Materials Science and Engineering A 462 (2007) 45–52

MATERIALS SCIENCE & ENGINEERING A

www.elsevier.com/locate/msea

Development of creep-resistant iron aluminides

D.G. Morris *, M.A. Muñoz-Morris

Department of Physical Metallurgy, CENIM, CSIC, Avenida Gregorio del Amo 8, 28040 Madrid, Spain

Received 30 August 2005; received in revised form 20 October 2005; accepted 22 October 2005

Abstract

Most studies of creep resistance in Fe–Al intermetallics are oriented at typical applications of 500–650 °C in competition with conventional stainless steels. These intermetallics show excellent oxidation and corrosion resistances even above 1000 °C, where conventional steels are no longer sufficiently resistant. This overview considers attempts at the development of good creep resistance for temperatures intermediate between these two temperature regimes.

A variety of cast Fe_3Al-based alloys containing solution or precipitate/dispersoid-forming additions will be reported. These alloys show good room temperature strength but weaken above 500 °C due to thermally activated deformation processes. It is shown to be difficult to improve creep strength by changing matrix diffusivity. Solution additions only slightly improve creep strength above 700 °C. Hardening in some alloys containing Fe_2Nb Laves precipitates will be discussed. These materials show good strength to 700 °C, but the fine precipitates coarsen rapidly at higher temperatures. Carbide and boride additions generally show poor strengthening due coarse dispersoid distributions, but excellent thermal stability allows good strength retention to very low strain rates. As well as such alloying and structural factors, the importance of processing control to obtain the desired stable microstructures will be considered.

Keywords: Intermetallic compound; Iron aluminide; High-temperature deformation; Creep

1. Introduction

Much of the interest in iron aluminides over the last about 20 years has grown from their possible application as lower density replacements for stainless steels at intermediate temperatures (500–600 °C) and in various industrial oxidising or corrosive environments [1–3]. In view of the outstanding corrosion, carburisation and oxidation resistance of such iron aluminides [4–8], attention has turned recently, in several countries, to a reconsideration of these materials for very high-temperature applications, above 800–1000 °C, where their special chemical resistances make them obvious materials of choice, provided other weaknesses such as poor high-temperature creep strength can be overcome. The present report examines some of the progress and problems associated with such developments.

A very large body of research has been carried out looking at the high-temperature plasticity [1,9–11] and creep [12–18] of iron aluminides. While many such studies have provided valuable information, for example, of the useful solution hardening obtained by Mo and of the useful strengthening by particles such as niobium carbides [14] and yttrium oxides [19], there is little information of strength and creep behaviour at much higher temperatures.

2. Creep resistance

The engineering need for structural stability during long hold periods under stress at high temperature can be expressed as a need for low creep rate ($\dot{\varepsilon}_{\rm min}$) through relationships such as that of Monkman and Grant [20], $\dot{\varepsilon}_{\rm min}\, t_{\rm f}$ = constant, where $t_{\rm f}$ is the required life time. The secondary creep rate ($\dot{\varepsilon}_{\rm min}$) can be described by expressions such as $\dot{\varepsilon}_{\rm min} = AD\sigma^n$, where A is a structural constant; D the diffusivity; σ the applied stress; n is the stress exponent of strain rate with values typically of the order of 4–5 for single phase metals and alloys. When a particle dispersion is introduced to give better creep strength, this equation shows very high apparent stress exponents, and it may be written in a modified form as $\dot{\varepsilon}_{\rm min} = AD(\sigma - \sigma_0)^n$, where the stress exponent is reduced again to a value of 4–5 and σ_0 represents the internal, threshold or back-stress created by the particles [21,22]. From the expressions above, it is clear

* Corresponding author. Tel.: +34 91 553 8900; fax: +34 91 534 7425.
E-mail address: david.morris@cenim.csic.es (D.G. Morris).

0921-5093/$ – see front matter © 2006 Elsevier B.V. All rights reserved.
doi:10.1016/j.msea.2005.10.083

that improvements to creep resistance can be obtained in several ways: by modifying the structural parameter *A*, by modifying the diffusivity *D*, or by introducing high particle back-stresses.

Intermetallics are claimed to be intrinsically creep-resistant since they have complex dislocation structures, as in Ni_3Al, that can be more readily pinned, or have low values of diffusivity. In the case of Fe_xAl alloys at high temperatures neither factor seems to be important. Thus, the dislocations found in Fe_xAl alloys after deforming at high temperatures are either single, simple dislocations of Burgers vector ⟨1 0 0⟩, or single dislocations of vector ⟨1 1 1⟩ [23]. At fairly high temperatures the degree of order (both for DO_3 and B2 order) falls and will even disappear at high temperatures for alloys with compositions near Fe_3Al, such that single 1/4 ⟨1 1 1⟩ dislocations will trail either very low energy APB faults or none at all. At the same time, a quick examination of diffusivity values at high temperature in Fe_xAl and comparison with bcc αFe or with fcc γFe [24,25] shows that diffusivity is even higher in Fe_xAl than in the other crystals. Furthermore, there is little Al composition dependence of diffusivity [24], and little influence of typical alloying additions on the diffusivity [14].

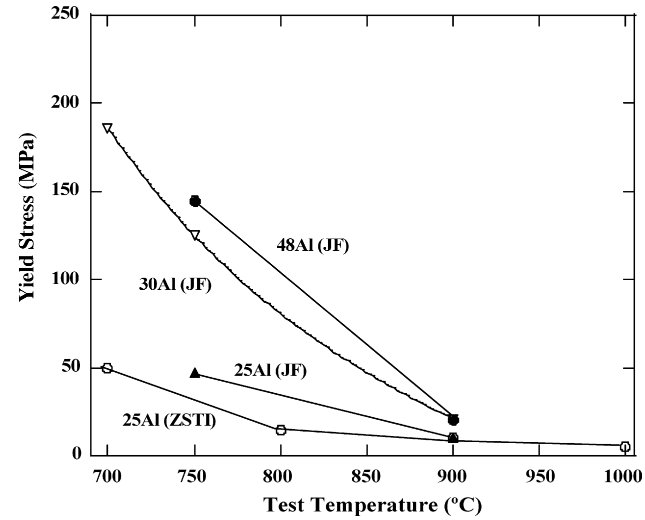

Fig. 1. Comparison of flow stress at high temperature in binary Fe–Al alloys with a range of Al contents between 25 and 48%. Data are taken from Refs. [16,26], and correspond to cast alloys with a large grain size tested at a strain rate of about 10^{-4} s^{-1}.

3. High-temperature deformation of single-phase iron aluminides

Detailed studies many years ago of the creep of binary Fe–Al alloys (e.g. [12]) showed that FeAl was relatively weak at high temperatures, and dislocation recovery to a subgrain structure took place during straining. Other studies [16,26] have examined the role of the Al content in Fe–Al alloys over the range about 25–50%. These studies confirm that the stress exponent of strain rate is 3–5, confirming that diffusional climb is controlling deformation, and that increasing Al content from a low to an intermediate value (to 30 at.%Al) leads to significant improvement in strength, while subsequent increases in Al content have little effect, see Fig. 1. Note that this figure, and many of the subsequent ones, show only behaviour at the very high temperatures of present interest, where strength is very sensitive to the test temperature, showing rapid fall as the temperature rises.

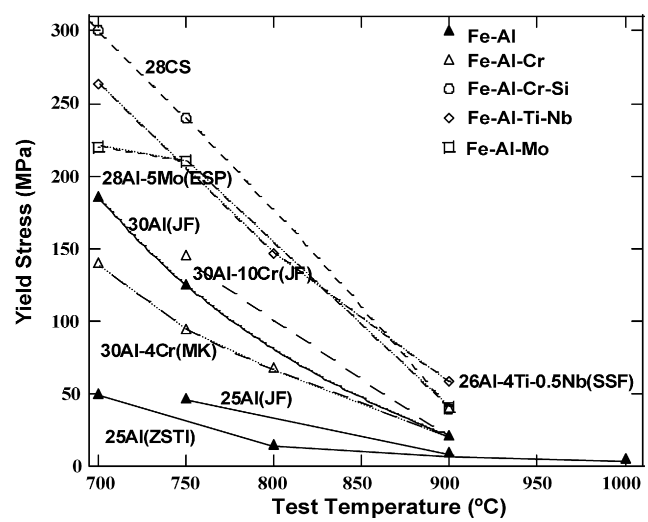

Fig. 2. Comparison of flow stresses of high temperature binary Fe–Al alloys and some ternary Fe–Al–X solution alloys. Data taken from Refs. [16,26–31].

The effects of various solution additions on the high-temperature flow of alloys of base composition Fe-near 25 at.%Al are shown in Fig. 2 [16,26–31]. Some solution additions are seen to have only minor influence on the flow stress—Cr is an example of such an addition. Other solution additions lead to significant strengthening, with Mo, Nb and Si being examples. For all these materials, the stress exponent remains close to 3–4, suggesting that either diffusion, or perhaps solute migration, is the important controlling process. Of interest is to note that significant improvements in creep strength and life have been reported for Fe_xAl at temperatures of 600–700 °C by the addition of such solution hardening additions [4,14,32]. When determined [14,32], the stress exponent of deformation rate in these materials is seen to be about 3–5, confirming the importance of diffusion/solute movement in controlling deformation. For such materials, when it is solute migration that controls deformation, there will not be dislocation rearrangement into a subgrain structure, but a more uniform and loose dislocation arrangement, as illustrated in Fig. 3. It is also interesting to note that creep testing (i.e. under conditions of high-temperature deformation with constant stress or load) and tensile testing (i.e. under conditions of high-temperature deformation with imposed constant strain rate) give similar stress levels and stress exponents, confirming the utility of simpler tensile tests for a quick evaluation of high-temperature creep behaviour.

4. High-temperature deformation of precipitation hardening iron aluminides

Very few studies have been carried out on iron aluminides strengthened by precipitation of second phase particles. We exclude from this statement the studies [4,14,32] on carbide reinforced materials, since in most cases the carbides are stable from the beginning of these deformation experiments with no