DOR: 20.1001.1.25383620.2021.5.2.4.0

The Influence of Boron Additions on Microstructure and Dry Sliding Wear of Cast FeAl-Based Alloys

M. Paryab[1], M. Ghanbari Haghighi[2,*]

[1]Mining and Metallurgical Engineering Department, Amirkabir University, Tehran, Iran.
[2]Advanced Materials Engineering Research Center, Karaj Branch, Islamic Azad University, Karaj, Iran.
Received 02 September 2021 - Accepted: 10 December 2021

Abstract

In this research, the influence of boron content on microstructure and dry sliding wear resistance of as-cast FeAl-based alloys was evaluated. The alloying process was carried out using vacuum induction melting and four specimens having different boron content of 0, 0.1, 0.5 and 1 at% were produced. As-cast specimens then were teste using standard pin-on-disk wear tester machine in 20 and 40 N applied load and a distance of 1000 m according to ASTM G99 standard. The surface of worn specimens then were examined using scanning electron microscope to determine the dominated wear mechanism. The investigations revealed that at lower applied load of 20 N, the governing wear mechanism is oxidative wear and for higher applied load of 40 N, delamination is the governing mechanism. Increasing the boron content increases the hardness as well as the wear resistance of the alloy which is related to the formation of Fe_2B compounds in the material and increasing the hardness.

Keywords: Iron Aluminide- FeAl, Boron Content, Casting, Microstructure, Wear Properties.

1. Introduction

Iron aluminides based on FeAl and Fe_3Al accordant with Fe-Al phase diagram form in the range of 20 to 35 atomic percent of Aluminum. This type of intermetallic compounds has $D0_3$ ordered crystalline lattice, excellent oxidation, and sulfidation resistance and low material cost [1-4]. These alloys have a density of about 5.4-6.7 gr/cm^3 and they are 30% lighter than prevalent high-temperature strength alloys such as stainless steels. Development of these alloys can help in save strategic elements such as Ni and Cr [5-7]. However limited ductility at ambient temperature and losing the strength at high temperatures have been a major deterrent to their commercial uses for structural applications. Nevertheless, by adding alloying elements such as Cr, B, Zr, Ti, W, … the mechanical properties of Fe_3Al-based alloys have been improved, generally the alloying elements that lead to creation of precipitate phases are added with a bite contents, because a large amount of alloying elements addition make the alloys brittle, the volume fraction of formed phases must be controlled.[8-10]. Iron aluminides (Fe_3Al) with $D0_3$ ordered lattice show proper high-temperature strength with increasing temperature until the critical temperature of $D0_3$ stability, at the higher temperatures mechanical properties of Fe_3Al-based alloys are decreased [9].
There are different ways to improve the mechanical properties of iron aluminides: solid solution hardening, the formation of precipitate hard phases at grain boundaries and inside the grains. The presence of B in the chemical composition of the iron aluminides, forms boride precipitates and Zr causes to form Laves phases [11-16], co-existence of B and Zr makes ZrB2 precipitate phases in Fe_3Al-based alloys [8, 10, 12]. Grain boundaries of ordered lattice Intermetallic compounds are weak, the presence of hard precipitate phases in grain boundaries strengthens these regions and improves the mechanical properties [4].
There are two major methods for production of iron aluminides: powder metallurgy and casting, but nowadays casting is preferred in order to the reduction of production costs.
The aim of the present study is a comprehensive investigation of the effects of B and Zr on microstructure, phase identification, ordering transitions and dry sliding wear properties of FeAl iron aluminides.

2. Materials and Methods

Based on the chemical compositions of investigated FeAl-based intermetallic with varying amount of boron content of 0, 0.1, 0.5 and 1 at% were produced. All the alloys were prepared by vacuum induction melting.
Primary needed materials were placed in the alumina crucible, melting and the alloying process was performed up to 1600 °C temperature with a 0.02mbar vacuum.
The melt was poured in a perfected cast iron mold, cylindrical samples with a diameter 40mm and a height 200mm were obtained.

*Corresponding author
Email address: mohsen.ghanbari@kiau.ac.ir

The microstructure and wear properties of the alloys were evaluated in the as-cast condition.

For the study of microstructure and worn surface of the specimens, light optical microscopy (LOM) and scanning electron microscopy (SEM) equipped with energy dispersive spectrometry (EDS) microanalysis were used.

The samples were polished by SiC abrasive papers and finally using diamond paste with a particles size of 0.1μm, the samples then were chemically etched using (1%HF, 33%CH_3COOH, 33%HNO_3, 33%H_2O) etching reagent.

Dry sliding wear test was used to evaluate the resistance of the material to wear.

Micro-mechanisms of wear and the morphology of debris have been studied using SEM.

The samples was prepared according to ASTM G99 (height =30 mm and diameter = 5mm) standard. The counter face was a heat treated and grounded disc of 52100 steel with a hardness of 58 RC and the tests were conducted in 20 and 40 N applied load at a distance of 1000 m.

3. Results and Discussions

3.1. Microstructure and Phase Analysis

Fig. 1. represents the microstructure of alloys in as-cast conditions, images of optical microscopy shows dendritic microstructure with precipitate phases in interdendritic regions.

According to Fig. 1.a, pure FeAl has coarse polygonal grains. By increasing the boron content in the alloy from 0 to 1 at%, the grain structure converted to the dendritic one gradually.

For the sample with 1 at% boron, dendritic microstructure is illustrated in Fig. 1.d Interdendritic regions containing eutectic FeAl-Fe_2B phases with lamellar morphology.

A precipitate forms a thin layer along the prior FeAl grain boundaries with a thickness of about 1.8 μm and the average distance between precipitates is 22 μm. The volume fraction of precipitate phases was calculated about 9.47%.

Boron has a low solid solubility in the crystalline lattice of FeAl, so during solidification draws back to the solidification front and precipitates as a FeAl-Fe_2B eutectic in interdendritic regions [10].

For a better understanding of the microstructure, SEM micrographs of the four specimens are seen in Fig. 2. As seen in this figure, grain boundary and interdendritic precipitates which dominantly is Fe_2B is illustrated in those figures.

This phase can strengthen the grain boundaries and also by increasing the content of boron in the chemical composition, the grains become finer as mentioned previously in the case of OM results.

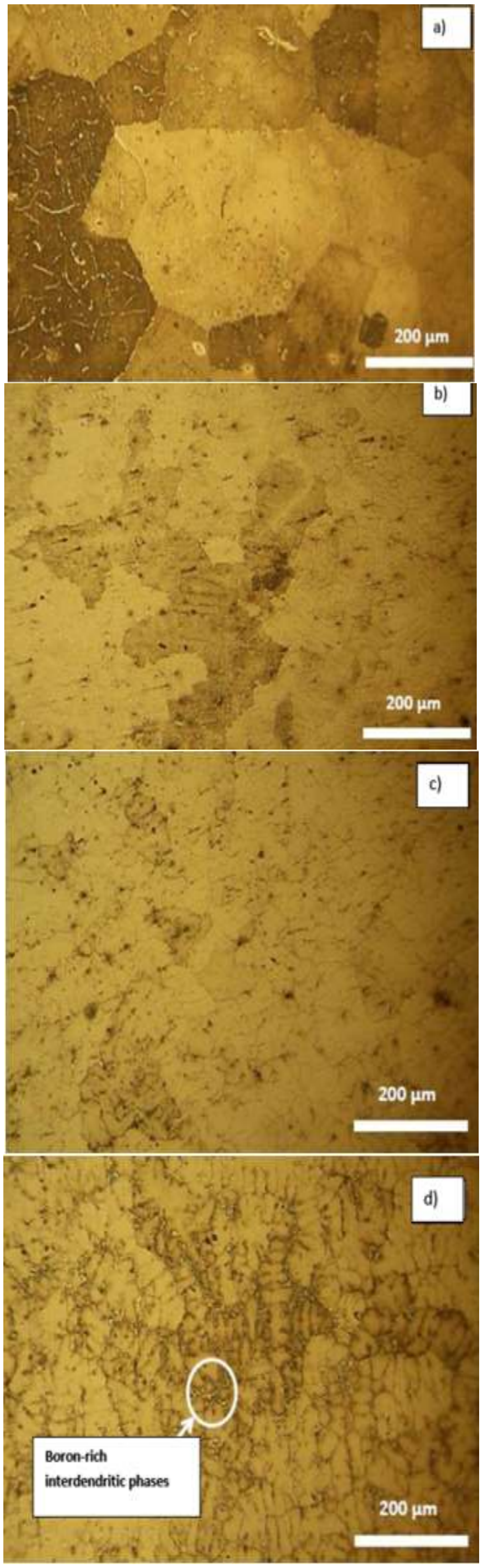

Fig. 1. LOM images of as-cast alloys a) FeAl b) FeAl-0.1B, c) FeAl-0.5B d) FeAl-1B.

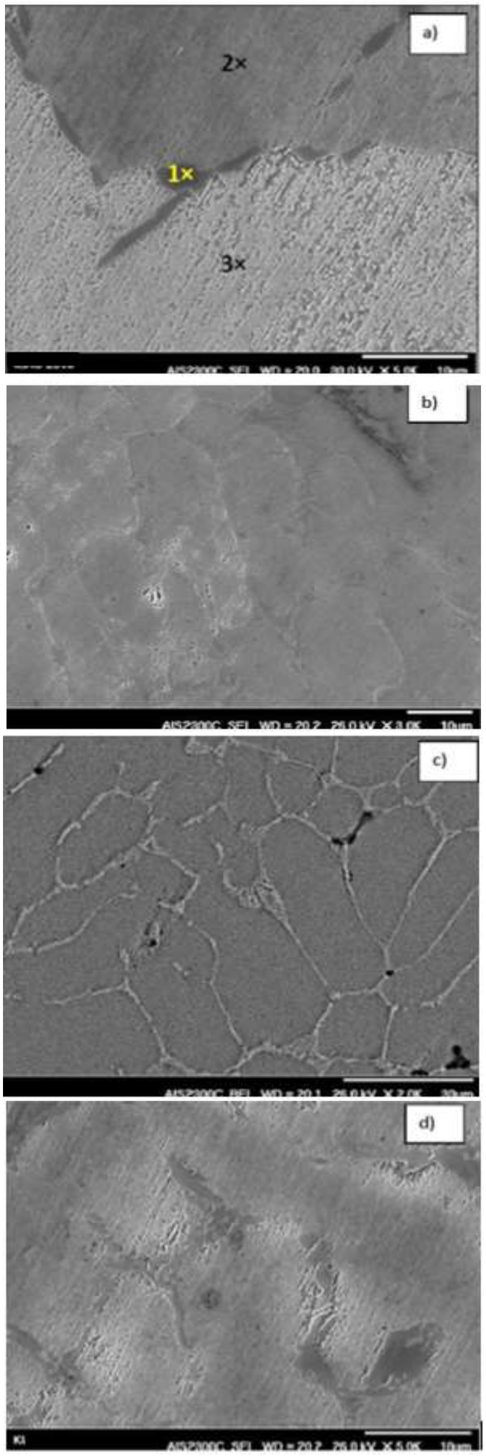

Fig. 2. SEM images of as-cast alloys a) FeAl b) FeAl-0.1B, c) FeAl-0.5B d) FeAl-1B.

3.2. Hardness Test

Results of hardness tests are shown in Table. 1. Hardness of the samples in as-cast conditions in agreement with the values reported in other reports[18]. Intermetallic compound have high hardness value which may be is due to the ordered structure of the alloy that caused high strength and high hardness.

High value of hardness and few slip systems are the main reasons for brittle nature of these alloys. In the case of wear properties of the material, high hardness caused the material to be more resistant to dry sliding wear. As seen in the table the hardness of the material increases with increasing of boron content. It is mainly due to the precipitation of some phases in the grain boundaries and formation of Lave phases which increase the hardness as well as the strength of the material.

Table. 1. The hardness value of the investigated materials [19].

Rockwell Hardness	Vickers hardness	sample
26	289	FeAl
34	343	FeAl-0.1B
39	367	FeAl-0.75B
41	434	FeAl-1B

3.3. Wear Test

Fig. 3. shows the effect of increasing Boron content on the weight loss of the samples after the wear test of 1000 m travelling in 20 and 40N of applied load [20].

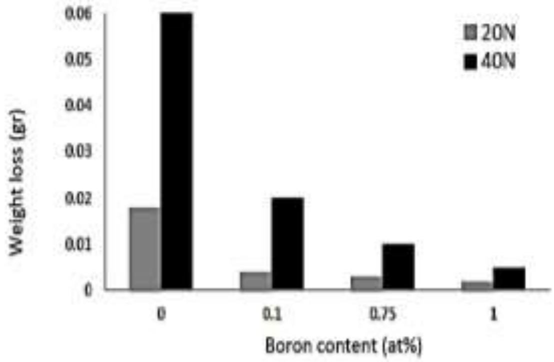

Fig. 3. the variation of weight loss of the samples after 1000 m of dry sliding test.

As seen here and mentioned previously, higher hardness of the material with higher content of boron is the main reason for improving wear resistance. It is dominated in the higher applied load of 40 N. in lower applied load of 20 N, the governing wear mechanism is oxidative. The worn surface s of the samples at the applied load of 20 N are shown in Fig. 4. As seen in the sample FeAl alloy, there seen grooves and oxidation signs [21]. The existence of grooves in this sample is due to lower hardness in comparison with the others containing boron. It caused higher weight loss in this sample. For other samples with higher boron content, the wear rate is lower than the pure alloy [22]. The EDS microanalysis of the surface is shown in Fig. 5. which evidences of oxygen is shown in the spectrum [23].

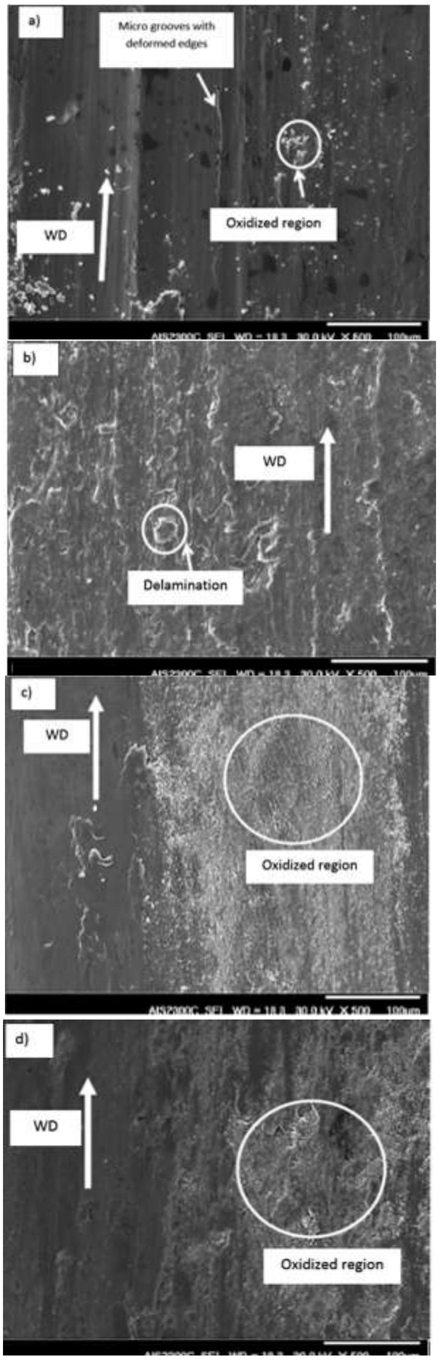

Fig. 4. Worn surface of the samples in the applied load of 20 N a) FeAl b) FeAl-0.1B, c) FeAl-0.75B d) FeAl-1B.

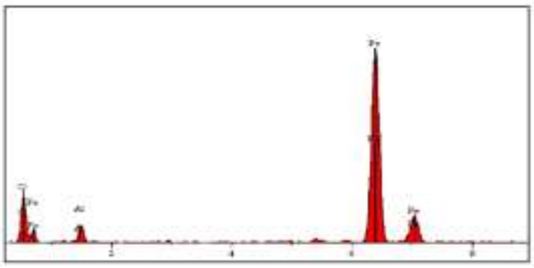

Fig. 5. Microanalysis of the surface of the samples at the load of 20 N.

At the load of 40 N, the governing mechanism is delamination, especially for the alloys with lower hardness. So as it is obvious in the weight loss of the samples, the sample with the lowest hardness, a dramatic failure is seen.

The signs of severe delamination is observed in the worn surface of the pure sample [24, 25]. For the samples with higher content of boron, lower delamination were observed which is due to the hardness and strength of the material.

The worn surface of the materials at the applied load of 40 N is shown in Fig. 6. [27].

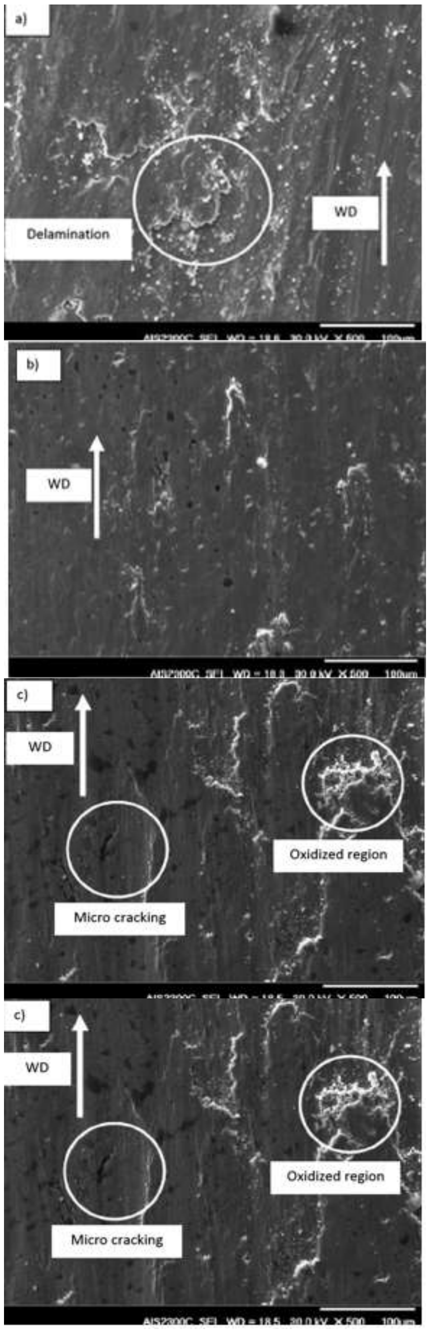

Fig. 6. The worn surface of the materials at the load of 40 N a) FeAl b) FeAl-0.1B, c) FeAl-0.75B d) FeAl-1B.

The evaluation of the debris removed from the surface at different loads demonstrate the oxidative mechanism at low applied loads and fresh metallic debris at higher applied load. The morphology of the debris is shown in Fig. 7 [28, 29].

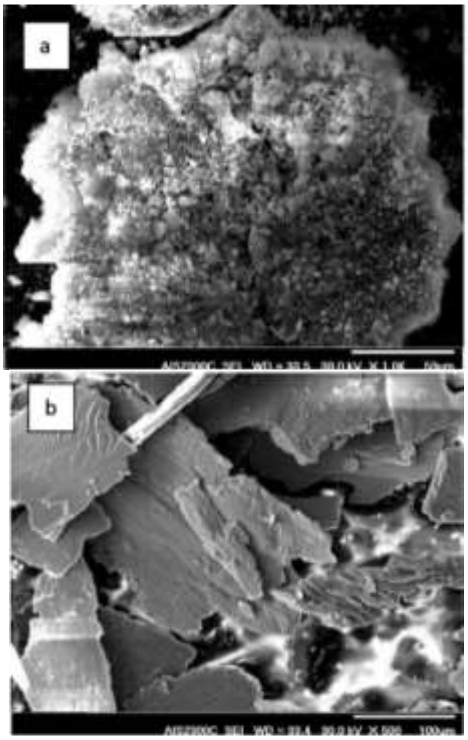

Fig. 7. SEM image of the a) oxide particles and b) fresh metallic particles removed from the surface during the wear.

4. Conclusion

From the results of this study the following discussions can be stated:

1. For FeAl intermetallic compounds, by increasing the boron content, some precipitations were formed in the grain boundaries. These precipitates are dominantly Fe_2B which increases the hardness and wear resistance of the alloy.
2. By increasing the boron content from 0.1 to 1 at% the hardness increases and so the wear resistance would be increased. At lower applied loads, the dominated mechanism for the samples with boron is mainly oxidative wear. For the pure FeAl sample both of oxidative and delamination was seen. At higher applied loads, the samples with low hardness show a delamination mechanism while for the samples with high hardness value, the sample shows only oxidative wear mechanism.

References

[1] Z. Zhang and W. Liu, Mater. Sci. Eng., A, 423, (2006), 343.
[2] J. Wang, , J. Xing, Z. Qiu, X. Zhi and L. Cao, J. Alloys Compd., 488, (2009), 117.
[3] K. Han, I. Ohnuma and R. Kainuma, J. Alloys Compd., 668, (2016), 97.
[4] G. Sauthoff, Intermetallics, VCH Verlagsgesellschaft, Weinheim, 1995.
[5] W. C. Luu amd J. K. Wu, Mater. Chem. and Phys., 70, (2001), 236.
[6] J. H. Westbrook and R. L. Fleischer, Intermetallic Compounds, Chichester, John Wiley & Sons Ltd, 2. (1994), 199.
[7] D. D. Risanti and G. Sauthoff, Intermetallics, 19, (2011), 1727.
[8] D. G. Morris and M. A. Muñoz-Morris, Mater. Sci. Eng., A, 462, (2007), 45.
[9] M. Palm, Intermetallics, 13, (2005), 1286.
[10] R. Krein, A. Schneider, G. Sauthoff and G. Frommeyer, Intermetallics, (2007), 15, 1172.
[11] P. Kratochvíl, P. Kejzlarb, R. Krála and V. Vodicková, Intermetallics, 20, (2012), 39.
[12] P. Kratochvíl, F. Dobeš, J. Pešička, P. Málek, J. Buršík, V. Vodičková and P. Hanus, Mater. Sci. Eng. A, 548, (2012), 175.
[13] X. Li, P. Prokopčáková and M. Palm, Micro. Mater. Sci. Eng., A, 611, (2014), 234.
[14] F. Stein, M. Palm and G. Sauthoff, Intermetallics, 13, (2005), 1275.
[15] P. Kratochvíl, P. Málek, M. Cieslar, P. Hanus, J. Hakl and T. Vlasák, Intermetallics, 15, (2007), 333.
[16] A. Wasilkowska, M. Bartsch, F. Stein, M. Palm, K. Sztwiertnia, G. Sauthoff and U. Messerschmidt, Mater. Sci. Eng., A, 380, (2004), 9.
[17] P. Lejček and A. Fraczkiewicz, Intermetallics, 11, (2003), 1053.
[18] J. W. Cohron, Y. Lin, R. H. Zee and E. P. George, Acta Mater., 46, (1998), 6245.
[19] F. Stein, A. Schneider and G. Frommeyer, Intermetallics, 11, (2003), 71.
[20] D. A. Alven and N. S. Stoloff, Mater. Sci. Eng., A, (1997), 239-240, 362-368.
[21] D. A. Alven and N. S. Stoloff, Scr. Mater., 34, 1996, 1937.
[22] Y. D. Huang, W. Y. Yang and Z. Q. Sun, Intermetallics, 9, (2001), 119.
[23] L. Anthonya and B. Fultz, Acta Metall. Mater., (1995), 43, 3885.
[24] D. G. Morris and M. A. Muñoz-Morris, Intermetallics, 13, 2005, 1269.
[25] H. Xiao and I. Baker, Scr. Metall. Mater., 28, (1993), 1411.
[26] J. T. Guo, O. Jin, W. M. Yin and T. M. Wang, Scr. Metall. Mater. (1993), 29, 783.
[27] K. Yoshimi, S. Hanada and M. H. Yoo, Acta Metall. Mater., (1995), 43, 4141.
[28] M. Zamanzade and A. Barnoush, Proc. Mater. Sci., (2014), 3, 2016.
[29] M. A. Martin, J. A. Fenske, S. L. Liu, P. Sofronis and I. M. Robertson, Acta Mater.,(2011), 59, 1601.