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General features of high temperature deformation kinetics for γ-TiAl-based alloys with DP/NG microstructures: Part I. A survey of mechanical data and development of unified rate-equations

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ABSTRACT

γ-TiAl-based alloys have attracted intense attentions in the past two decades and are regarded as promising candidate materials for high-temperature applications due to their low density, high specific strength, superior creep and oxidation resistance, etc. It is well known that there are four typical microstructures in TiAl-based alloys, namely, full-lamellar (FL), near-lamellar (NL), duplex (DP) and near-gamma (NG). The FL/NL-TiAl alloys possess superior high temperature mechanical performance such as creep resistance, but their deformability is relatively lower. In contrast, the DP/NG-TiAl alloys have much better formability while the creep resistance is reduced. Hence the DP/NG microstructure is preferable for hot-working and thought to the prerequisite for secondary processing, and the present paper is primarily focused on the high temperature deformation behavior of DP/NG-TiAl alloys. Till date, considerable research efforts have been directed towards the deformation kinetics or mechanical properties of various DP/NG-TiAl alloys, and a mass of experimental data has been accumulated. In order to explore their general features of high temperature deformation kinetics, in this paper the tensile/compression mechanical data of various DP/NG-TiAl alloys from the literature published in the past twenty years has been summarized and reviewed. Three deformation mechanisms (dislocation creep, grain boundary sliding and diffusion creep) have been identified, and for each the effects of major factors (i.e., alloy composition, microstructure and grain size) on deformation kinetics have been analyzed and discussed in detail. The results revealed that the high temperature deformation kinetics of DP/NG-TiAl alloys is less sensitive to composition except some dispersion-hardened alloys such as carbon-containing TiAl alloys. Instead, the γ grain size became the major limiting factor. Based on this observation, a series of unified rate-equations has been successfully developed.

1. Introduction

γ-TiAl-based alloys have attracted significant attentions due to their superior high temperature performances such as low density, high specific strength and stiffness, good resistance against oxidation and corrosion, and good creep properties, etc. [1–4], which make them to be the top candidate materials for high-temperature structural use [5–7]. As a class of hard-to-deform materials, components made by TiAl alloys are preferably fabricated by casting. It has reported that the blades in the last two stages of the low-pressure-turbine (LPT) in GEnx engine are made by cast GE alloy (Ti-47Al-2Cr-2Nb (at%)) [8,9], which is a significant milestone for application of TiAl alloys. With the development of alloy design strategy, the β-solidifying TiAl alloys which generally contain considerable amounts of (meta) stable β/B2 phase have attracted intense attentions. Due to the soft b.c.c. structure at high temperatures, the β/B2 phase can significantly improve the hot-

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workability of TiAl alloys such as the so-called TNM alloy [4,10]. Recently, the PW1100G engine with wrought TNM alloy as LPT blades successfully passed the test flight [11]. Indeed, TiAl alloys have received great success in gas turbine industries nowadays. Moreover, it was reported that there are about thousand TiAl turbocharger wheels and exhaust valves in service to date [12]. More information about the recent advances in manufacturing technologies of TiAl-based alloys has been summarized in Ref. [12,13]. However, in comparison with ordinary disordered alloys, TiAl alloys are essentially hard-to-working due to their lower diffusibility, reduced grain boundary mobility, higher deformation resistance and intrinsic brittleness [14,15]. These drawbacks (which result in high costs) not only retard the commercial application of TiAl alloys, but also lead to difficulty when identifying the suitable processing routes. A systematic understanding of the limiting factors governing deformation and a detailed analysis of deformation kinetics are required.

According to the binary Ti-A1 phase diagram [8], γ-TiAl based alloys can solidify in a single phase state when the Al content exceeds ~53 at%. However, like many intermetallic phases, the single phase γ-TiAl suffers from both poor ductility and fracture toughness [2]. In contrast, considerably improved ductility and toughness can be achieved in ($\alpha_2+\gamma$) dual-phase alloys with lower Al contents, and hence a broad range of engineering alloys with baseline compositions of Ti-(42-49)Al-X (at% and hereinafter) have emerged in the past two decades. The microstructure and morphology of dual-phase alloys is complex but can be roughly classified into four groups designated near-γ (NG), duplex (DP), nearly lamellar (NL) and fully lamellar (FL). Of these microstructures, FL/NL alloys are preferable for application due to their superior high-temperature performances, whereas DP/NG alloys are suitable for processing because of the better plasticity and less plastic anisotropy. Indeed, DP/NG microstructures with fine and uniform grains are considered to be the prerequisite for the secondary processing of TiAl alloys. Because the present study was organized from the viewpoint of hot forming, DP/NG-TiAl alloys have been primarily concerned.

The mechanical behavior of DP/NG-TiAl alloys in terms of deformation kinetics has been intensely studied from low temperature yielding up to high temperature creep, and a mass of experimental data has been accumulated. Owing to the complexity of microstructures and compositions, these experimental results, however, show a large scatter and their internal relationship is ambiguous. Then a question is raised: what are the general features of deformation kinetics for various DP/NG-TiAl alloys?

To clarify this question seems attractive and essential both from scientific and technical aspects. Unfortunately, there are only a few studies concerning this point. Mukherjee and Mishra [16] have attempted to develop unified constitutive relationship on superplastic deformation for various TiAl alloys, but they failed in rationalizing it. Zhang and Deevi [17] have analyzed the dislocation creep kinetics of more than 60 TiAl-based alloys and developed a set of unified rate-equations for that, but the model they proposed has some apparent drawbacks which have been already pointed out by Appel et al. [8], and will be further discussed in the present study. In a word, efforts on analyzing the general features of deformation kinetics are largely insufficient and they are certainly not in proportion with the rapid accumulation of mechanical data.

Given this situation, a series of papers was organized such that the general deformation kinetics of TiAl-based alloys with DP/NG microstructures for various mechanisms (dislocation creep, grain boundary sliding and diffusion creep) has been systematically discussed. The ultimate goal is to develop unified rate-equations and deformation mechanism maps for various DP/NG-TiAl alloys. In this prior paper, the tension/compression mechanical data from the literatures published in the past twenty years has been summarized, and the effects of major factors (i.e., alloy composition, microstructure and grain size) on deformation kinetics have been analyzed and discussed. Trials have been made to develop unified rate-equations for various deformation mechanisms of DP/NG-TiAl alloys.

2. Basic theories

In general, plastic flow is always thermo-activated and therefore is a kinetic process. As pointed by Frost and Ashby [18], once a crystal subjected to an applied stress, a number of mechanisms may simultaneously initiate and contribute to the deformation independently or alternatively. Then the one which predicts the highest strain-rate would control the deformation at certain conditions. Then a rate-equation is essential to physically or empirically quantify the relationship between strain-rate and other macro- or micro-scale variables such as applied stress, strain, temperature, grain size, dislocation density, sub-structure, etc. In a simplest case, if the crystals exhibit stable-structure or steady-flow during deformation, the evolution of internal variables and strain accumulation effect can be ignored. Hence the rate-equation is simplified into the following type which has been widely used to describe the deformation kinetics:

$$\dot{\varepsilon} = f(\sigma, T) \tag{1}$$

where T is the absolute temperature, $\dot{\varepsilon}$ and σ donate the equivalent strain rate and equivalent stress, respectively (in this study they represent the uniaxial tensile strain rate and uniaxial tensile flow stress, respectively). At high temperatures where creep is predominated, the strain rate is linearly dependent on stress in a logarithmic scale, and Eq. (1) can be expressed by the well-known Dorn equation [19]:

$$\frac{\dot{\varepsilon}kT}{GbD_{\text{eff}}} = A\left(\frac{\sigma}{G}\right)^n \tag{2}$$

where A is Dorn constant, the value of which is determined by the rate-controlling process. D_{eff} is the effective diffusion coefficient. G is the shear modulus. n is the stress exponent, and its value ranges from 1 up to larger than 10 according to different rate-controlling process. Although there are several problems (discussed in Section 4), in the present study we will develop the rate-equations in the form of Eq. (2) for each deformation mechanism.

3. Analysis of deformation kinetics

To date, there are a number of independent high temperature deformation mechanisms which have been found, and some of them have been identified in TiAl-based alloys, including dislocation creep, grain boundary sliding (together with the accommodation processes) and diffusion creep.

3.1. Dislocation creep

3.1.1. Power-law creep

Creep resistance is one of the most important mechanical properties for TiAl alloys, since it determines the service range in competition with other structural materials. In the past two decades, there has been a systematic effort to study the creep behavior of TiAl alloys by hot tension roughly under a stress level of 80–500 MPa and in a temperature range of 676–877 °C [20]. Most studies are concentrated in FL/NL-TiAl alloys which are preferable for application due to the superior high temperature performance. However, a number of investigations have also provide abundant

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