Materials Science and Engineering A 510–511 (2009) 373–376

Contents lists available at ScienceDirect

Materials Science and Engineering A

journal homepage: www.elsevier.com/locate/msea

Creep strength of centrifugally cast Al-rich TiAl alloys

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ARTICLE INFO

Article history:
Received 14 January 2008
Received in revised form 16 January 2008
Accepted 19 January 2008

Keywords:
TiAl alloys
Creep
Centrifugal casting
Microstructure
TEM

ABSTRACT

High-temperature creep of a binary $Al_{60}Ti_{40}$ (at.%) alloy in the as-cast state and after annealing at 1223 K for 200 h which produced nearly lamellar γ-TiAl + r-Al_2Ti microstructure was studied utilizing creep compression tests in a temperature range between 1173 and 1323 K in air. The material was manufactured by centrifugal casting. Microstructural characterization was carried out employing light-optical scanning (SEM) and transmission electron microscopy (TEM) as well as X-ray diffraction (XRD) analyses. It is shown that the alloy exhibits reasonable creep resistance at 1173 K, especially in relation to its low density of around 3.8 g/cm^3. Stress exponents calculated as $n = \Delta\log$ (strain rate)/$\Delta\log$ (stress) = 4 were found to be relatively constant for the temperature and stress regime investigated. This indicates that dislocation climb may be the rate controlling creep mechanism. The assessment of creep tests conducted at identical stress levels and varying temperatures yielded activation energies for creep of around Q = 457 kJ/mol in the as-cast condition. This value is significantly higher than those found in literature for interdiffusion of Al or Ti in γ-TiAl. It is concluded that the difference is a due to the instability of the microstructure of the as-cast multi-phase alloy.

1. Introduction

In the last decades Ti-rich TiAl-based intermetallic alloys have been developed successfully as materials for high-temperature structure applications because of their low density and high specific strength. Favourable creep properties have been achieved by producing alloys with specific lamellar microstructure of γ-TiAl and the Ti-rich α_2-phase [1,2]. TiAl alloy systems with increased aluminium content are expected to enable a significant additional weight reduction up to 20% and a higher oxidation resistance, due to the formation of adherent Al_2O_3 scale [3]. Furthermore Al-rich TiAl alloys offer a sufficient strength at high temperatures, which would enable them to be used at significantly higher temperatures than Ti-rich γ-TiAl-based alloys. During investigations of the phase equilibria in the Al-rich part of the Ti–Al system, Fig. 1, it was found by Palm et al. [4–6] that lamellar γ-TiAl + r-Al_2Ti microstructures can be generated by means of heat treatment and the mechanical properties of these alloys could be improved by the formation of lamellar microstructure. Based on these findings an elaborate investigation has been started which aims at the production and detailed characterization of two-phase microstructures of γ-TiAl + r-Al_2Ti and a subsequent evaluation of the resulting mechanical properties.

2. Experimental methods

Centrifugal casting with induction skull melting technology has shown high potential for manufacturing γ-TiAl components [7]. Hence, test bars of $Al_{60}Ti_{40}$ were produced successfully with this technology by ACCESS in Aachen. In general, the alloy showed a good melting and casting behaviour. Nevertheless, some pores have been found by non-destructive X-ray inspection in the centre line of the test bars in the as-cast condition, probably caused by uncontrolled solidification initiated by a high thermal gradient.

The microstructure of $Al_{60}Ti_{40}$ in the as-cast state and after annealing was studied by light-optical, scanning (SEM) and transmission electron microscopy (TEM) and X-ray diffraction (XRD) analyses.

Chemical analysis has been utilised in order to compare the composition of the material obtained with our target composition by using inductively coupled plasma-optical emission spectroscopy (ICP-OES). The analysis of gaseous impurities was realized by hot gas extraction. In general, the concentration of impurities in the material remains on a very low level. The composition with respect to aluminium is varying within around 0.3% of the objectives.

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0921-5093/$ – see front matter © 2009 Published by Elsevier B.V.
doi:10.1016/j.msea.2008.01.102

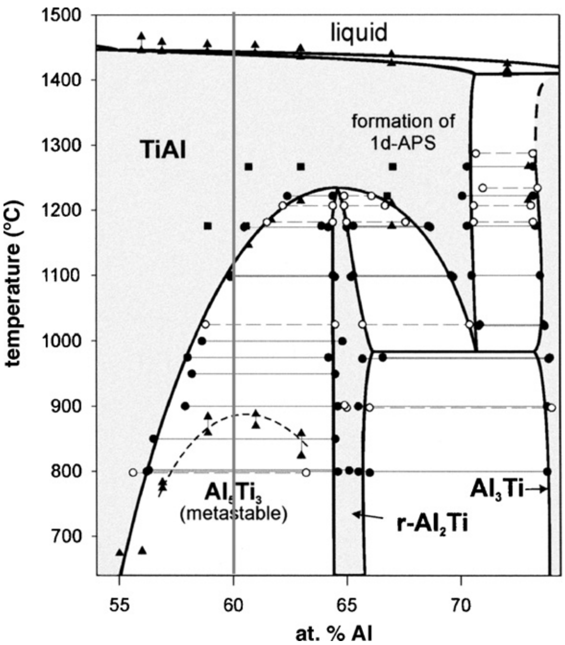

Fig. 1. Phase diagram of the Al-rich part of the Al–Ti system [4].

Elevated temperature mechanical properties were characterised utilising compression creep tests on a screw-driven Zwick Z 100 at temperatures ranging from 1173 to 1323 K in air. The specimens were 5.5 mm high and 3.1 mm × 3.8 mm in cross-section, prepared from the cast bars via electro-erosion and subsequent grinding and polishing of the parallel load-bearing surfaces to minimize friction.

3. Results and discussion

Both, optical microscopy (Fig. 2) and XRD analysis (not shown here) revealed a single-phase γ-TiAl microstructure which would contradict the phase diagram, Fig. 1, recently assessed by Ref. [6]. However, further in-depth characterization of the microstructure by combined TEM imaging techniques reveal a γ-TiAl matrix with domains of the metastable phase Al_5Ti_3 (5–10 nm domain size). Corresponding diffraction patterns, dark field images and Fourier transformed images are shown in Fig. 3(a)–(c), respectively. The very small size of these Al_5Ti_3 domains results in a very strong X-ray diffraction peak broadening. Together with the relatively low volume fraction it was, thus, impossible to detect these nano-sized second phase particles by XRD analysis.

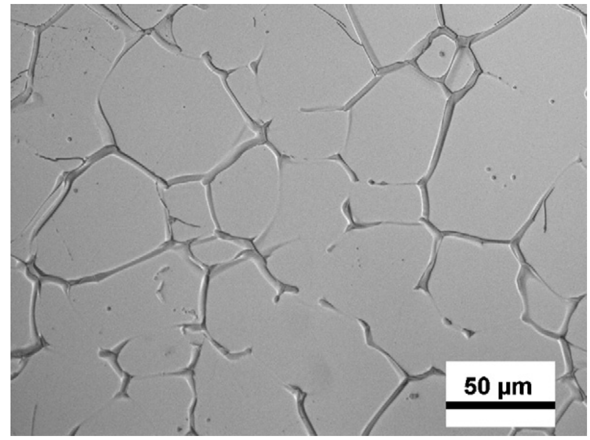

Fig. 2. Optical micrograph of $Al_{60}Ti_{40}$ in the as-cast state.

After heat treatment at 1223 K for 200 h and water quenching [4] the microstructure was transformed to a relatively coarse, nearly lamellar microstructure of the two phases γ-TiAl + r-Al_2Ti (Fig. 4), which were expected to form in accord with the phase diagram, Fig. 1. The grain size before and after annealing was determined as the average linear intercept length on polished and etched specimens. It has been found that the grain size (45 μm) remains constant, thus it does not change upon annealing.

Compression tests were carried out at three different strain rates, namely 10^{-3}, 10^{-4} and $10^{-5}\,s^{-1}$ until a constant stress level was reached (which is considered here as steady-state). At lower strain rates compressive creep tests at constant true stress were carried out instead taking one sample for three different stress levels. Beginning with a low stress value the stress was increased to a higher level after steady-state was attained. Fig. 5 exemplifies this approach at the example of the as-cast alloy at 1173 K and a stress sequence of 80, 120 and 150 MPa. The minimum creep rate at a given stress from these tests and the steady-state stress at a given strain rate from the former constant strain rate tests were taken and plotted in double-logarithmic representations. In Fig. 6 the stress dependence of the minimum creep rate of $Al_{60}Ti_{40}$ in the as-cast state [8] and after annealing is shown for 1173 and 1323 K. As expected, the creep rates decrease with decreasing temperature as well as with a reduction in stress. Compared with the creep results of a fully lamellar Ti-42 mol% Al alloy tested in argon gas atmosphere at 1200 K [9] (also shown in Fig. 6) it is obvious that both, the as-cast and the annealed $Al_{60}Ti_{40}$ alloy exhibit reasonable creep resistance at 1173 K, especially with regard to their lower density of around 3.8 g/cm^3. It should be mentioned that the high Al content

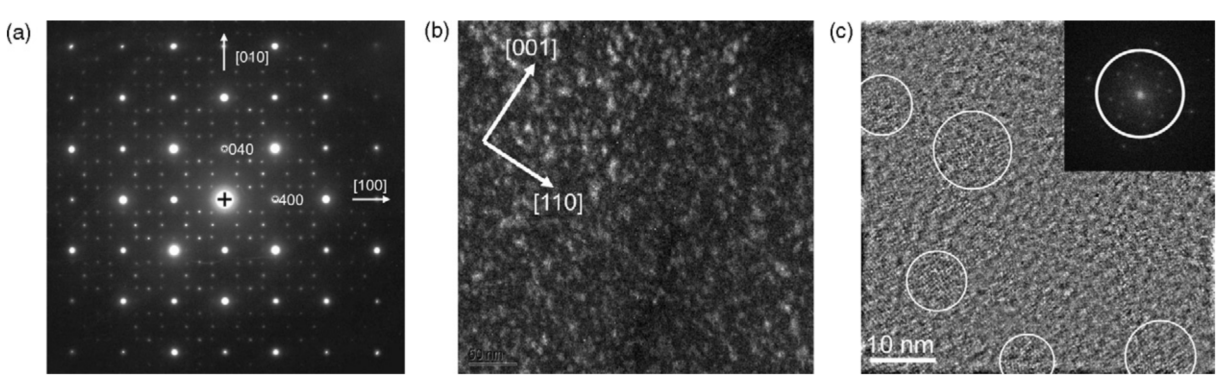

Fig. 3. (a) Selected-area electron diffraction pattern, zone axis [0 0 1]; (b) dark-field image taken with (1 1 1) Al_5Ti_3; (c) back transformation from the FFT of a high-resolution TEM image. The direct beam and the diffraction spots of the Al_5Ti_3 phase (shown in the inset) were used for the back transformation. The observed small domains of Al_5Ti_3 (lattice fringes) are marked.