Effect of carbon on mechanical properties of Fe-23 wt% Al alloy

R. G. BALIGIDAD*
Defence Metallurgical Research Laboratory, Kanchanbagh, P.O. Hyderabad 500 058, India
E-mail: rbaligidad@yahoo.com

A. RADHAKRISHNA
17-1-388/49A, Laxminagar, Saidabad, Hyderbad, India

D. S. SARMA
Institute of Technology, Banaras Hindu University, Varanasi 221 005, India

Published online: 16 September 2005

The ordered intermetallics based on FeAl are being developed for elevated temperature structural applications. However, limited ductility at room temperature, poor strength, and creep properties have been a major deterrent to their acceptance for broad-based applications [1]. Recently, it has been shown that carbon may be an important alloying addition to Fe_3Al-based alloys as this leads to improved strength, creep resistance, machinability, and resistance to environmental embrittlement [2–5]. These improvements in the properties were attributed to the formation of perovskite based $Fe_3AlC_{0.5}$ precipitates. Here, we report the effect of carbon addition on the mechanical properties of Fe-23 wt% Al alloy.

About 35 kg melts of iron aluminides based on FeAl with the following compositions: Fe-23Al-0.27C and Fe-23Al-1.3C were prepared by a combination of air induction-melting with flux cover (AIMFC) and electroslag remelting (ESR) (all compositions are in wt% unless otherwise specified). The melting practice has been described in detail elsewhere [5, 6]. Longitudinal sections of cast ESR ingots were cut using abrasive cut-off wheel, mechanically polished and etched with an etchant comprising of 33% HNO_3 + 33% CH_3COOH + 33% H_2O + 1% HF by volume for microstructural examination. The bulk hardness measurements were made on metallography polished samples using a Vickers hardness machine with 30 kg load. Longitudinal ASTM–E 8M tensile specimens of 4.0 mm gauge diameter and 20 mm gauge length for room and high temperature tests were machined with length parallel to ingot axis and polished using 600 grit abrasive. Tensile test were carried out at room temperature (298 K), 673, 873, 973, and 1073 K on Fe-23Al-1.3C alloy and at room temperature (298 K) and 873 K on Fe-23Al-0.27C alloy in 100 kN Instron 1185 Universal Testing Machine at an initial strain rate of 0.8×10^{-4} s^{-1}. Standard Charpy V-notch impact specimens of 10 × 10 mm cross-section and 55 mm length were used for impact testing. Impact tests were carried out on Tinius Olsen Instrumented Impact-Testing Machine using 30 kg hammer. Selected tensile and impact fracture samples were examined in SEM. Stress rupture specimens of 5 mm gauge diameter and 25 mm gauge length were machined and polished using 600 grit abrasive. All the creep tests were carried out at 873 K and 140 MPa till the specimen failed. Minimum creep rates (MCR) were measured as the slope of the linear portion of the strain versus time curves.

Optical micrographs revealed the presence of two phase structure in both the Fe-23Al-0.27C (Fig. 1a) and Fe-23Al-1.3C (Fig. 1b) alloys. These phases were identified to be FeAl (matrix) and $Fe_3AlC_{0.5}$ (precipitates) in Fe-23Al-0.27C alloy and FeAl (matrix) and graphite (precipitates) in Fe-23Al-1.3C alloy by XRD and EPMA line scanning in the previous study [7]. These results are also consistent with the Fe-Al-C phase diagram [8]. The graphite precipitates in the Fe-23Al-1.3C alloy bear a flake and star shape, which is similar to one of the several basic shapes of graphite. The present alloys exhibits better machinability as compared to the binary FeAl alloys [9, 10]. All the samples studied in the present work were successfully machined by turning operation on the lathe. This improvement in machinability has been attributed to the reduced susceptiblility to the hydrogen embrittlement on account of blocking of interstitial sites by carbon in the alloys [11]. Further, machining of Fe-23Al-1.3C alloy is comparatively easier than Fe-23Al-0.27C alloy. This may be attributed to the presence of soft graphite precipitates which may help in the formation of small and uniform size chips during machining.

Table I summarizes the hardness, tensile properties of as-cast ESR ingots of Fe-23Al-0.27C and Fe-23Al-1.3 alloy. Each hardness data point reported here represents an average of five measurements and each tensile and creep rupture data point reported here represents an average of two tests. The tensile strength of the present as-cast ESR ingot of Fe-23Al-0.27C alloy is superior to that reported for the thermomechanically processed and heat treated binary Fe-22Al alloy (Table I) [12]. This may be attributed to the precipitation

* Author to whom all correspondence should be addressed.

DOI: 10.1007/s10853-005-4534-7

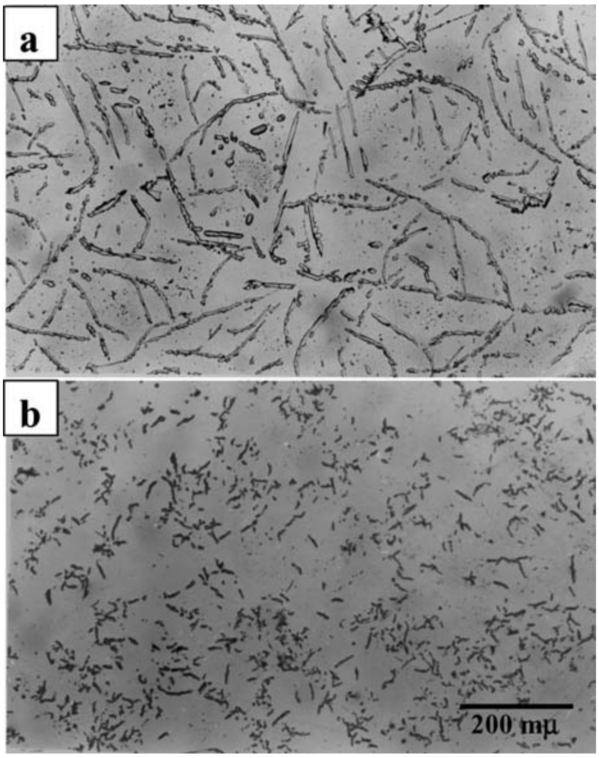

Figure 1 Optical micrographs of ESR cast samples of (a) Fe-23Al-0.27C and (b) Fe-23Al-1.3C alloys.

strengthening arising out of precipitation of hard uniformly distributed $Fe_3AlC_{0.5}$ precipitates as well as solid solution strengthening by interstitial carbon present in the alloys. The increase in carbon content from 0.27 to 1.3 wt% has resulted in the reduction of hardness from 343 to 301 HV and room temperature strength from 440 to 379 MPa. This reduction in strength with an increase in carbon addition from 0.27 to 1.3 wt% may be attributed to the precipitation of carbon as soft graphite (Fig. 1b) as against hard $Fe_3AlC_{0.5}$ precipitates (Fig. 1a) present in the Fe-23Al-0.27C alloy. A similar reduction in the compressive yield strength in as-cast ESR Fe-23Al alloys by an increase in the carbon content from 0.27 to 1.3% has been reported earlier [7].

TABLE I Room and high temperature mechanical properties of Fe-23Al

Alloy composition (wt%)	Hardness	RT tensile properties			Creep properties (873 K, 140 MPa)	
		UTS (MPa)	YS (MPa)	EL (%)	Life (hr)	MCR (%/hr)
Fe-23Al-0.27C (ESR cast)	343	495	440	0.5	66	0.2
Fe-23Al-1.3C (ESR cast)	301	418	379	0.6	9.4	0.95
Fe-22Al[a] (Hot worked and heat treated)	–	412	360	2.2	46.4	0.23

[a]After Ref. [12] and [16].

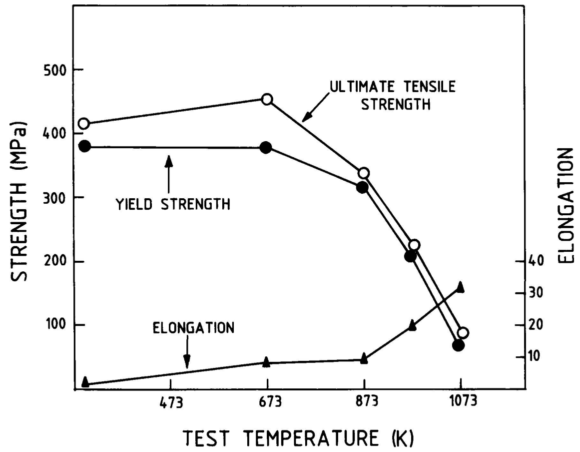

Figure 2 Showing variation of tensile properties of cast ESR Fe-23Al-1.3C alloy.

The tensile yield strength of ESR cast Fe-23Al-1.3C alloy gradually drops up to 873 K, beyond which it decreases rapidly (Fig. 2). Similar behaviour was also observed in binary Fe-21Al and Fe-24Al alloys by Mendiratta [13] and Gaydosh *et al.* [14], respectively. The sudden drop in the strength is accompanied by a significant increase in the tensile elongation (Fig. 2). An examination of fracture surfaces of the alloys tested at room temperature as well as at 873 K revealed transgranular cleavage failure mode (Figs. 3a and b). While that tested at 973 K failed by microvoid coalescence (Fig. 3c). This indicates the ductile-brittle (tensile) transition temperature (DBTT) is in the vicinity of 873–973 K.

Binary FeAl alloys generally exhibit very poor toughness. The Charpy impact test results of a boron modified Fe-22Al alloy with 2–4% ductility showed 3–5 J absorbed energy [15]. In the present work, both the alloys have exhibited relatively low impact energy (2 J) as compared to boron modified Fe-22Al alloy and the impact samples of both the alloys failed by quasi-cleavage. This clearly indicates that carbon does not have an effect on either the impact energy or the fracture mode.

The results on creep and stress-rupture tests of Fe-23Al–0.27C and Fe-23Al–1.3C alloys are also summarized in Table I. The minimum creep rates and stress-rupture life reported in the literature for binary Fe-22Al alloy at 886 K and 138 MPa has been included in Table I for comparison [16]. It is evident that creep properties obtained in the present Fe-23Al alloy containing 0.27 wt% C are substantially superior. The improved creep properties could be attributed to the presence of uniformly distributed $Fe_3AlC_{0.5}$ precipitates (Fig. 1a) as well as the solid solution strengthening by interstitial carbon present in the alloys. The increase in the carbon content from 0.27 to 1.3 wt% has resulted in poor minimum creep rate and stress-rupture life. This may be due to the precipitation of carbon as a soft graphite phase as against hard $Fe_3AlC_{0.5}$ precipitates.

In conclusion, a small amount (0.27 wt%) of carbon addition to binary Fe-23Al alloy has resulted in improved tensile strength, creep properties, and machinability. Increases in carbon content from 0.27 to 1.3 wt% produced further improvement in

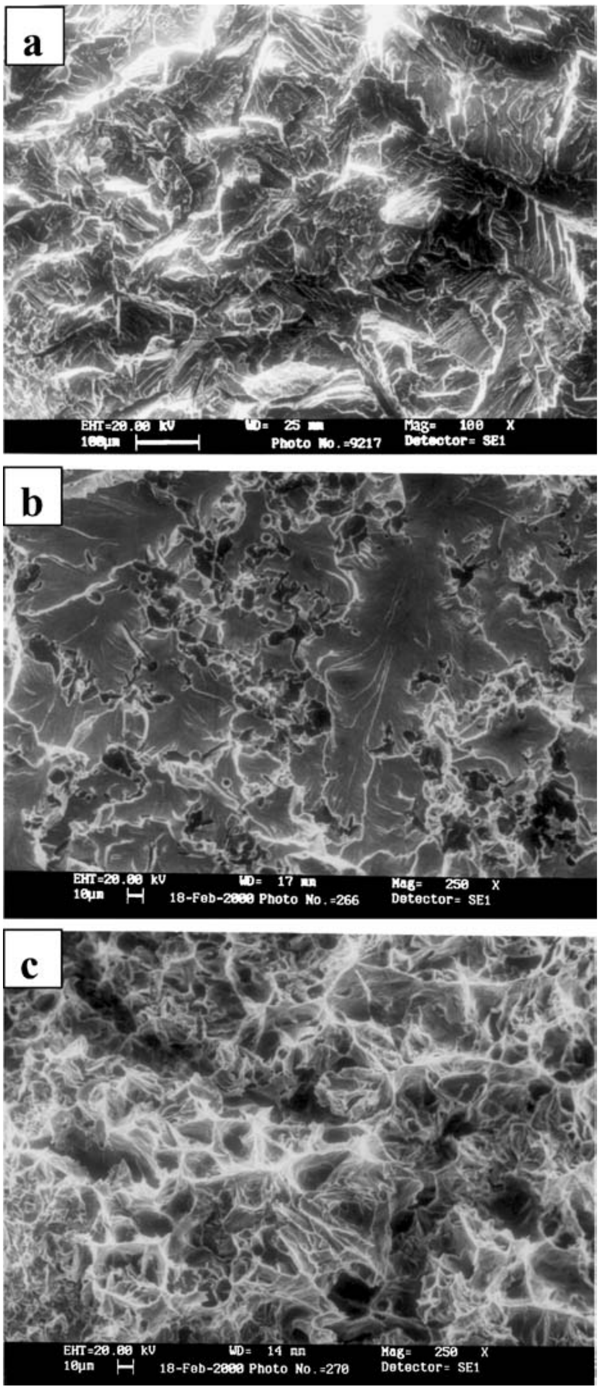

Figure 3 SEM photographs showing the change in tensile fracture mode from transgranular cleavage (a) at room temperature and (b) 873 K to ductile dimple failure, and (c) at 973 K in cast ESR Fe-23Al-1.3 C alloy.

machinability but resulted in poor tensile strength and creep properties. The carbon containing ESR cast alloys exhibited poor room temperature, tensile ductility, and toughness as compared to the wrought binary FeAl alloy. The tensile yield strength of ESR cast Fe-23Al-1.3C alloy exhibited sudden drop above 873 K and ductile-brittle (tensile) transition temperature (DBTT) in the vicinity of 873–973 K.

Acknowledgments
The authors are grateful to the Defence Research and Development Organization, Ministry of Defence, New Delhi for the financial support in carrying out this research work. The authors wish to thank Dr. D. Banerjee, C C R & D Headquaters, Delhi and Dr. A Srirama Murthy, Director DMRL, Hyderabad for their interest and encouragement. The authors would like to thank fellow officers and staff of ERG (melting and casting), ACG (chemical analysis), GMS (sample making), CDG (radiography, forging, and rolling), MBG (tensile and creep), and SFAG (metallography).

References
1. V. KRISHNA, in "Intermetallic Compounds, Principal and Practice," edited by J. H. Westbrook and R. L. Fleisher (New York, Wiley, 1994) Vol. 2, p. 199.
2. R. G. BALIGIDAD, U. PRAKASH, A. RADHAKRISHNA, V. RAMAKRISHNA RAO, P. K. RAO and N. B. BALLAL, *ISIJ Int.* **36** (1996) 1453.
3. R. G. BALIGIDAD, U. PRAKASH and A. RADHAKRISHNA, *Mater. Sci. Eng.* A **230** (1997) 188.
4. R. G. BALIGIDAD, U. PRAKASH, A. RADHAKRISHNA, V. RAMAKRISHNA RAO, P. K. RAO and N. B. BALLAL, *Scripta Metall.* **36** (1997) 105.
5. R. G. BALIGIDAD, U. PRAKASH and A. RADHAKRISHNA, *Intermetallics* **6** (1998) 765.
6. R. G. BALIGIDAD, U. PRAKASH, V. RAMAKRISHNA RAO, P. K. RAO and N. B. BALLAL, *Ironmak Steelmak* **21** (1994) 324.
7. A. RADHAKRISHNA, R. G. BALIGIDAD and D. S. SARMA, *Scripta Metall.* **45** (2001)
8. M. PALM and G. INDEN, *Intermetallics* **3** (1995) 443.
9. N. S. Stoloff and C. T. Liu, *Intermetallics* **2** (1995) 75.
10. A. PATRICK FERGUSON and C. T. LIU, *Scripta Metall.* **26** (1995) 1669.
11. U. PRAKASH and G. SAUTHOFF, *Scripta Metall.* **44** (2001) 73.
12. C. T. LIU, E. H. LEE and C. G. MCKAMEY, *Scripta Metall.* **23** (1989) 875.
13. M. G. MENDIRATTA, S. K. CHATTERJEE and H. A. LIPSITT, in "Proceedings of the 3rd International Conference on Rapid Solidification Processing, Principals and Technologies, Gaitherburg, MD", edited by R. Meazdiyasani (National Bureau of Standards, Washington, DC, 1983) p. 240.
14. D. J. GAYDOSH, S. L. DRAPER and M. V. NATHAL, *Metall. Trans. A* **20** (1989) 1701.
15. P. J. ALEXANDER, in "Processing, Properties and Application of Iron Aluminides", edited by J. H. SCHNEIBEL and M. A. CRIMP (The Materials, Metals and Minerals Society, Warrendale, PA, 1994) p. 19.
16. J. H. SCHNEIBEL, in "Processing, Properties and Application of Iron Aluminides", edited by J. H. Schneibel and M. A. Crimp (The Materials, Metals and Minerals Society, Warrendale, PA, 1994) p. 329.

Received 18 February
and accepted 13 April 2005