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Influence of nanoprecipitates on the creep strength and ductility of a Fe–Ni–Al alloy

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ABSTRACT

Creep studies of a duplex Fe–Ni–Al intermetallic alloy, in two microstructural states, have been carried out at temperatures between 725 and 800 °C (about 0.6 T_m). In the as-cast state, the alloy contains a large volume fraction of nanoprecipitates (50–100 nm) which confer a very high creep strength with a stress exponent of 3 and an activation energy of 280 kJ/mol. The different microstructure obtained in the second state of the alloy, obtained after annealing at 1000 °C for 24 h, leads to a much lower creep strength with a higher stress exponent as well as a large value of the apparent activation energy. While volume diffusion appears to control creep in the as-cast state, both thermal and athermal processes seem to contribute to the different creep rate of material in the annealed state. The latter also exhibits a much larger ductility (12%) relative to that observed in the as-cast material (3%), due to the presence of large numbers of interfaces between the two phases present where strain incompatibilities can be accommodated.

1. Introduction

There is considerable interest in the development of high-temperature, oxidation–corrosion resisting materials for industrial applications in the power generation, automobile and petrochemical industries at temperatures higher than the creep limit for ferritic-martensitic steels or the oxidation–corrosion limit for austenitic stainless steels (Brady et al., 2008; Yamamoto et al., 2007; Klueh et al., 2007). Much of this research centres on the development of high-temperature Ni-base superalloys and understanding the role of microstructure on creep behaviour. Such materials are in

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fact composite materials composed of ordered γ' particles within a disordered γ matrix, and aspects of load sharing and phase morphology dependence need to be considered (Ankem et al., 2006). Several recent studies have explored the importance of variations of precipitate size or volume fraction with exposure temperature (Manonukul et al., 2002; Nganbe and Heilmaier, 2004), as well as ways in which strengthening contributions due to different particle natures of sizes must be handled.

Iron aluminide alloys have also received extensive attention (McKamey et al., 1991; Morris et al., 2008) especially since the high Al content ensures outstanding oxidation–corrosion resistance. The creep resistance of such materials is poor unless stable nanoparticles are introduced (Morris-Muñoz, 1999), however, and they are rather brittle for industrial applications unless grain size is greatly reduced (Morris and Muñoz-Morris, 2007, 1999).

A different approach to obtaining balanced ductility, creep strength and oxidation–corrosion resistance involves alloying the Fe–Al base with Ni to obtain duplex, or precipitation strengthened materials (Jung and Sauthoff, 1989; Letzig et al., 1999; Stallybrass et al., 2005; Guha et al., 1991, 1992; Guha and Baker, 1996). Alloys with compositions along the tie-line Fe + NiAl are a mixture of αFe (bcc structure) with β' (Ni,Fe)Al (B2 structure): at high Fe contents, the αFe matrix has precipitates of β' phase, while at low Fe content, the β' matrix has precipitates of α phase (Jung and Sauthoff, 1989; Letzig et al., 1999; Stallybrass et al., 2005). Alloys with β' phase matrix are generally brittle (Letzig et al., 1999), and more attention has been devoted to alloys with α phase matrix. These show extensive β' phase precipitation and considerable changes of particle size may occur during during creep (Stallybrass et al., 2005). Strengthening has been shown for both disordered α phase precipitates in the β' phase matrix and for ordered β' phase precipitates in the disordered α phase matrix. Improved strength and oxidation–corrosion resistance are expected for alloys with higher Ni contents, about 20–50% (atomic percent shown throughout), with a duplex mixture of fcc γ Fe,Ni phase and β' (Fe,Ni)Al phase (Letzig et al., 1999; Guha et al., 1991, 1992; Guha and Baker, 1996). These materials are also relatively ductile when the β' phase content is less than about 50–60%.

The present study examines creep in a cast $Fe_{45}Ni_{35}Al_{20}$ alloy with duplex structure (Muñoz-Morris and Morris, 2007). The alloy composition balances the mechanical, corrosion-oxidation, and cost factors discussed earlier. The Al content ensures that the primary β' phase dendrites are surrounded by a significant volume fraction of γ phase, giving good strength and some ductility. High-temperature annealing leads to some coarsening of the microstructure, with some strength loss but a considerable improvement of ductility (Muñoz-Morris and Morris, 2007). The relatively low Ni content ensures relatively low raw material costs and avoids the formation of bcc αFe phase or γ Ni_3Al phase. Coarse constituents of the α phase, with low Al and Ni content, may degrade oxidation–corrosion behaviour, while large amounts of γ phase lead to poor ductility (Letzig et al., 1999). Previous studies have shown that considerable structural changes occur on annealing the $Fe_{45}Ni_{35}Al_{20}$ material. On annealing at high-temperature (1000 °C), coarse precipitates of β' phase form inside the γ phase regions, with coarse needle precipitates of γ phase forming inside the β' phase dendrites (Muñoz-Morris and Morris, 2007; Muñoz-Morris et al., 2008). During annealing at intermediate temperatures (700–800 °C), fine precipitates of αFe phase form inside the β' phase dendrites. The fine precipitates provide additional strengthening (Guha et al., 1992; Muñoz-Morris et al, 2008), while a detailed study of coarsening kinetics (Muñoz-Morris et al, 2008) has suggested that an upper temperature limit for retaining usefully fine precipitates of the αFe phase may be about 700–750 °C.

The present study examines the creep behaviour of the $Fe_{45}Ni_{35}Al_{20}$ alloy at temperatures near 750 °C, the upper limit where precipitate particles will be expected to remain relatively fine. Material has been examined in both the as-cast state where a high volume fraction of fine α phase precipitates already exists within the β' phase, as well as in an annealed and quenched state where no precipitates are present initially but are expected to form and grow rapidly during creep testing. Of particular interest is to determine the creep mechanisms that control strain for these two microstructures as well as the strain partitioning that occurs between the more ductile γ phase regions and the more brittle β' phase dendrites. While creep of single phase alloys will typically show stress exponents of near 4–7, when dislocation climb or recovery control deformation (Kassner et al., 2007), precipitation strengthened alloys may show low or high stress exponents (McLean, 1985) depending on whether climb or recovery control deformation, and whether general climb, local climb or detachment processes determine the interaction of dislocations with particles. The controlling mechanisms are