% Al. The most effective elements for increasing high-temperature strength and room-temperature ductility of these FeAl alloys were small additions of Mo, Zr and B in combination, with the synergistic effects being much more potent than the single element effects [12,17]. While Zr and B additions were very important for improved room-temperature ductility, Mo+Zr+B additions produced the best tensile and creep-rupture strength at 600°C (Fig. 2a) in an alloy designated FA-362 (Table 1). The FA-362 alloy also showed the highest room-temperature ductility in air (11.8%)

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ever reported for bare FeAl specimens. Preoxidation at 700°C further increased the tensile ductility to 14.7% [6]. Boron additions had also been found to have an important beneficial effect on the room-temperature ductility of an Fe-40 at.% Al alloy [19], and Mo, Zr, and B are all important additives for high-temperature strength in Fe$_3$Al alloys as well [20-22]. The initial weldability tests of these FeAl alloys showed that all alloys with 0.24 at.% B additions were unweldable due to hot-cracking, and that the B-free FeAl alloys showed even marginal weldability [17]. However, the best weldability was found in the FA-385 and FA-388 alloys that contained 0.13-0.24 at.% C instead of B [17]. Therefore, a second phase of FeAl alloy development at ORNL focused on improving the weldability of these alloys.

DEVELOPMENT OF WELDABLE FeAl ALLOYS

WELDABILITY - The goal of the second phase of the program was to improve the weldability of the FA-385/FA-388 based alloys without further degrading the good mechanical properties achieved in the FA-362/FA-372 type alloys. The FA-385 alloy was chosen as the base FeAl alloy for further composition modifications because while carbon improved weldability, it was also already known that too much carbon had a deleterious effect on the room-temperature ductility and high-temperature strength of both FeAl and Fe$_3$Al type alloys [7,12,17]. The modified alloy compositions (FA-385-M1 thru -M11) are also shown in Table 1. The Sigmajig test [23] was used to quantitatively measure the threshold stress for hot-cracking in thin-sheet specimens of all these FeAl alloys (Fig. 2b) [24]. From the standpoint of hot-cracking resistance, the best FeAl alloys were FA-385 modified with micro-additions of boron (0.01-0.021 at.%, FA-385M1 and -385M2, respectively, Table 1). For perspective, threshold hot-cracking stresses above 100 MPa are considered to be good, with 300 series austenitic stainless steels falling in the range of 100-280 MPa [23]. There are very few weldability studies of FeAl iron-aluminides. Of the Fe$_3$Al alloys developed at ORNL, the most weldable (FA-129) has a threshold hot-cracking stress of 172 MPa while others fall in the range of 100-140 MPa [25]. The modified FeAl alloys with Cr, Nb, and with Cr+Nb+Ti also showed good weldability, but did not have good mechanical behavior. By contrast, FA-385 alloys modified with small amounts of boron showed the best strength at 600°C (Fig. 2a), and room-temperature properties roughly similar to the base FA-385 alloy. From these results, further FeAl alloy development focused on the FA-385 and the B-micro-alloyed FA-385 alloys for microstructure/processing optimization for improved mechanical behavior. A parallel effort began in 1992 to explore FeAl weld-overlay cladding on structural steels to try to take immediate advantage of the newly discovered weldability and the inherent FeAl oxidation/corrosion resistance for industrial applications.

ENVIRONMENTAL EFFECTS AND ROOM-TEMPERATURE DUCTILITY - One difficult problem was the fact that most of the hot-rolled sheet-specimens of the FeAl alloys showed relatively low ductility in air (<1%), with some showing only a fracture stress of 300 MPa or less. One typical example (ε_t<0.1%) is shown for a FA-385 specimen punched from sheet that was hot-rolled at 900°C and then heat-treated for 1h at 900°C and tensile tested in air (Fig. 3a and 3b). After Liu and co-workers found that environmental embrittlement was a major cause for low ductility in FeAl alloys tested in air at room temperature in 1989 [4], an identical FA-385 specimen was tested in oxygen at room temperature and showed 10.5% elongation (fig. 3a) and much higher UTS. A higher heat-treatment of 1h at 1000°C produced 1.8% elongation in air and 14.7% in oxygen for the same hot-rolling condition. The hot-rolled sheet material had a relatively large recrystallized grain size of >250 μm. Hot-extrusion at 900°C of the same FA-385 alloy produced a much finer grain size of 25-80 μm (similar to FA-385M1 shown in Fig. 4a), which increased the ductility in air (to 8.4%), and the strength (UTS-760 MPa) relative to the hot-rolled material. The much smaller difference between the elongation of the hot-extruded material in air and in oxygen clearly shows that the finer-grained microstructure also made the FA-385 alloy more resistant to moisture-induced hydrogen embrittlement. The oxide present from the stress-relief heat-treatment in air also contributes to this effect, as observed by Liu for preoxidation of FeAl [6], and analogous to the beneficial effect of oil observed by Sikka et al [9] in Fe$_3$Al alloys. These results demonstrate the importance of moisture/hydrogen effects on the mechanical behavior of FeAl at room-temperature in air, and the importance of microstructure/processing control in minimizing or eliminating such embrittlement effects.

PHYSICAL PROPERTIES - The lack of physical properties on FeAl prompted an effort in 1993-1994 to better determine them for the FA-385 alloy to a) aid in selecting engineering applications appropriate for FeAl, b) help select and determine substrate behavior for FeAl weld-overlay cladding, and c) help optimize processing parameters. FeAl with 36 at.% Al has a density of about 6 gm/cm^3 [27,28], has the ordered-B2 phase structure from room-temperature until it disorders at about 1100-1125°C, has a solidus of 1402°C [29], and is non-magnetic. It has a relatively high Young's modulus of 180 GPa. The B2→α transition can be seen in the plot of specific heat versus temperature shown in Fig. 5a. The thermal expansion and thermal conductivity of FeAl/FA-385 are shown in Figs. 5b and 5c, respectively [29,30]. The thermal expansion of FeAl is somewhat similar to type 316 austenitic stainless steel up to about 1000°C, but its thermal conductivity is significantly lower than that found in austenitic stainless steel. The combination of higher thermal expansion and low conductivity can easily lead to high near-surface stresses if

FeAl specimens are cooled too fast. The FA-385 alloys shows a hardness of 260 dph (diamond-pyramid hardness) for ingot-metallurgy (IM) material extruded at 900°C, and >300 dph for powder-metallurgy (PM) material extruded at 1100°C and below. Abrasive wear testing at room-temperature shows that FeAl/FA-385 has good wear-resistance, similar to type 304 and 4340 steels, and is somewhat more wear-resistant than Fe₃Al [28].

Recently, the FeAl/FA-385 alloy has also been shown to have relatively high electrical resistivity at room-temperature, ranging from 1.6 to 1.8 µohm-m, which is 40-60% higher than Fe₃Al and over 200% more than that of many iron alloys [31,32]. This property is very important for use of FeAl as efficient and long-life resistance-heating elements.

FeAl WELD-OVERLAY CLADDING - The first attempts to weld-deposit FeAl/FA-385 and related alloys onto type 304L austenitic stainless and 2¼Cr-1Mo bainitic steel substrates were made using a gas-tungsten-arc (GTA) process with sheared strips of FeAl sheet as weld-consumables and no preheat or post-weld heat-treatment [17]. The multiple-pass weld-deposits showed no sign of hot-cracking problems and showed good mixing and adherence to the steel substrate. However, all of the FeAl weld-deposits showed cold-cracking that occurred as the specimens cooled in air. The FeAl cold-cracking was believed related to a combination of factors, which included moisture/hydrogen embrittlement, poor as-welded microstructure/mechanical behavior, and residual stresses. Microcompositional analysis (X-ray energy-dispersive spectroscopy (XEDS) in scanning and transmission electron microscopes (SEM and TEM, respectively)) also indicated that the actual FeAl weld-deposits contained only 32-34 at.% Al compared to 36 at.% present initially. Considerable efforts were then devoted to utilizing these initial results to develop more appropriate methods for producing crack-free FeAl weld-overlays on steels and to better understanding the mechanisms causing the cold-cracking.

Two paths to improved FeAl weld-overlay technology were pursued in parallel: 1) develop preheat and post-weld heat-treatments necessary to eliminate cold-cracking in FeAl, and 2) obtain commercial FeAl weld-wires with enough extra Al to compensate for Al-loss during the welding process. On 12.5 mm thick steel substrates, it was found that crack-free single-pass FeAl/FA-385 weld-overlay deposits could be made on both 304L and 2¼Cr-1Mo steels with only a 200°C preheat and no post-weld heat-treatment. The B-micro-alloyed FeAl behaved about the same as the FA-385 alloy. On thicker (25.4 mm) steel substrates, post-weld heat-treatments were required to produce crack-free FeAl weld-deposits. Good crack-free multiple-layer FeAl weld-overlay deposits could be made on the thicker 2¼Cr-1Mo steel substate with a preheat of 200°C, a minimum interpass temperature of 350°C and a post-weld heat-treatment at 750-800°C followed by furnace cooling (Fig. 6a). Good crack-free single-layer FeAl weld-overlay deposits

can also be made on the thicker 304L substrates using the same thermal treatments (Fig. 6b).

Commercial FeAl weld-wires (3.2 mm diam.) have been aspiration-cast by Haynes International, and the aim and actual wire compositions and the compositions of weld-deposits using those wires are given in Table 2. The I-01 wire results show the loss and dilution of Al that occurs with one weld-pass (from 31 down to 21 wt.%), while the I-02 and -03 FeAl overlay compositions are higher after two passes (26-27 wt.% is close to Fe-44 at.% Al, which is quite brittle). The series I and III wires with more Al have to date produced FeAl deposits free of cold-cracks on the 2¼Cr-1Mo steel substrate. The IV-01 wires, with less Al and added Cr, were able to produce crack-free single-layer FeAl deposits on 2¼Cr-1Mo, 9Cr-1MoVNb and 304L steels. Crack-free single layer deposits of FeAl/FA-385 have also been made on a thin sheet substrate of Rolled Alloy 253MA (similar to type 308 austenitic stainless steel) (Fig. 6c), and the FeAl/steel interface shows no cracking or adverse reaction products (ie, Ni₃Al) even after aging for 1800h at 760°C (Fig. 6d) [33]. Sulfidation testing at 800°C of the FeAl clad removed from the 2¼Cr-1Mo steel substrate (Fig. 6a) shows the same outstanding sulfidation resistance exhibited by Fe₃Al (Fig. 6e) [34,35].

Insight into the residual stresses in the FeAl weld-overlay cladding on 2¼Cr-1Mo steel after post-weld heat-treatment at 700°C have been obtained by Wang et al. [36] using neutron diffraction techniques. They have found that high tensile stresses (>400 MPa) exist in the FeAl clad; this stress develops during cooling after the post-weld heat treatment at 700°C due the mismatch in thermal expansion coefficients between the FeAl clad and the steel substrate. Finite-element modeling of the weld-overlay processes suggests that the tensile stresses in the FeAl would be even higher without the post-weld heat treatment. Comparing the residual stress with the effects of microstructure/composition on the room-temperature mechanical properties of FeAl indicates that weld-deposits with more than 2-3% ductility and UTS > 500-600 MPa stand the best chance of being resistant to cold-cracking [37]. The final compositions listed in Table 2 were chosen with that goal in mind.

DEVELOPMENT OF FeAl COMPONENTS FOR INDUSTRIAL APPLICATIONS

EFFECTS OF FABRICATION ON FeAl MECHANICAL PROPERTIES(Cast FeAl) - The easiest way to make metal components is to cast them if the alloy has acceptable properties. There have been very few properties measurements of as-cast iron-aluminides. One of the first such studies found as-cast Fe₃Al/FA-129 to have very low room-temperature strength (<300 MPa) and ductility (1-2% in air), even though those properties for that same alloy were very good in the wrought condition (UTS - 931 MPa, elongation - 17%)

[38,39]. The poor as-cast properties were attributed to a combination of factors that included a) grain size being too large (>0.5 mm), b) weak grain boundaries, c) coarse NbC particles and d) the wrong matrix phase (100% ordered DO$_3$). Consistently, the best room-temperature ductility and fatigue crack growth resistance found in this same Fe$_3$Al/FA-129 alloy and other similar alloys occurred in wrought material which retained the B2 instead of the DO$_3$ phase [6,38-42]. Studies of scale-up and industrial melt-practice variables at ORNL for both Fe$_3$Al and FeAl showed that a) various melting processes could easily control target chemistries, b) air-induction-melting (AIM) introduces moisture and porosity whereas vacuum or inert gas processes did not, and c) an Al$_2$O$_3$ crucible is better than MgO [8,11,12]. A new method of loading and drying the elemental charge for aluminides to take advantage of the exothermic heat of reaction, termed Exo-Melt™, has been developed at ORNL to further improve IM technology for these intermetallic alloys [43,44].

The as-cast properties of the B2-phase FeAl/FA-385 and B-modified alloys from vacuum-induction-melted (VIM), 33 kg rectangular ingots have only recently been determined at ORNL [26], and are shown in Figs. 2, 7 and 8. The room-temperature ductility of FeAl/FA-385 is 1.8-2.4% in air, and is similar with and without heat-treatment. The smaller difference between tests run in air and oxygen (Fig. 2a) indicates that moisture embrittlement has less of an effect in the as-cast compared to hot-rolled material, despite the coarse grain size of the as-cast structure (0.25-0.67 mm, Fig. 4b). The YS and UTS of the cast FA-385 are not much different than wrought properties (Fig. 3b). Figure 7 shows the effects of B-micro-alloying additions on the room-temperature strength and ductility of as-cast material. The B-doped FeAl alloys have twice the ductility in air and show better resistance to the moisture effect compared to the FA-385 without B. The B-doped alloys are also stronger, with 50 wppm (210 appm) B having more effect (Fig. 7b). At higher temperatures, FA-385 retains its YS (about 400 MPa) to about 600°C while the B-doped alloys retain their YS to about 750°C (Fig. 8a). These FeAl alloys become significantly weaker and much more ductile at 800°C, and make a transition from transgranular cleavage to ductile-dimple failure at 750-800°C (Fig. 8d). The B-micro-alloying addition also significantly enhances the creep-rupture strength of these FeAl alloys at 600°C/207 MPa (fig. 9). TEM analysis indicates that B-micro-alloying additions enhance the formation of fine ZrC particles, so that precipitation-strengthening is the main reason for the better high-temperature strength of the B-modified FA-385 alloys. While all the as-cast FeAl alloys show much higher YS relative to type 316 austenitic stainless steel at temperatures below 750°C, the B-doped alloys also have a UTS advantage over 316 at 750-800°C. The as-cast FeAl alloys show better strength at 600-750°C than was found in previous work on wrought FeAl (FA-362) or Fe$_3$Al (FA-129) alloys at those temperatures [12,38]. The high-temperature strength of these cast FeAl alloys is much better than binary Fe-(40-45) at.% Al alloys doped with 500 appm B [45], and their creep strength at 600°C is better than ODS Fe-40 Al (with Zr and B added) [20].

(Powder Processing of FeAl) - Recent work on FeAl has shown that PM (including mechanically-alloyed [MA] and oxide-dispersion-strengthened [ODS] materials) can enhance strength, ductility and toughness of FeAl and Fe$_3$Al alloys [20,46]. Moreover, powders enable iron-aluminide coating technologies to produce coextruded composite tubing [47] or thermal spray coatings. A commercial heat (880 kg) of nitrogen-atomized FeAl/FA-385 (-100 mesh, spherical) powder was produced by Ametek. Most particles ranged from 70-130 µm in diameter, with a small volume fraction of fine (<5-20 µm) particles also present. Some of this powder was consolidated by direct extrusion (12:1 reduction ratio) at 950-1100°C. The FA-385 powder extruded at 1100°C showed good consolidation with no voids and a grain size <20 µm. The PM FA385 showed >9% ductility in air (>11% in O$_2$) and more strength (YS-500 MPa, UTS>1000 MPa, O$_2$) at room-temperature than IM processing of that same alloy (Fig. 3). Tests of the PM alloys show a YS of 155-230 MPa at 800°C. These good properties of extruded FeAl powders indicate that extruded cladding on steel tubes or piping should also behave well. Components produced by extrusion or direct forging of powders should also be feasible for fabrication from FeAl. MA and ODS processing should further enhance the high-temperature strength of these particular FeAl alloys, in order to exploit the better oxidation/sulfidation resistance of these alloys relative to conventional high-temperature alloys like FeCrAl, 800H and MA956 [20,35].

Recently, the fine-sized component of these FeAl/FA-385 powders was used to produce plasma-spray coatings on conventional steels and nickel-based superalloys. FeAl coatings of 0.13-0.2 mm thickness were produced directly on a type 316 austenitic stainless steel substrate using particle velocities ranging from subsonic to Mach II [48]. These coatings showed good density and adherence to the steel substrate interface (Fig. 10). Higher velocity spraying will further increase the FeAl coating density.

(Industrial Component Testing of FeAl) - To take advantage of the good mechanical properties observed in the as-cast FeAl, a 1,320 kg heat of FA-385M2 (200 appm B) was melted using the Exo-Melt™ technology by Alloy Engineering & Casting Company. Radiant heating tubes were centrifugally cast (Fig. 11) and U-bends were sand cast. The radiant heating tubes are 95.25 mm in outer diameter, 2.44 m long, with different wall thicknesses varying from 6.35 to 19.05 mm. The target alloy chemistry was easily achieved, and the tubes were pressure-checked and showed no leaks. Properties tests of these FeAl tubes is now in progress. These radiant tubes are of direct interest to large automakers and others with large heat-treating

furnaces in need of better materials performance in oxidizing, carburizing and nitriding atmospheres. These tubes also demonstrate that it is feasible to also consider FeAl for commercially cast components that are currently being explored for Fe_3Al and Ni_3Al as replacements for corrosion/heat-resistant steels or Fe-Cr-Ni alloys.

Thermal-spray FeAl/FA-385 coatings on alloy 600 are currently being tested for corrosion protection in molten $NaCl/NaCO_3$ at 900°C by an industrial contractor. Monolithic specimens of the similar FeAl/FA-350 alloy (Table 1) showed excellent resistance to such corrosion, but the application requires that a code-approved structural material be used, so an FeAl coating is necessary.

Another large power-generating equipment manufacturer is currently testing hot-extruded IM FeAl/FA-385 and the B-modified alloys for fretting, cavitation erosion and wear resistance. FeAl is being tested because it is has lower density that steels or nickel-based alloys and has demonstrated good abrasion/wear resistance [28].

(Some Other Potential FeAl Industrial Applications) - Many of the current or potential applications for Fe_3Al, and in some cases Ni_3Al, should also be considered for FeAl [8,9,43,44]. Fe and Al are abundant, and FeAl has potential to be cheaper than Fe-Cr-Ni or Ni-based superalloys when produced in large quantity. The FeAl has better high-temperature strength than Fe_3Al, and its excellent oxidation, sulfidation and molten salt corrosion resistance is less affected by alloying additions (particularly Cr) [15,34,35]. Such FeAl applications may include:

•Sintered porous gas-metal filters made from powders for coal-gasification and clean-up of hot-gases with high sulfur content;
•Resistance heating elements;
•Shields and coatings for superheater and reheater tubes in coal-fired power plants, and possibly piping;
•Sensor sheaths in molten Al or other similar metals (preoxidized FeAl/FA-385M1 survived 48h in Al at 775-800°C);
•Automotive exhaust or catalytic converter components, (particularly heaters to reduce cold-start emissions);
•Hot-dies and tooling for metals forming;
•Natural gas burner nozzles;
•Radiant heating tubes and cast furnace fixtures.

Further work to demonstrate the ability to produce actual FeAl components with good mechanical properties that are better than conventional materials should facilitate more applications of FeAl for its high-temperature oxidation/corrosion benefits.

SUMMARY

FeAl alloys with 36 at.% Al have been developed with significantly improved weldability, and which show good room-temperature and high-temperature mechanical properties with proper control of the microstructure and processing. These alloys also have the outstanding oxidation/sulfidation resistance characteristic of FeAl alloys with 35-40 at.% Al. Larger-scale component fabrication using commercial processes is feasible and is being demonstrated. Good as-cast properties are found, and PM methods show even better properties. FeAl coatings and claddings for steels are feasible, and improved technology to produce those is being developed.

ACKNOWLEDGEMENTS

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Table 1 - Minor Element Composition of Developmental FeAl (Fe-35.8 at.% Al) Alloys

Alloy	Cr	Nb	Ti	Mo	Zr	C	B
FA-324							
FA-350					0.05		0.24
FA-362				0.2	0.05		0.24
FA-372				0.2	0.05		
FA-383					0.05		
FA-384	2			0.2	0.05		
FA-385				0.2	0.05	0.13	
FA-386				0.2	0.05	0.24	
FA-387				0.2			0.24
FA-388				0.2		0.25	
FA-385M1				0.2	0.05	0.13	0.01
FA-385M2				0.2	0.05	0.13	0.021
FA-385M3	2			0.2	0.05	0.13	
FA-385M4		0.5		0.2	0.05	0.13	
FA-385M5	2	0.5		0.2	0.05	0.13	
FA-385M6	2	0.5		0.2	0.05	0.25	
FA-385M7	2	0.5		0.2	0.1	0.25	
FA-385M8	2	0.5	0.05	0.2	0.05	0.13	
FA-385M9	2	0.5	0.05	0.2	0.05	0.25	
FA-385M10	2	0.5	0.05	0.2	0.05	0.13	
(+ 0.5Ni + 0.3Si + 0.016P)							
FA-385M11	2	0.5	0.05	0.2	0.05		
(- 0.25W)							

Table 2 - Compositions of Developmental FeAl Weld Filler-Metals

| Wire and description	Al	Cr	Nb	Ti	Mo	Zr	C	B	Comments
ORNL Weldable FeAl Alloy Reference Materials									
FA-385	21.1				0.42	0.1	0.03		
FA-385M1	21.1				0.42	0.1	0.03	0.0025	
FA-385M2	21.1				0.42	0.1	0.03	0.005	
FA-385M3	21.1	2.3			0.42	0.1	0.03		
FA-385M4	21.1		1.0		0.42	0.1	0.03		
Haynes Wires, aspiration-cast, 0.125 in. diam.									
O1 aim	30	5	0.5	0.5	0.25	0.2	0.1		
actual	31.2	3.3	0.5	0.7	0.3	0.2	0.12	0.007	no cracks
weld deposit	21.2	2.9	0.4	0.4	0.5	0.2	0.13	0.007	
1 pass 2¼Cr 1Mo									
O2 aim	30	5	0.5	0.5	0.25	0.2	0.1	0.0025	
actual	31.3	3.2	0.5	0.7	0.3	0.2	0.12	0.009	
weld deposit	26.8	3.2	0.4	0.5	0.4	0.2	0.12	0.012	
2 passes 2¼Cr 1Mo									
O3 aim	30	5	0.5	0.5	0.25	0.2	0.1	0.005	
actual	31.5	3.5	0.5	0.6	0.3	0.2	0.11	0.017	
weld deposit	26.2	3.2	0.4	0.4	0.4	0.2	0.11	0.015	2nd layer cracked
2 passes 2¼Cr 1Mo									
Haynes Wires, aspiration-cast, 0.156 in. diam									
III-O1 aim	30	7	0.6	0.5	0.25	0.2	0.1		
actual									
weld deposit									no cracks
1 pass 2¼Cr 1Mo steel									
III-O2 aim	30				0.4	0.1	0.03		FA-385 repeat
actual									
weld deposit									no cracks
1 pass 2¼Cr 1Mo steel									
IV-O1 aim	25	7			0.4	0.1	0.03	0.005	
weld deposit									no cracks
(1 pass 2¼Cr 1Mo, 9Cr 1MoNbV, and 304L steels)									
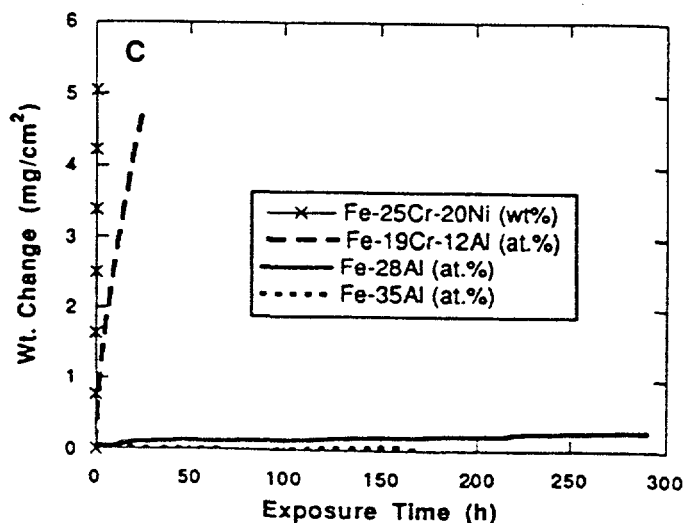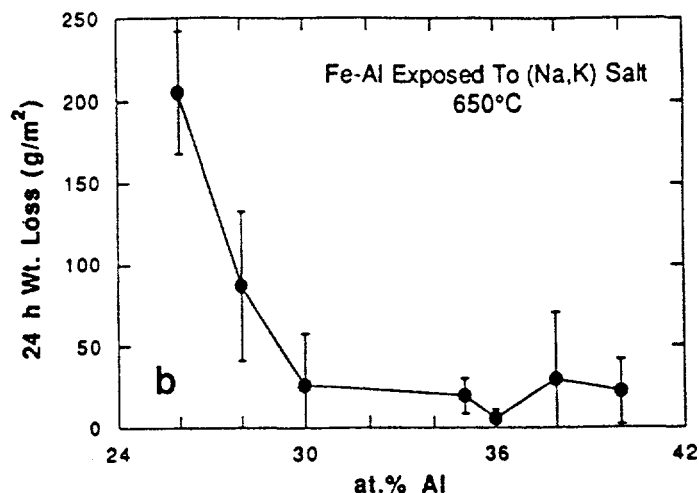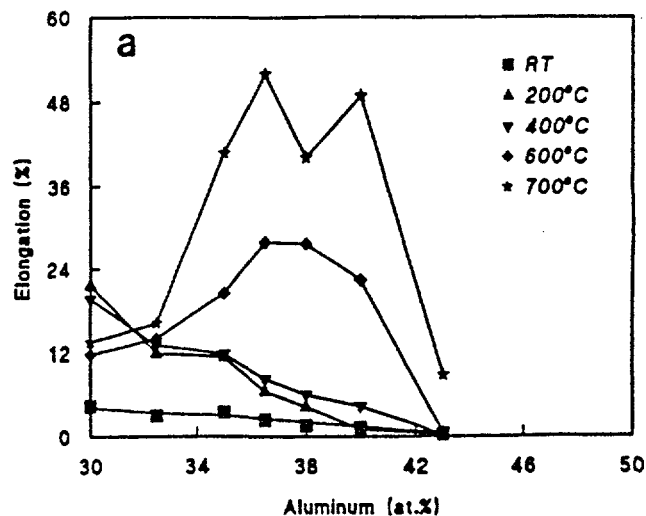
Figure 1 - Properties as functions of Al content for binary FeAl alloys, including a) tensile elongation in air from room temperature to 700°C [12] and b) 24h weight loss for exposure to molten (Na,K) nitrate salt at 650°C [15], and c) weight gain of Fe_3Al (Fe-28 Al) and FeAl (Fe-35 Al) as a function of time for exposure to a sulfidizing gas mixture ($PS_2=10^{-6}$ atm, $PO_2=10^{-22}$ atm) at 800°C [12,16].
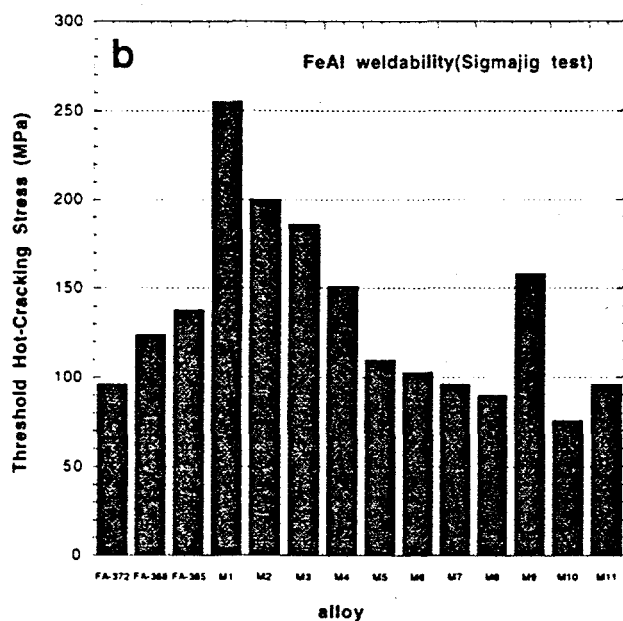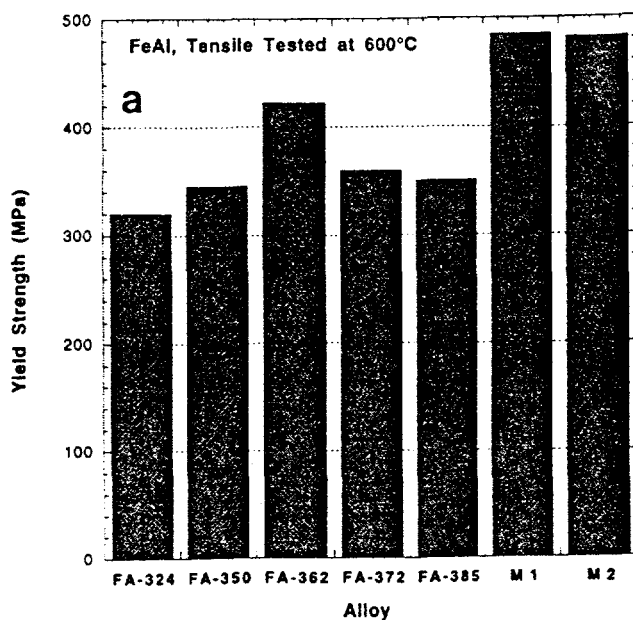
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Figure 2 - a) Yield strength of several FeAl alloys tensile tested at 600°C in air [12,17,18]. Specimens were punched from thin sheet hot-rolled at 850-900°C and heat-treated for 1h at 700-800°C prior to testing [12,17,18]. b) Weldability as measured by the threshold hot-cracking stress for various FeAl alloys thin-sheet specimens using the Sigmajig test [24]. Compositions corresponding to these alloy designations can be found in Table 1.
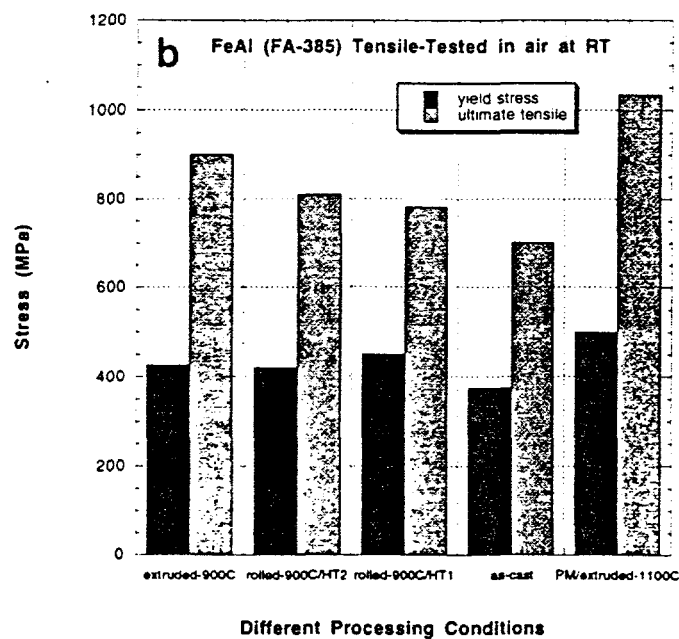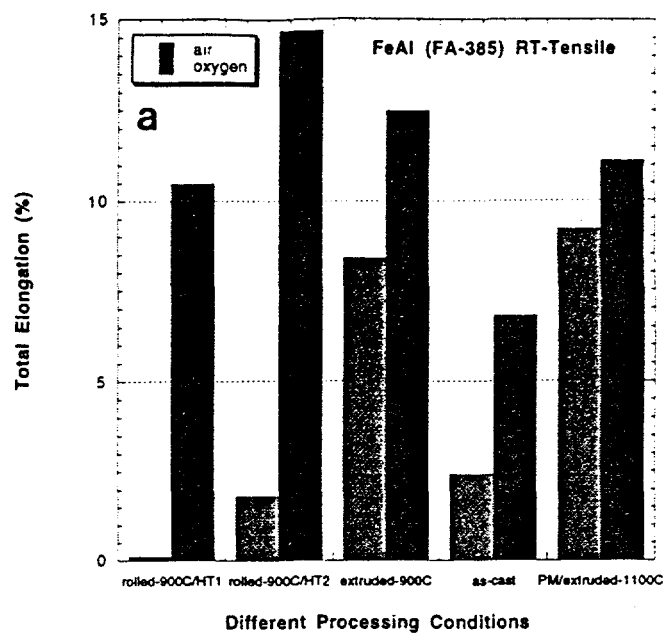
Figure 3 - Tensile data at room-temperature for FeAl (FA-385) processed by different methods showing a) total elongation in both air and oxygen test environments, and b) yield and ultimate tensile strengths for tests run in oxygen [26]. HT1 is a heat-treatment of 1h at 900°C, and HT2 is 1h at 1000°C. All other specimens were only stress-relieved for 1h at 750°C in air.

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SPECIFIC HEAT CAPACITY OF IRON ALUMINIDES

THERMAL EXPANSION OF IRON ALUMINIDES

THERMAL CONDUCTIVITY OF IRON ALUMINIDES
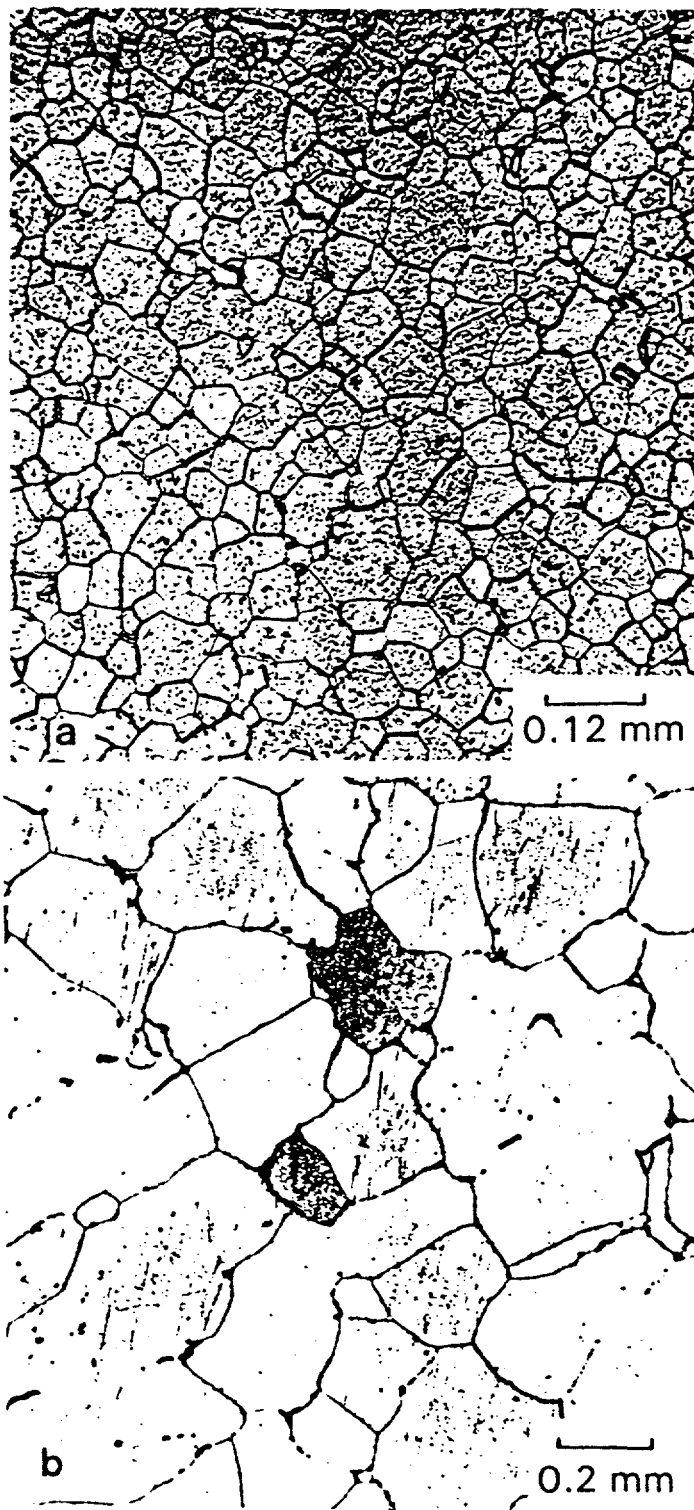
Figure 4 - Metallography of FeAl (FA-385M2) showing the effect of processing differences on grain size. a) hot-extruded at 900°C and b) as-cast; both were also stress-relieved for 1h at 750°C, which does not affect the grain structure.
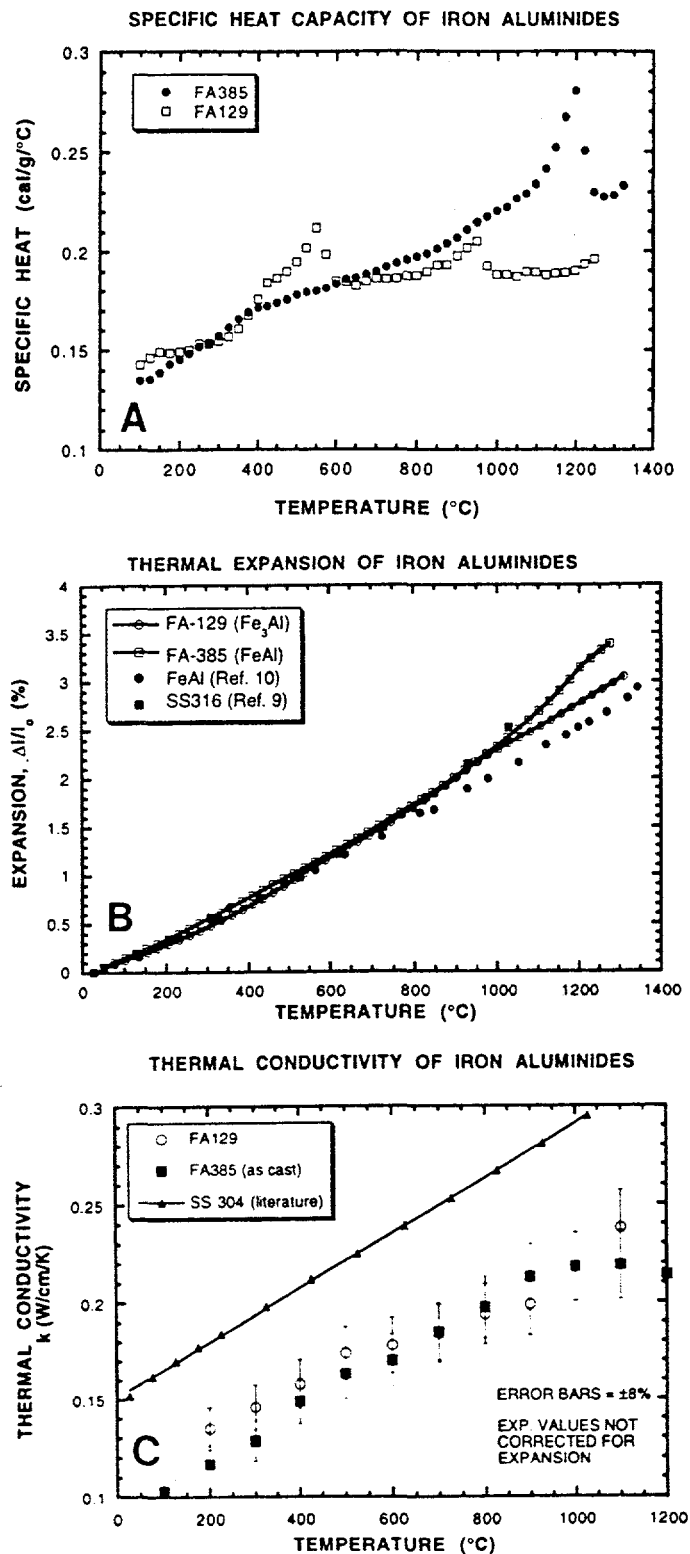
Figure 5 - Physical properties of FeAl/FA-385 and Fe₃Al/FA-129, including a) specific heat capacity, b) thermal expansion and c) thermal conductivity [29,30].

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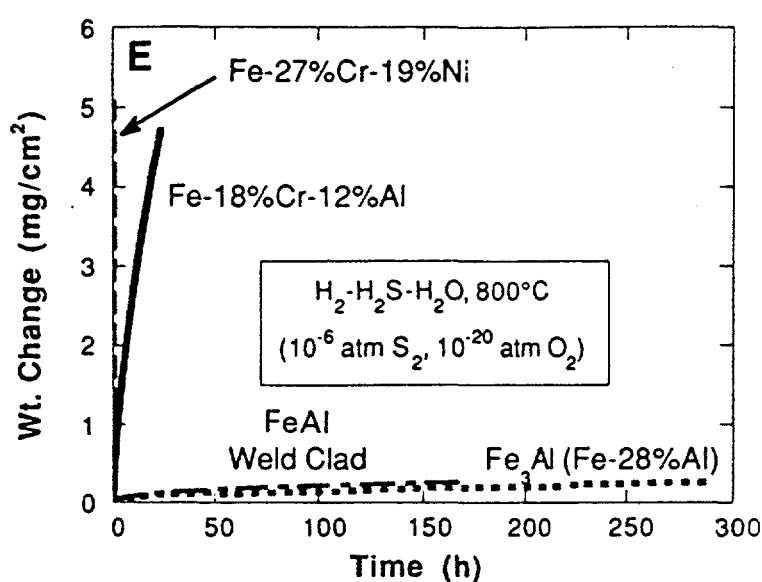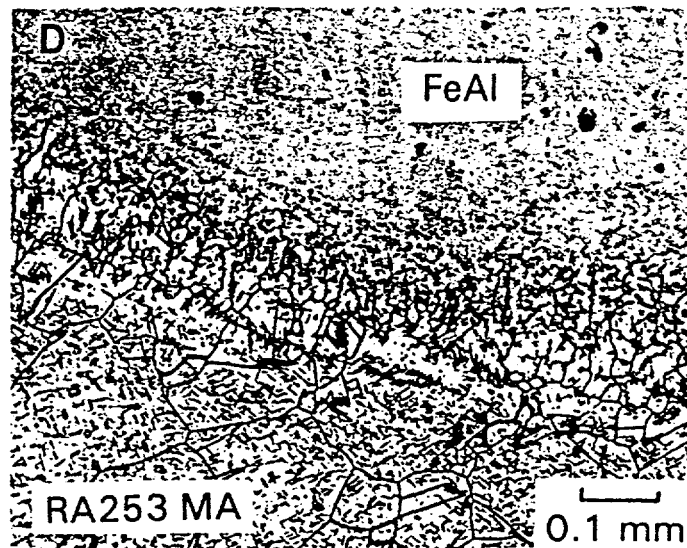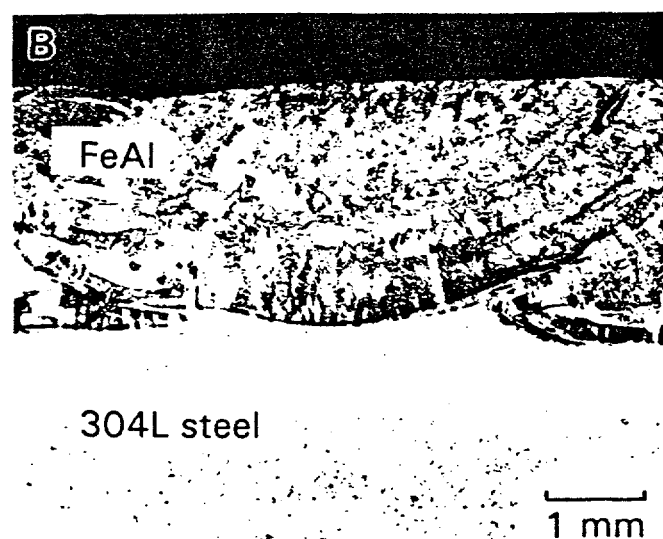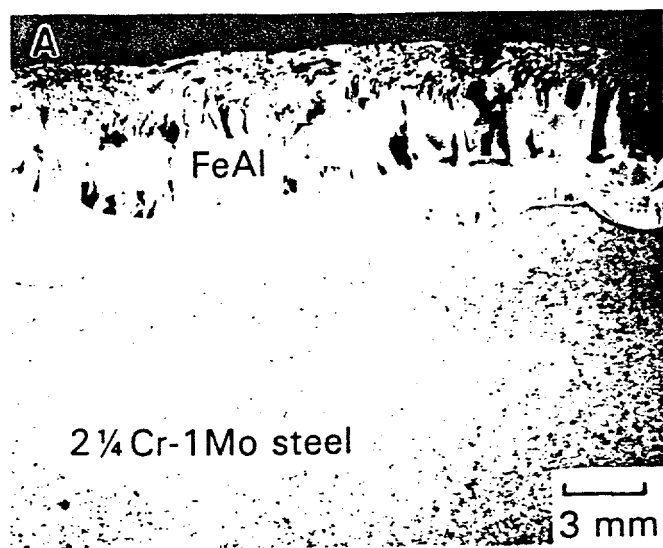
Figure 6 - Metallographic/optical results for FeAl/FA-385 GTA weld-overlay on steel substrates, including a) cross-section of a 3-layer FeAl desposit on 2¼Cr-1Mo steel, b) cross-section of 1-layer FeAl deposit on 304L steel, c) photograph of 1-layer FeAl deposit on Rolled Alloy 253MA [33], d) cross-section of c) aged for 1800 h at 760°C showing good FeAl/steel bonding and no adverse reaction products [33]. e) shows the results of the FeAl weld-clad in a) removed and tested at 800°C in a sulfidizing environment [34]. The FeAl weld-clad deposit performs as well as monolithic Fe₃Al, which has outstanding sulfidation resistance at those conditions [34,35].

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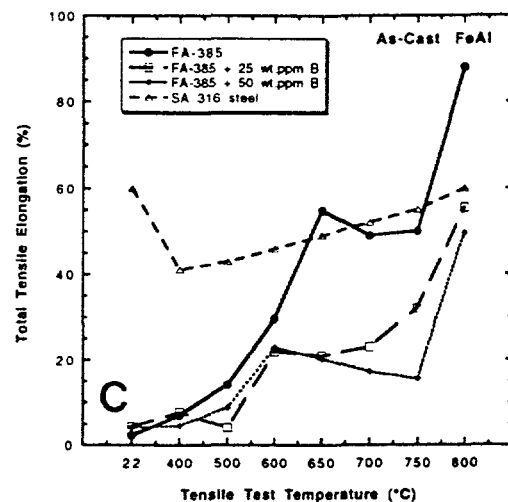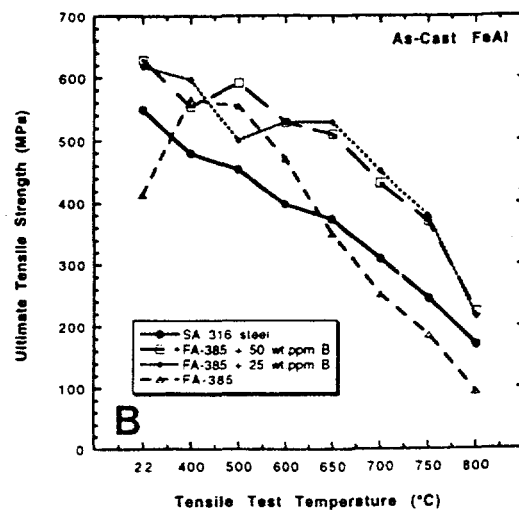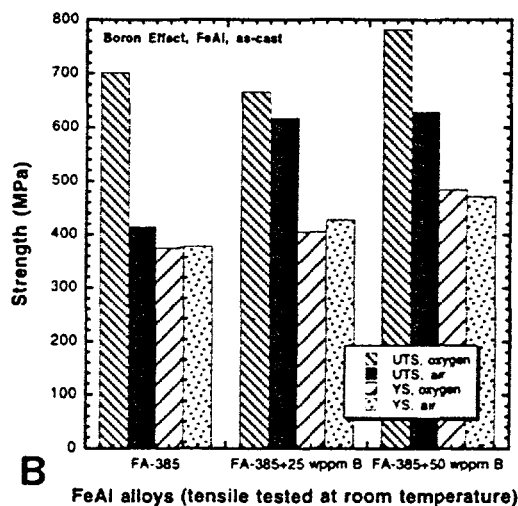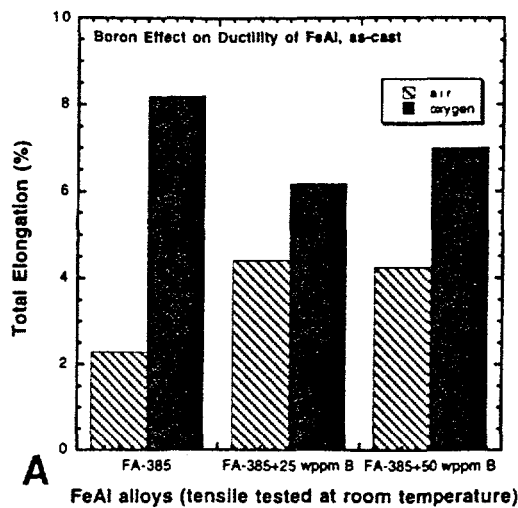
Figure 7 - Effects of B micro-alloying additions on as-cast FeAl/FA-385 alloys tensile tested at room-temperature, including a) total elongation and b) YS and UTS [26].
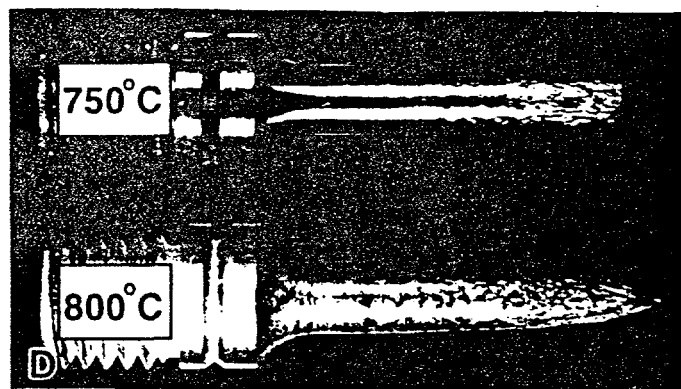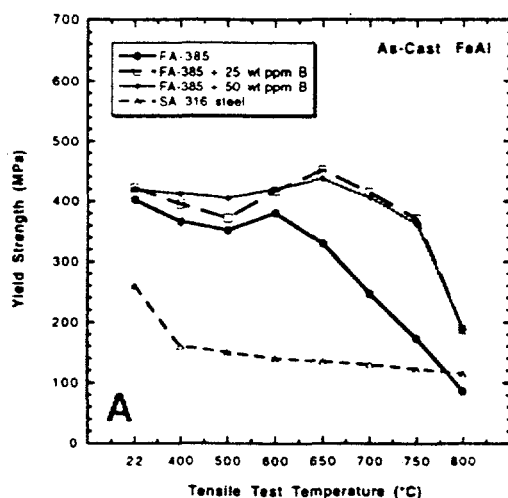

Figure 8 - Tensile properties as a function of temperature for as-cast FeAl/FA-385 and B-modified alloys tested in air, including a) YS, b) UTS, c) total elongation and d) macro-photo of fractured specimens [26]. Data on solution-annealed type 316 austenitic stainless steel are included for comparison. In d) fracture is a mixture of transgranular cleavage and ductile failure at 750°C, but is completely ductile-dimple failure at 800°C.
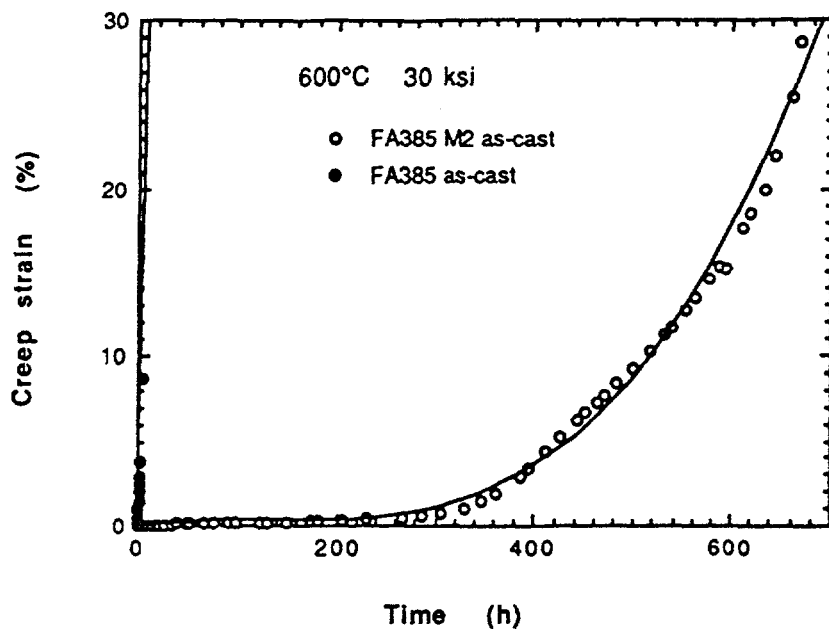
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Figure 9 - Creep-rupture data of FeAl (FA-385 and FA-385M2) tested in air at 600°C and 30 ksi(207 MPa) [26].
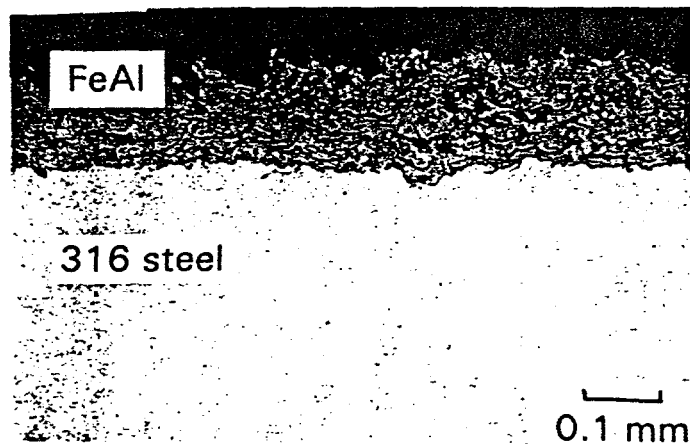

Figure 10 - Plasma-spray (sub-sonic) of a 0.15 mm thick coating of FeAl/FA-385 onto a type 316 austenitic stainless steel substrate [48].
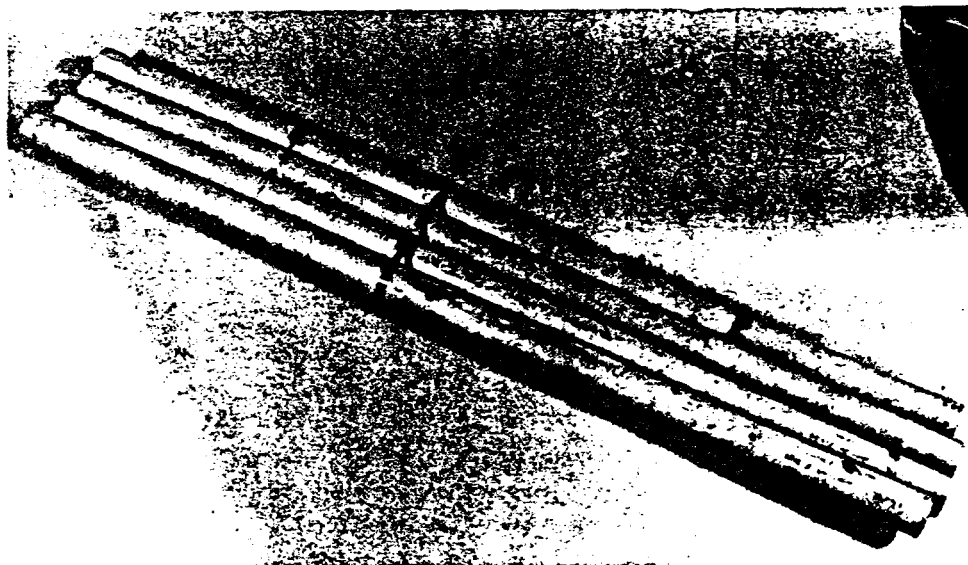

Figure 11 - Centrifugally-cast FeAl/FA-385M2 radiant heating tubes (2.44 m long, 95.25 mm O.D., with different wall thicknesses from 6.35 to 19.05 mm) produced by Alloy Engineering & Casting Company using the Exo-Melt™ process [46].

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