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The effect of vacancies on the environmental yield strength dependence of boron-free and boron-doped Fe-40Al

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Abstract

The effect of environment on the yield strength of boron-free and boron-doped Fe-40Al was considered. Special attention was given to the role of excess thermal vacancies. It was found that samples given a vacancy-relieving heat treatment had a 12% lower yield strength when tested in air than when tested in vacuum. This was attributed to an environmental softening effect. However, samples with a large amount of quenched-in vacancies exhibited no environmental yield strength dependence. These observations were found in both the boron-free and boron-doped alloys. © 2000 Elsevier Science Ltd. All rights reserved.

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1. Introduction

Over the past 12 years a significant amount of work has been done to investigate environmental effects on the ductility of FeAl-based alloys at ambient temperatures [1–8]. However, little effort has been spent to consider the effect of environment on the yield stress of these alloys. Studies of environmental effects have often not reported yield stress data [5–7]. In other studies, secondary effects such as excess thermal vacancies (which we will discuss later), may have obscured the environmental dependence of the yield stress [1–4]. However, a recent study on strain rate and environmental effects on the tensile properties of Fe–40Al did indeed reveal an environmental yield stress dependence [8]. In that study, samples subjected to a vacancy relieving heat treatment were observed to have a 15–20% lower yield stress when tested in air than when tested in vacuum. This "environmental softening" effect was observed over a strain rate range of 3.3×10^{-6} to 6.6×10^{-1} s^{-1}. Additionally, the yield stress values of samples tested in air were found to gradually increase with increasing strain rate, while those of samples tested in vacuum remained constant. The purpose of the present investigation was to clarify the role of excess thermal vacancies in either revealing or obscuring the environmental yield stress dependence of boron-free as well as boron-doped Fe–40Al.

2. Experimental

Two FeAl-based alloys were prepared from high-purity starting elements by arc-melting and drop casting into a Cu mold. The first alloy was boron-free Fe–40Al (compositions are in at.% unless otherwise noted). The second alloy was a boron-doped version of the first alloy, i.e. Fe–40Al + 500 ppm (by weight) B. The as-cast ingots were clad in mild steel and hot extruded at 850°C using a 9:1 reduction ratio. Sample blanks from the extruded rods were given one of two heat treatments: (1) 700°C/72 h/OQ (oil quench), or (2) 700°C/72 h/FC (furnace cool) + 400°C/168 h/OQ. Note that for heat treatment no.2 the samples were furnace cooled directly from 700 to 400°C. All heat treatments were done in air. These heat treatments resulted in fully recrystallized microstructures with grain sizes of 35 and 15 μm for the Fe–40Al and Fe–40Al + B alloys, respectively. For both alloys the grain size was independent of the choice of the two heat treatments. Round, button-head tensile samples with a gauge length of 17.8 mm were machined from the sample blanks. The surfaces of the samples were prepared by mechanical polishing followed by

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electropolishing. Tensile tests were performed at room temperature in air or vacuum ($\sim 2\times10^{-4}$ Pa) with an engineering strain rate of 2.4×10^{-3} s^{-1}. After testing, the fracture surfaces were examined using a scanning electron microscope (SEM).

3. Results

The tensile test data and corresponding fracture modes for all samples in this study are summarized in Table 1. The yield strength of Fe–40Al is shown in Fig. 1 for different heat treatments and test environments. The yield strength of samples quenched from 700°C was substantially higher than that of samples quenched from 400°C. Furthermore, the yield strength of samples quenched from 400°C was found to be a function of test environment, being 12% lower when tested in air (380 MPa) than when tested in vacuum (427 MPa). For samples quenched from 700°C, the yield strength was essentially independent of test environment (487 MPa in air vs. 497 MPa in vacuum). The experimental uncertainty in the tensile tests was estimated to be ±10 MPa. Therefore, the 47 MPa difference in the samples quenched from 400°C was believed to be meaningful, while the 10 MPa difference in the samples quenched from 700°C was not.

Table 1
Room temperature tensile properties of Fe–40Al and Fe–40Al + B

Quench temperature(°C)	Test environment	Vacancy concentration	Yield stress (MPa)	UTS (MPa)	Elong.(%)	Fracture mode
Fe–40Al						
400	Air	Low	380[d]	439[d]	2.5[d]	Pred. TG[b]
400	Vacuum	Low	427[d]	604[d]	4.6[d]	Mixed[c]
700	Air	High	487	513	1.2	Pred. IG[a]
700	Vacuum	High	497	613	2.0	Pred. IG
Fe–40Al + B						
400	Air	Low	373	537	3.9	Pred. TG[b]
400	Vacuum	Low	417	804	7.4	Pred. TG[b]
700	Air	High	511	664	2.5	Mixed
700	Vacuum	High	504	856	6.4	Mixed

[a] Pred. IG = predominantly intergranular fracture (some transgranular also observed).
[b] Pred. TG = predominantly transgranular fracture (some intergranular also observed).
[c] Mixed = significant amounts of both transgranular and intergranular fracture.
[d] Average of two tests.

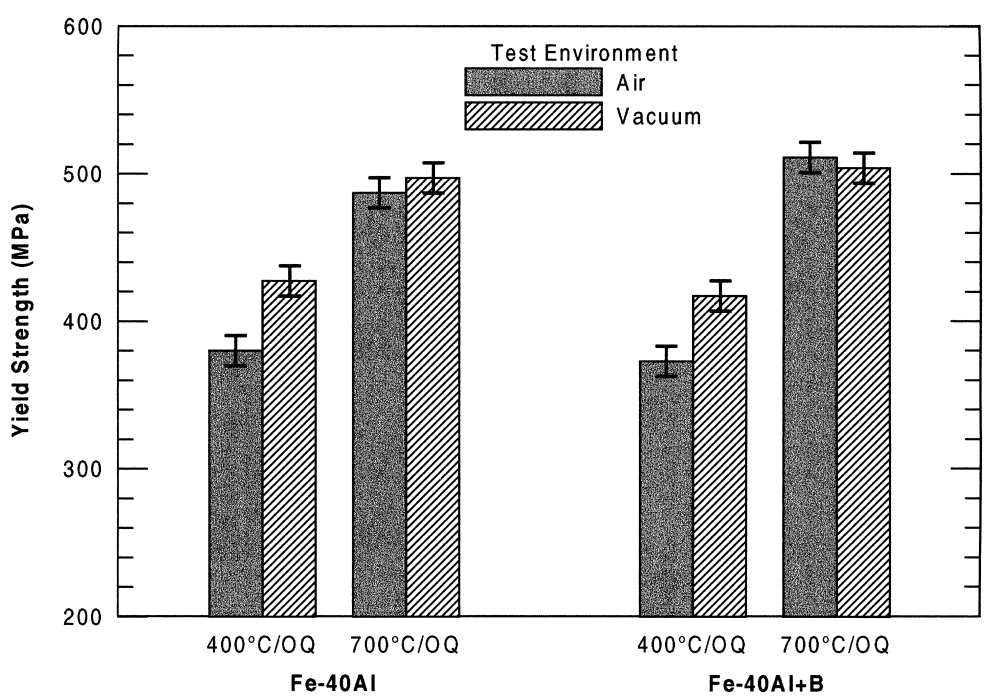

Fig. 1. The yield strength of Fe–40Al and Fe–40Al + B quenched from both 400 and 700°C tested in both air and vacuum.

The yield strength of the Fe–40Al + B samples is also shown in Fig. 1. The trends observed for the boron-free Fe–40Al alloy were also observed for the boron-doped alloy. That is, the yield strength of samples quenched from 400°C was found to be 12% lower in air than in vacuum. Similarly, no meaningful effect of test environment on yield strength was observed for samples quenched from 700°C.

The measured ductilities (% elongation to fracture) of Fe–40Al revealed two clear trends. The first was that samples quenched from 700°C were more brittle than those quenched from 400°C, presumably due to the presence of excess thermal vacancies. This was true for both air and vacuum test environments. A change in fracture mode from transgranular or mixed mode to intergranular accompanied this embrittlement. The second trend was that samples tested in vacuum exhibited better ductilities than samples tested in air. Similar trends were observed in the ductility data for Fe–40Al + B. Additionally, the increased tendency toward intergranular fracture in samples containing excess thermal vacancies was also observed in the boron-doped samples. That is, the fracture mode changed from transgranular to a mixed mode with the increased vacancy concentration. The negative effects of excess thermal vacancies [9–12] and environmental embrittlement (in air) [1–5,13], as well as the positive effect of boron additions [2,9,13–15] on the ambient temperature ductility of FeAl-based alloys have been known for some time and will not be discussed further in this manuscript.

4. Discussion

The two heat treatments used in this study were chosen to produce two different levels of excess thermal vacancies. The vacancy concentration of Fe–40Al quenched from 700°C was measured to be 0.19% by Pike et al. [16]. This is quite close to the value of 0.21% predicted by the thermodynamic model of Chang et al. for 700°C [17,18]. No experimental data are available for Fe–40Al quenched from 400°C, but the thermodynamic model predicts a vacancy concentration of 0.01% at this temperature. The annealing time of 168 h at 400°C given to the samples in this study may not be sufficient to fully reach the equilibrium vacancy concentration, but a study by Nagpal and Baker (using a shorter time of 120 h) indicated that this heat treatment eliminates a substantial amount of excess thermal vacancies [19]. Based on these comments it is safe to say that a difference in vacancy concentration of approximately one order of magnitude can be expected between the two heat treatments employed in this study. It is unlikely that the boron-doped FeAl alloy would have significantly different vacancy concentrations than the boron-free alloy. Indeed, a recent study by Baker et al. demonstrated that boron additions had little effect on the vacancy concentration of FeAl over a range of compositions [20].

In both boron-free and boron-doped Fe–40Al the environmental softening effect was observed only in samples which had been given the vacancy relieving heat treatment at 400°C. For the samples with a higher vacancy concentration (quenched from 700°C) no environmental softening was observed. This is consistent with early work done on both of these alloys by Liu and George [2]. In that study samples were pulled out of the hot zone of the furnace from 700°C and undoubtedly had a significant excess thermal vacancy concentration. As was the case with the samples quenched from 700°C in present study, no environmental effect on yield strength was observed. The present results are also consistent with the more recent study by Pike and Liu where the environmental softening effect of FeAl was first noted [8]. In that study all samples were given a vacancy relieving heat treatment.

The nature of the environmental softening effect observed in FeAl-based alloys is a matter for more extensive studies. However, it is likely that the presence of hydrogen is the key factor. A recent study by Tu et al. reported that the yield stress of Fe_3Al (Fe–28Al) measurably decreased when subjected to hydrogen charging prior to testing [21]. Recent unpublished work by the present authors has also determined that the yield strength of both Fe_3Al (Fe–28Al) and FeAl (Fe–40Al) decreases when given a hydrogen charge prior to tensile testing [22]. Moreover, the presence of hydrogen has been shown to enhance dislocation mobility in other intermetallics such as Ni_3Al [23].

At this time many questions exist as to the role of excess thermal vacancies in obscuring the environmental yield stress dependence of FeAl-based alloys. For example, do the vacancies play a direct role in inhibiting the effect (e.g. hydrogen atoms may be attracted by vacancies rather than dislocations), or do the vacancies simply raise the yield strength to a point where the environmental softening contribution is obscured? Further work is necessary to address these issues.

5. Conclusions

1. The yield strength of both boron-free and boron-doped Fe–40Al subjected to a low temperature, vacancy-relieving heat treatment (400°C) was found to be around 12% lower when tested in air than when tested in vacuum. This was attributed to an environmental softening effect.
2. The environmental softening effect was not observed for either alloy when a significant excess thermal vacancy concentration was present, i.e. when samples were quenched from 700°C.

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References

[1] Liu CT, Lee EH, McKamey CG. Scripta Metall 1989;23:875.
[2] Liu CT, George EP. Scripta Metall 1990;24:1285.
[3] Gaydosh DJ, Nathal MV. Scripta Metall 1990;24:1281.
[4] Liu CT, George EP. High temperature ordered intermetallic alloys 4. MRS Symp Proc 1991;213:527.
[5] Kasul DB, Heldt LA. Metall Trans 1994;25A:1285.
[6] Cohron JW, Lin Y, Zee RH, George EP. Acta Mater 1998;46: 6245.
[7] Cohron JW, George EP, Zee RH. In: Baker I et al., editors. Interstitial and substitutional solute effects in intermetallics. Warrendale, USA:TMS, 1998. p. 71.
[8] Pike LM, Liu CT. Scripta Mater 1998;38:1475.
[9] Crimp MA, Vedula KM, Gaydosh DJ. High temperature ordered intermetallic alloys 2. MRS Symp Proc 1987;81:499.
[10] Nagpal P, Baker I. Mater Char 1991;27:167.
[11] Gaydosh DJ, Draper SL, Noebe RD, Nathal MV. Mater Sci Eng A150:7
[12] Baker I, Nagpal P. In: Darolia R et al., editors. Structural intermetallics. Warrendale, USA: TMS, 1993. p. 463.
[13] George EP, Liu CT. In: Nathal MV et al., editors. Structural intermetallics 1997. Warrendale, USA:TMS, 1997. p. 693.
[14] Crimp MA, Vedula KM. Mater Sci Eng 1986;78:193.
[15] Gaydosh DJ, Draper SL, Nathal MV. Metall Trans 1989; 20A:1701.
[16] Pike LM, Chang YA, Liu CT. Acta Mater 1997;45:3709.
[17] Chang YA, Neumann JP. Progr Solid State Chem 1982;14: 221.
[18] Chang YA, Pike LM, Liu CT, Bilbrey AR, Stone DS. Intermetallics 1993;1:107.
[19] Nagpal P, Baker I. Metall Trans 1990;21A:2281.
[20] Baker I, Li X, Xiao H, Carleton R, George EP. Intermetallics 1998;6:177.
[21] Tu JP, Meng L, Liu MS. Scripta Mater 1998;38:833.
[22] Pike LM, Liu CT, George EP. unpublished research.
[23] Bond GM, Robertson IM, Birnbaum HK. Acta Metall 1989; 37:1407.