

MELTING AND CASTING OF FeAl-BASED CAST ALLOY

CONF-980202--

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

D. Wilkening
Columbia Falls Aluminum Co.
2000 Aluminum Dr.
Columbia Falls, Montana 59912

J. Liebetrau and B. Mackey
AFFCO, L.L.C.
P.O. Box 1071
Anaconda, Montana 59711

RECEIVED

AUG 13 1998

OSTI

ABSTRACT

The FeAl-based intermetallic alloys are of great interest because of their low density, low raw material cost, and excellent resistance to high-temperature oxidation, sulfidation, carburization, and molten salts. The applications based on these unique properties of FeAl require methods to melt and cast these alloys into complex-shaped castings and centrifugal cast tubes. This paper addresses the melting-related issues and the effect of chemistry on the microstructure and hardness of castings. It is concluded that the use of the Exo-Melt™ process for melting and the proper selection of the aluminum melt stock can result in porosity-free castings. The FeAl alloys can be melted and cast from the virgin and revert stock. A large variation in carbon content of the alloys is possible before the precipitation of graphite flakes occurs. Titanium is a very potent addition to refine the grain size of castings. A range of complex sand castings and two different sizes of centrifugal cast tubes of the alloy have already been cast.

INTRODUCTION

The FeAl-based intermetallics are attractive structural materials because of their many unique properties. The most exciting of these properties include: (1) lower cost because they use the most abundantly available elements - iron and aluminum, (2) significantly lower density because of their large aluminum content, (3) exceptional oxidation resistance [refs. 1,2], (4) unmatched high-temperature sulfidation

MASTER

JST

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISCLAIMER

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

sulfidation resistance [refs. 3-5], (5) molten salt resistance [ref. 6], and (6) enhancement of corrosion and other properties through preoxidation. The interest in the iron aluminides and especially FeAl is reflected by the very nature of this conference. Numerous publications [7-14] exist in literature on studies dealing with the basic understanding of compositional effects on the flow and fracture behavior of the FeAl system. In fact, a most recent review article by Baker and Munroe [15] has updated the current status of the basic understanding of FeAl alloys.

The attractive properties of FeAl-based alloys have identified many potential applications (which are discussed in the next section) for these alloys. However, only limited information exists regarding melting, casting, and processing of these materials. Several papers in this conference will deal with powder processing of FeAl-based alloys. The purpose of this paper is to describe our results on the melting and casting of FeAl-based alloys.

ALLOY COMPOSITIONS

The base composition of the FeAl-based alloy with the desired range for each element is shown in Table 1. Melting of other than nominal compositions will also be discussed in the later sections of this paper.

Table 1. Composition range of FeAl Alloy

Element	Target	Range (wt %)
Fe	Balance	Balance
Al	21.5	21.0 to 22.1
Zr	0.17	0.15 to 0.2
C	0.085	0.07 to 0.01
B	0.005	0.005
Mo	0.42	0.4 to 0.45

MELTING PROCESS

The large amount of aluminum in the FeAl-based alloy is one of the major reasons for its melting-related issues. The melting issues include:

1. The large aluminum content of the alloy reduces by over 25% the melting capacity of steel-based, rated commercial melting furnaces. This aspect needs to be recognized by the steel foundry melters in order to use the melting process successfully.
2. The addition of a large amount of aluminum to molten iron is not commercially done. If the commercial process of killing steel by the addition of aluminum is extended, it results in a large rise in bath temperature due to the exothermic [16] nature of the FeAl formation (see Fig. 1). The large increase in bath temperature can have several consequences, including: (a) excessive metal oxidation or slag formation that results in the lack of alloy composition control; (b) overheating of the bath can attack the furnace lining; (c) the overheated bath requires cooling to the desired pouring temperature, which results in both energy loss and time loss; and (d) the formation of slag.

Issue No. 1 can be dealt with through personal education. However, Issue No. 2 has been dealt with through the development of the Exo-Melt™ process [17]. This process uses a furnace-loading scheme (Fig. 2) that effectively uses the heat of formation of FeAl to melt the alloy. The iron content of the alloy is divided into two parts. The top of the furnace uses equal atomic ratios of iron and aluminum to form FeAl. The excess iron is stored at the furnace bottom, and the alloying elements are trapped between the top and bottom layers. As the induction process starts, iron starts to heat first because of its electrical and magnetic properties. As it heats up to 800 to 1000°C, it melts the aluminum through conduction and some through coupling with the induction coil. As the aluminum melts, it reacts with the heated iron to form FeAl. The heat of formation of the FeAl raises the local temperature to form liquid FeAl. The molten FeAl liquid travels down because of gravity and quickly shares its energy with extra iron at the bottom of the furnace and overall bath temperature reaches approximately 1250°C. Additional power input is

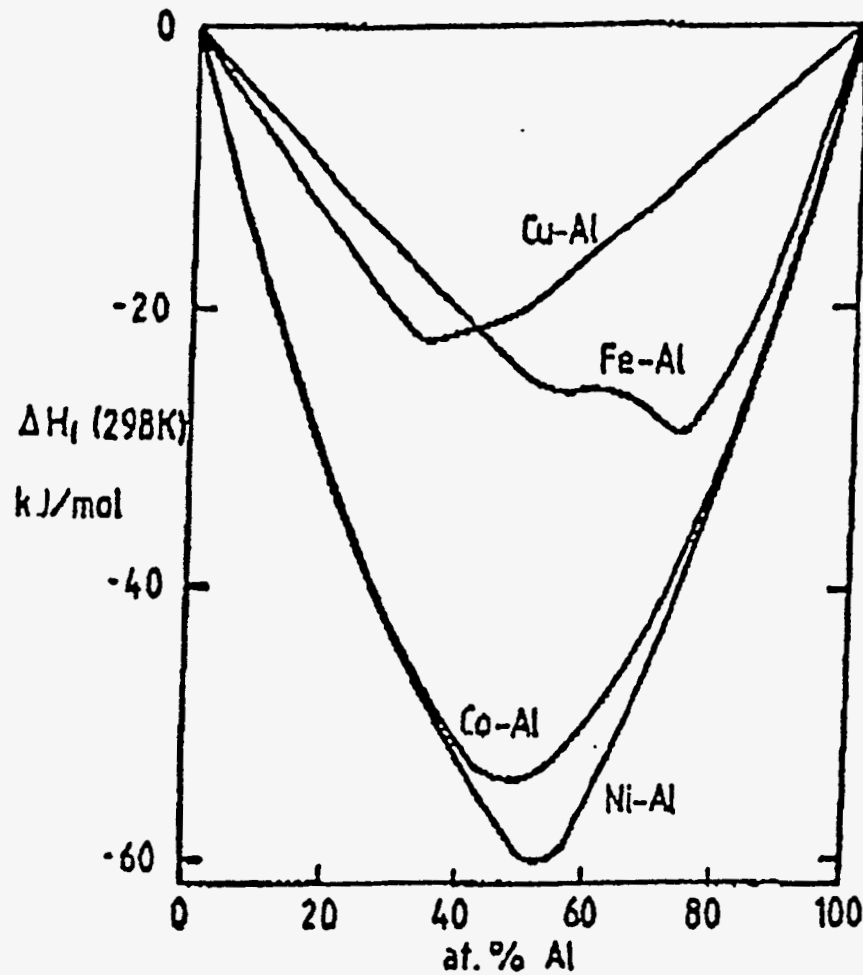


Fig. 1. Extent of exothermic reaction in aluminum binary systems with transition metals: iron, cobalt, nickel, and copper [16].

used to bring the furnace to bath temperature for pouring into the desired mold cavities. Thus, the Exo-Melt™ process effectively uses the heat of formation of FeAl for the benefit of raising the melt temperature rather than overheating the bath.

The Exo-Melt™ process has already been successfully used for FeAl by two commercial melters: United Defense LP (Anniston, Alabama) and Alloy Engineering & Casting Company (Champaign, Illinois). A slightly modified version of the Exo-Melt™ process was used by AFFCO, L.L.C. (Anaconda, Montana) for melting of nearly 14,000 kg of the FeAl-based alloy.

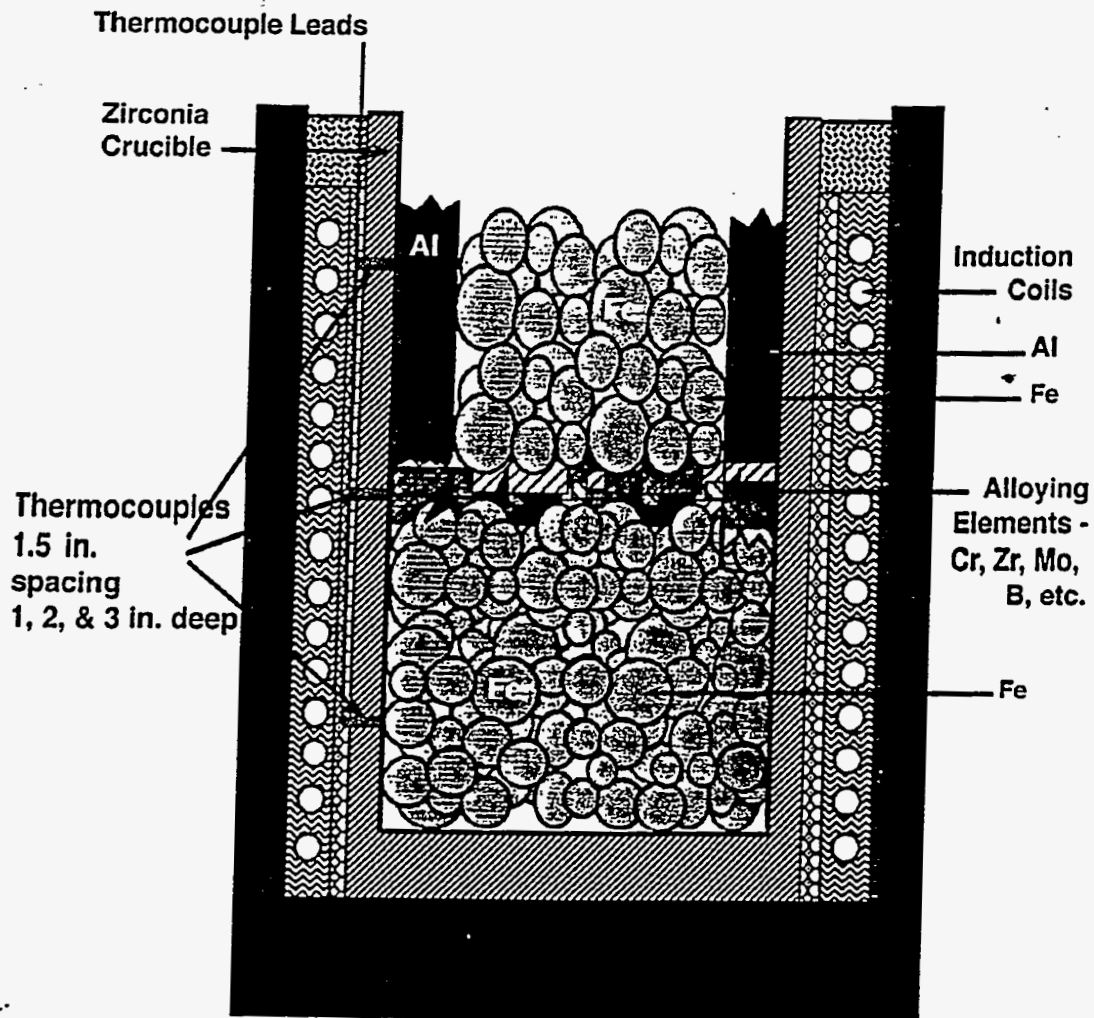


Fig. 2. Furnace-loading scheme of the Exo-Melt™ process for melting of iron aluminides.

MELT STOCK EFFECTS AND COMPOSITION CONTROL

One of the most important effects of the melt stock in this alloy is the potential of porosity. The porosity results from the large amount of dissolved hydrogen in the melt that results from the reaction of aluminum with moisture [ref. 7] ($2 \text{ Al} + 3 \text{ H}_2\text{O} \rightarrow \text{Al}_2\text{O}_3 + 6 \text{ H}$). A typical example of the gross porosity that can occur in the FeAl-based alloy is shown in Fig. 3. The extent of hydrogen generation and, thus, porosity can be controlled by the use of: (1) dry charge, especially of aluminum; and (2) larger aluminum melt stock

to minimize the surface to volume ratio, which significantly reduces the melt hydrogen content.

Besides the melt stock control, the dissolved hydrogen [18] in the melt can be further reduced by blowing the melt with argon.



Fig. 3. Gross porosity observed in a 230-kg air-melted ingot of iron aluminide.

The pure melt stock used in the laboratory heats results in excellent control of chemistry of the alloy. However, the commercial melt stock tends to vary from one foundry to another, based on their customer and the product being cast. The melting of FeAl-based alloys for casting of skirts for aluminum baths used steel pins and aluminum blocks. Chemical analysis of the trial melts at ORNL of two 7-kg heats of the alloy with the melt stock supplied by AFFCO, L.L.C. are given in Table 2. Observations from Table 2 show the following:

Table 2. Chemical analysis of two 7-kg heats melted at
the Oak Ridge National Laboratory

Element	Heat, ^a weight percent	
	16592	16593
C	0.13	0.14
Mn	0.36	0.29
S	0.022	0.025
Si	0.08	0.06
Ni	0.12	0.14
Cr	0.08	0.09
Mo	0.32	0.43
Cb	<0.01	<0.01
Cu	0.22	0.27
Al	22.4	22.2
B	--	--
Zr	<0.01	0.15
Fe	<i>b</i>	<i>b</i>
N ₂	0.002	0.001
O ₂	0.006	0.005

^aThe heats were melted using the same melt stock as that used at AFFCO L.L.C. (Anaconda, Montana).

^bBalance.

1. Carbon content of both heats (16592 and 16593) is approximately 0.13 wt %. No carbon was added to the melt. All of it was derived from the steel melt stock.
2. No zirconium was added to heat 16592. However, heat 16593 recovered 100% of the added zirconium.
3. The oxygen and nitrogen contents of these heats are extremely low, which is typical of aluminides [11].

4. Impurities of Mn = 0.3, S = 0.02, and Cu = 0.24 were also picked up in these heats from the melt stock.
5. The Si = 0.07 and Ni = ~ 0.13 are also present in these heats.

Effect of the impurity elements on the properties of the alloy are not known.

CHEMICAL ANALYSIS OF LARGE COMMERCIAL-SIZE

HEATS (340 TO 455 kg)

Chemical analysis of five large heats melted at AFFCO, L.L.C. are presented in Table 3. The melt stock for these five heats was the same as that used for two 7-kg heats at the Oak Ridge National Laboratory (ORNL). Three of the five heats were made by using virgin stock (no revert). The fourth heat consisted of 50% revert stock (rejected FeAl alloy castings and pigs of extra melt stock from other heats) and 50% virgin stock. For these heats, the slag was coagulated using commercial additives and removed. The fifth heat was again a virgin heat but used a lower carbon content plate as melt stock rather than high-carbon, round pin stock. Other variable for the five heats included:

Heat 1: Used argon gas cover but added no zirconium.

Heat 2: Used argon gas cover and doubled the nominal zirconium content to compensate for the high-carbon content of the alloy.

Heat 3: Used argon gas cover and trippled the nominal zirconium content to accomplish grain refinement through precipitation of ZrC.

Heat 4: Used argon gas cover and removed the slag.

Heat 5: Used no argon gas cover.

Observations of chemical analysis in Table 3 indicate the following:

1. The carbon content of four heats that used the same melt stock is similar and is also similar to the heat melted at ORNL with the same melt stock (see Table 2). Heat 5 showed lower carbon because of its lower carbon plate melt stock.

Table 3. Comparison of detailed chemical analysis of first five heats
(340 to 455 kg each)

Element	Heat, weight percent				
	1	2	3	4 ^a	5 ^b
C	0.16	0.13	0.15	0.15	0.12
Mn	0.35	0.32	0.30	0.36	0.68
S	0.016	0.023	0.023	0.019	0.007
Si	0.08	0.03	0.04	0.08	0.08
Ni	0.09	0.09	0.09	0.09	0.03
Cr	0.10	0.10	0.10	0.11	0.11
Mo	0.50	0.48	0.50	0.52	0.50
Cb	<0.01	<0.01	<0.01	<0.01	<0.01
Cu	0.18	0.22	0.31	0.22	0.08
Al	22.7	22.8	22.5	22.3	21.9
B	0.014	0.015	0.012	0.012	0.012
Zr	<0.01	0.32	0.33	0.33	0.23
Fe	<i>c</i>	<i>c</i>	<i>c</i>	<i>c</i>	<i>c</i>
N ₂	<0.001	<0.001	<0.001	<0.001	<0.001
O ₂	0.004	0.002	<0.017	0.008	0.001

^aThis is a mix of revert and virgin stocks.

^bThis heat used plate stock instead of pins, which were used for other heats.

^cBalance.

2. The zirconium content was intentionally trippled in heats 2, 3, and 4 and doubled in heat 5. The target value of the zirconium was 0.15%. Data in Table 3 indicate that 70% of the zirconium was recovered as opposed to 100% recovery in the heat melted at ORNL. Part of the reason for lower recovery may be the oxidation of zirconium through the transfer to the ladle and a longer holding time than in the case of small heats at ORNL.

3. With or without the argon gas cover, the oxygen and nitrogen contents of heats 1, 2, 4, and 5 were extremely low. The higher value of oxygen in heat 3 was accounted for by trapped oxide particles in the chemistry sample.
4. The use of 50% revert and 50% virgin as opposed to all of the virgin stock did not cause any unusual deviation in the chemical analysis.

MICROSTRUCTURE AND HARDNESS DATA

Optical microstructure of heats 16592 and 16953 sand cast at ORNL into step blocks are shown in Fig. 4. Both heats showed carbide precipitation. However, the heat containing zirconium had somewhat finer carbides, and it showed smaller grain size.

The hot-hardnesses on these two heats are compared with the nominal alloy of pure melt stock in Fig. 5. The zirconium-free heat showed the lowest hardness at room temperature. However, at $> 200^{\circ}\text{C}$, the higher carbon castings were consistently higher in hardness than the nominal alloy. Data in Fig. 5 also show stable hardness up to 600°C , followed by a more rapid drop at the higher temperatures.

It became obvious from the casting trials at AFFCO, L.L.C. that different melt stocks may result in FeAl alloys with the carbon content spread over a wide range. Thus, a large number of castings with carbon content varying from 0.05 to 2.3 wt % were examined for microstructure and room-temperature hardness. The microstructure revealed carbide precipitation in the castings up to a carbon content of 1%. At 1.5 and higher carbon levels, the alloy showed graphite flakes in addition to carbides. The hardness increased with increasing carbon content until the carbides were precipitating, but it decreased when graphite flakes precipitated (Fig. 6).

Titanium addition was most potent in refining the cast microstructure. The microstructure of a sample from a 770-kg heat containing 0.75 wt % Ti, melted at United Defense LP, is shown in Fig. 7. Exceptionally fine microstructure of this heat is evident.

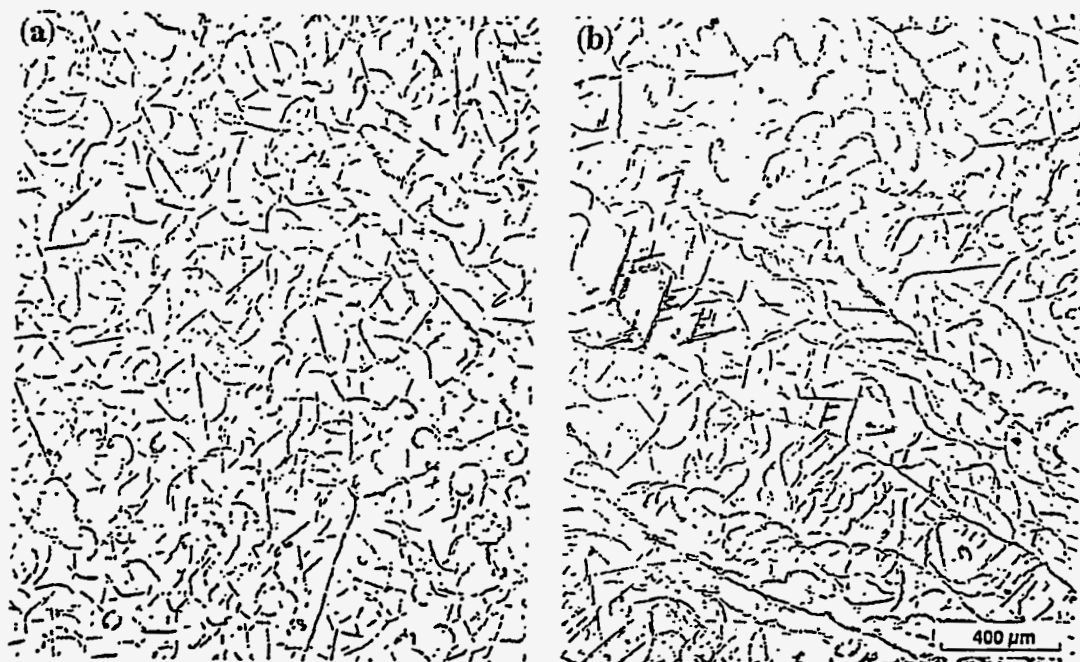


Fig. 4. Effect of zirconium on the microstructure of 7-kg heats of FeAl alloy sand cast at the Oak Ridge National Laboratory using AFFCO, L. L. C. melt stock: (a) no zirconium and (b) 0.15 wt % Zr.

APPLICATIONS AND CASTINGS

The FeAl-based alloys are being considered for a large range of applications, which require their casting into complex shapes and by both static and centrifugal casting methods. The sand castings of the grate bar and pellet tip of the FeAl alloy are shown in Fig. 8. The grate bars have successfully operated at temperature of 1000°C for nearly eight months. For the aluminum bath applications, the FeAl alloy has been cast into both straight and curved skirts [Fig. 8(a)]. For several other applications, the alloy has been cast into thin wall (12 mm) tubes of 95 mm OD and thick wall (25 mm) tubes of 150 mm OD. Microstructures and properties of the large castings from commercially used melt stock is currently being investigated.

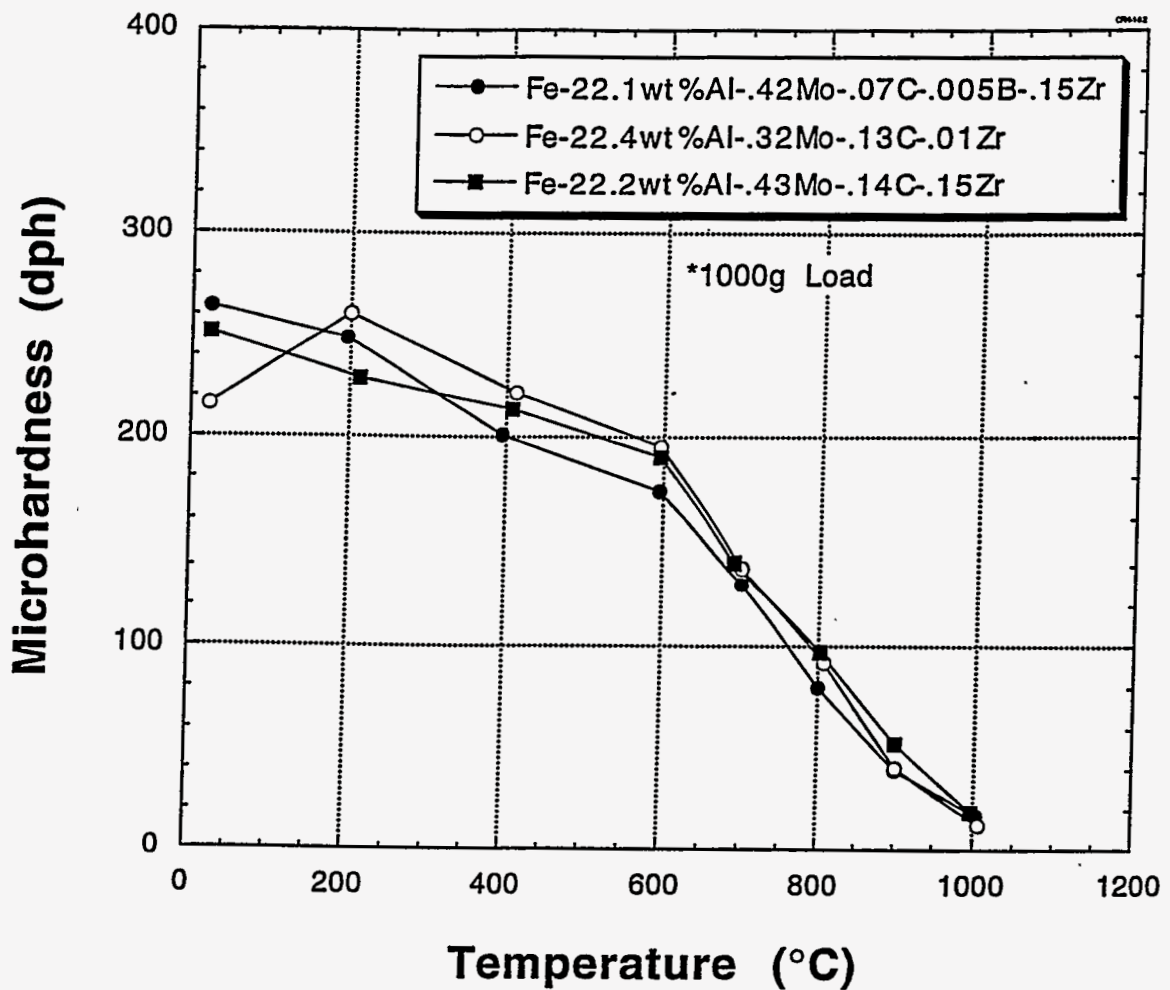


Fig. 5. Hot-hardness of cast FeAl alloys with and without zirconium and of low and high carbon.

SUMMARY AND CONCLUSIONS

FeAl-based alloys are of great interest because of their low density, lower raw material cost, and excellent resistance to high-temperature oxidation, sulfidation, carburization, and molten salts. The applications, based on these unique properties of FeAl, require methods to melt and cast these alloys into complex-shaped sand castings and centrifugal cast tubes. This paper has addressed the melting and related issues and the effect of chemistry on microstructure and hardness of castings. The following conclusions are:

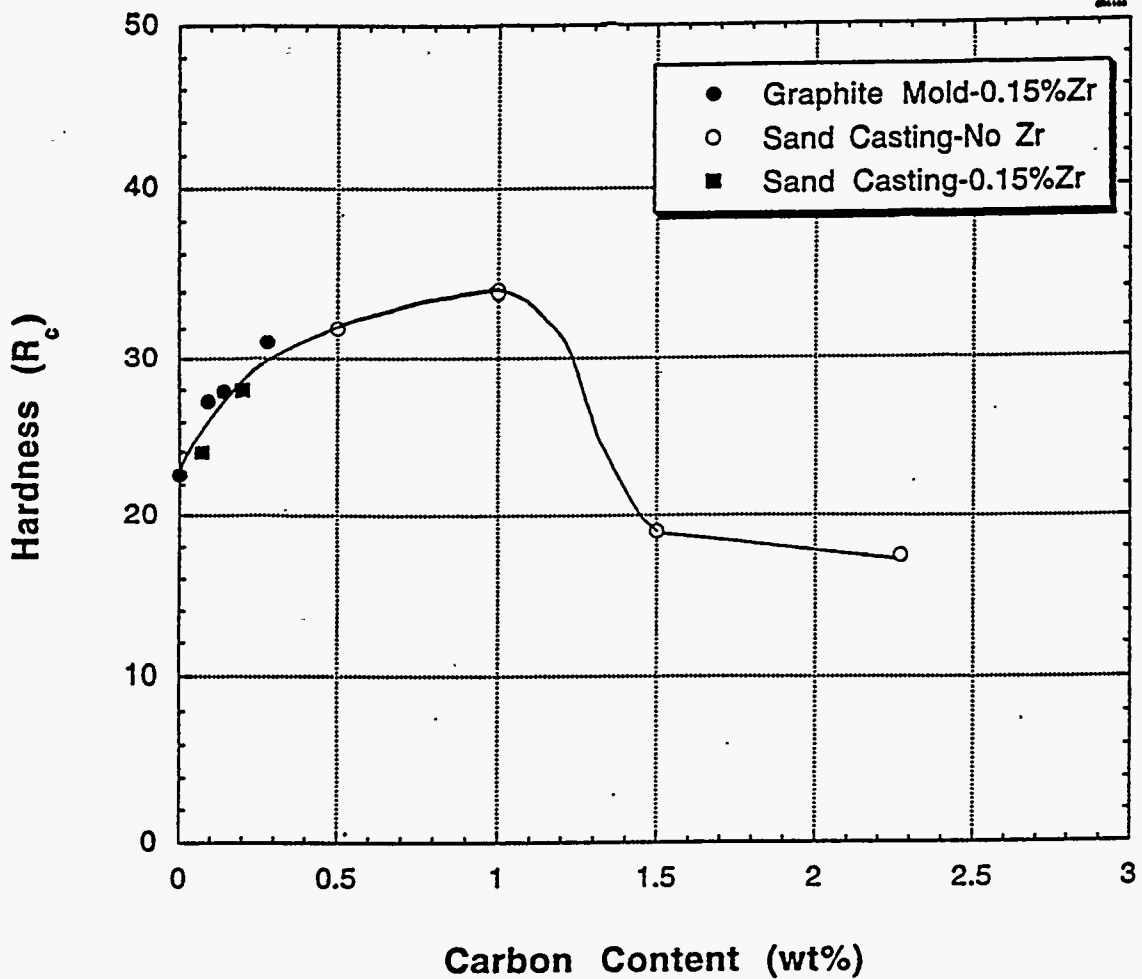


Fig. 6. Effect of carbon content on the room-temperature hardness of as-cast FeAl-based alloys.

1. FeAl-based alloys have been successfully melted at three foundries by the Exo-Melt™ process.
2. Alloy chemistries are easily achievable. Casting porosity control requires care in selecting and using the aluminum melt stock.
3. Carbon increases the hardness of the castings up to 1 wt % and at higher levels, graphite flakes precipitate out.
4. Titanium addition is a very potent grain refiner for FeAl-based alloys.

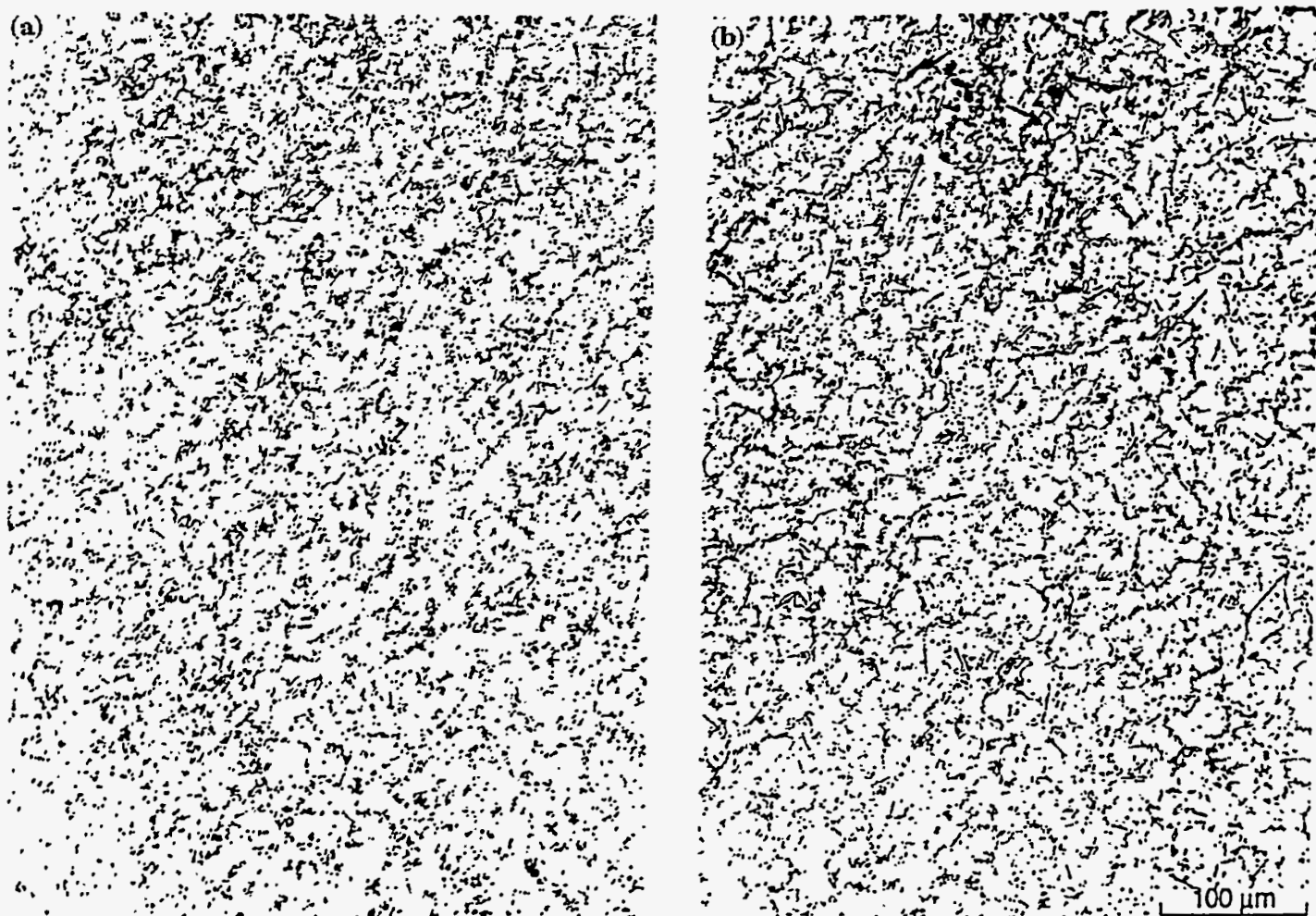


Fig. 7. Effect of titanium on grain refinement of cast FeAl. Two different grain-refined locations in the casting are shown in (a) and (b).

REFERENCES

1. K. Natesan and P. F. Tortorelli, *International Symposium on Nickel and Iron Aluminides: Processing, Properties, and Applications*, eds., S. C. Deevi, V. K. Sikka, P. J. Maziasz, and R. W. Cahn (Materials Park, OH: ASM International, 1996) pp. 265-82.
2. P. F. Tortorelli and J. H. DeVan, *Oxidation and Corrosion of Intermetallic Alloys*, eds. G. Welsch and P. D. Desai (West Lafayette, IN: Purdue University, 1996), pp. 267-321.

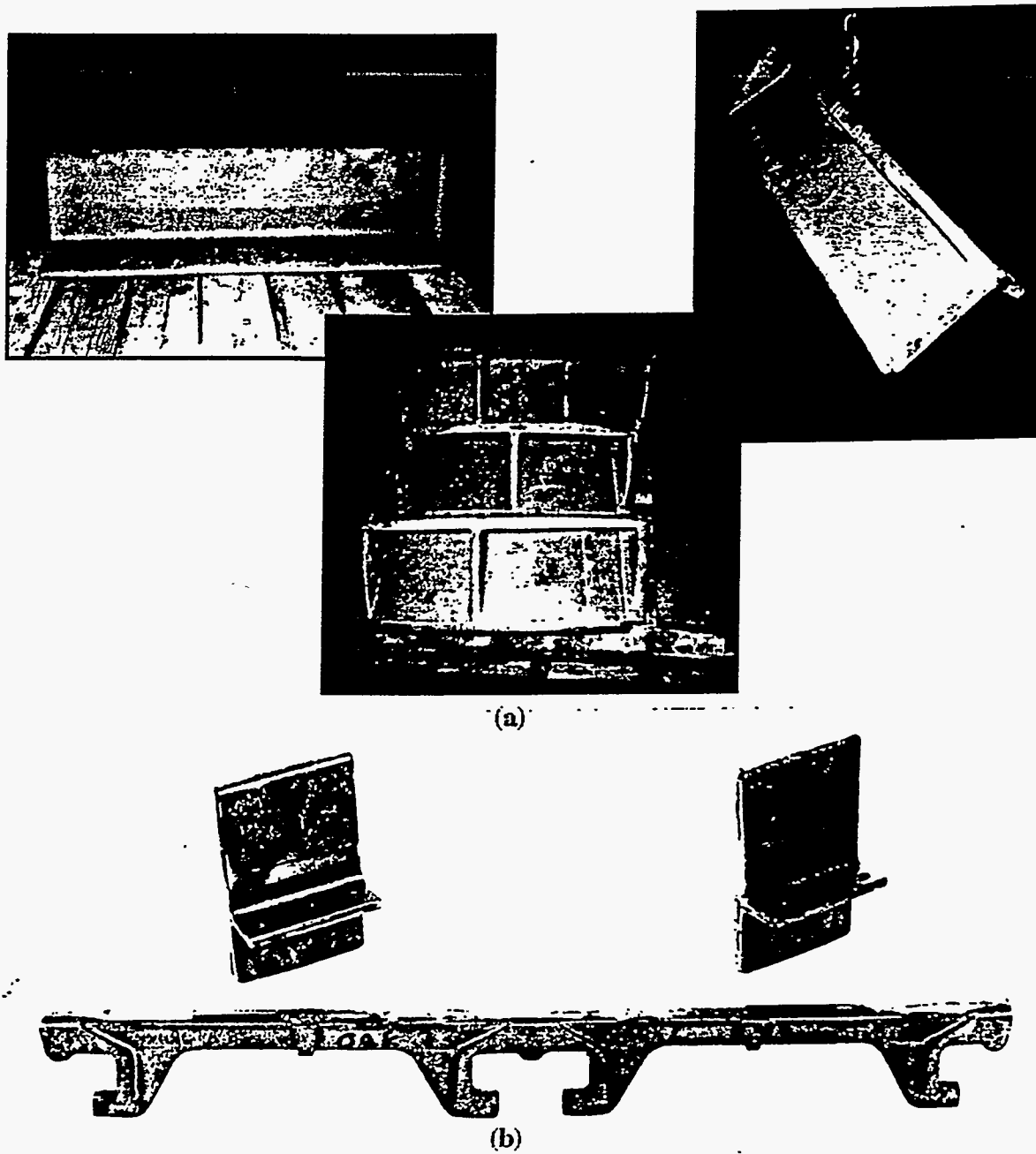


Fig. 8. Photographs of cast components of FeAl alloys: (a) skirts and (b) grate bar and pellet tips.

3. C. G. McKamey, J. H. DeVan, P. F. Tortorelli, and V. K. Sikka, *J. Mater. Res.*, **6**, 1779-1805 (1991).
4. P. F. Tortorelli, G. M. Goodwin, M. Howell, and J. H. DeVan, *Heat-Resistant Materials II*, eds. K. Natesan, P. Ganesan, and G. Lai (Metals Parks, OH: ASM International, 1995), pp. 585-90.

5. K. Natesan and R. N. Johnson, *Heat-Resistant Materials II*, eds. K. Natesan, P. Ganesan, and G. Lai (Metals Parks, OH: ASM International, 1995), pp. 591-99.
6. P. F. Tortorelli and P. S. Bishop, *Influence of Compositional Modifications on the Corrosion of Iron Aluminides by Molten Nitrate Salts*, ORNL/TM-11598, Oak Ridge National Laboratory, Oak Ridge, TN, January 1991.
7. C. T. Liu, E. H. Lee, and C. G. McKamey, *Scripta Met.*, **23**, 875-880 (1989).
8. N. S. Stoloff and C. T. Liu, *Intermetallics*, **2**, 75-87 (1994).
9. P. J. Maziasz, C. T. Liu, and G. M. Goodwin, *Heat-Resistant Materials II*, eds. K. Natesan, P. Ganesan, and G. Lai (Metals Parks, OH: ASM International, 1995), pp. 555-66.
10. P. J. Maziasz, G. M. Goodwin, D. J. Alexander, and S. Viswanathan, *International Symposium on Nickel and Iron Aluminides: Processing, Properties, and Applications*, eds., S. C. Deevi, V. K. Sikka, P. J. Maziasz, and R. W. Cahn (Materials Park, OH: ASM International, 1996) pp. 157-76.
11. S. C. Deevi and V. K. Sikka, *Intermetallics*, **4**, 357-375 (1996).
12. L. M. Pike, Y. A. Chang, and C. T. Liu, *Proc. Processing, Properties, and Applications of Iron Aluminides*, eds. J. H. Schneibel and M. A. Crimp (Warrendale, PA: The Minerals, Metals & Materials Society, 1994), pp. 217-30.
13. I. Baker and E. P. George, *International Symposium on Nickel and Iron Aluminides: Processing, Properties, and Applications*, eds., S. C. Deevi, V. K. Sikka, P. J. Maziasz, and R. W. Cahn (Materials Park, OH: ASM International, 1996) pp. 145-56.
14. N. S. Stoloff and V. K. Sikka, eds., *Physical Metallurgy and Processing of Intermetallic Compounds* (New York: Chapman & Hall, 1996).
15. I. Baker and P. R. Munroe, *Internal Metallurgical Reviews*, to be published.
16. R. M. German, *Thermal Analysis in Metallurgy*, eds., R. D. Shull and A. Joshi (Warrendale, PA: The Minerals, Metals & Materials Society, 1992), pp. 205-31.

17. V. K. Sikka, S. C. Deevi, and J. D. Vought, *Adv. Mater. & Processes*, **147**(6), 29-31 (1995).
18. L. L. Rishel and H. D. Brody, *Heat-Resistant Materials*, eds. K. Natesan and D. J. Tillack (Materials Park, OH: ASM International, 1991), 149-58.

ACKNOWLEDGMENTS

The authors would like to thank R. W. Swindeman and C. R. Brinkman for reviewing the paper and M. L. Atchley for typing, editing, and preparing the final 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, under contract DE-AC05-96OR22464 with Lockheed Martin Energy Research Corp.