Journal of Alloys and Compounds 698 (2017) 786–793

Contents lists available at ScienceDirect

Journal of Alloys and Compounds

journal homepage: http://www.elsevier.com/locate/jalcom

Flow behavior and processing maps of Ti-44.5Al-3.8Nb-1.0Mo-0.3Si-0.1B alloy

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ARTICLE INFO

Article history:
Received 31 May 2016
Received in revised form
10 December 2016
Accepted 16 December 2016
Available online 22 December 2016

Keywords:
TiAl alloy
Flow behavior
Processing maps
Dynamic recrystallization

ABSTRACT

The flow behavior of Ti-44.5Al-3.8Nb-1.0Mo-0.3Si-0.1B alloy was investigated by means of uniaxial hot compression tests performed with a Gleeble 3500 simulator within a temperature range of 1100−1250 °C and a strain rate region of 0.01−1 s^(−1) up to a true deformation of 0.7. The results show that the flow stress increases with increasing strain rate and decreasing temperature. The flow stress curves were composed of three stages: work hardening, softening and steady. Processing maps were developed on the basis of the dynamic materials model. The microstructure of specimens deformed at different conditions was analyzed and connected with the processing map. The predominant flow stability region and instability region mechanism of this alloy were validated by microstructure observation. Based on the constructed processing maps and microstructure analysis, the optimal hot processing window of this alloy corresponds to the temperature range of 1200−1250 °C and strain rate range of 0.01−0.5 s^(−1). The excellent deformability of this alloy is ascribed to soft β phase and hard α_2/γ lamellar colonies decomposition at elevated temperature.

1. Introduction

New structural materials have to be “stronger and lighter” to withstand the extremely high demanding conditions in the next generation of automotive and aircraft engines, which are targeted to exhibit higher efficiency leading to reduced fuel consumption as well as significantly decreased CO_2 emissions. Gamma titanium aluminides (γ-TiAl) based alloys possess numerous attractive properties which meet these demands, including low density, high specific yield strength, high specific stiffness, good oxidation resistance, resistance against “titanium fire”, and good creep properties at high temperatures [1–5]. Particularly at temperatures between 600 and 750 °C, γ-TiAl alloys are superior to Ti-alloys in terms of their specific strength, and they have great potential to partly replace tons of existing steels and nickel-based alloys currently used. For example, Ti-48A1-2Cr-2Nb (in this paper all compositions are given in atomic percent (at.%) unless indicated otherwise) is considered as the first choice to enter commercial jet engine service [6].

One of the reasons why γ-TiAl alloys have not found widespread application yet are the difficulties associated with its processing ability [7]. To overcome the problem, considerable efforts have been made to improve their workability, such as adding alloying elements, hot work and heat treatment. Conventional high Nb containing γ-TiAl alloys, which show only a small volume fraction of β-phase at hot-working temperature [8], can only be forged under isothermal conditions, which is not economically feasible for most applications [9]. Therefore, the development of alloys with good hot workability, and can be processed by near conventional forging operations is an important step towards the mass production of TiAl parts. In order to increase the deformation window a novel Nb and Mo containing γ-TiAl based alloy (so-called TNM alloy) was developed, which solidifies via the β-phase and exhibits an adjustable β/B2-phase volume fraction [7,10]. A typical β solidify γ-TiAl alloys are TNM alloys: Ti-(42−45)Al-(3−5)Nb-(0.1−2)Mo-(0.1−0.2)B proposed by Clemens [7,11,12]. At elevated temperatures TNM alloys system possesses a large amount of disordered β phase with body-centered cubic (bcc) lattice, and the β phase is softer than α and γ phases which improve hot workability, so the alloy can be processed under near conventional conditions, which means that conventional forging equipment with minor and inexpensive

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http://dx.doi.org/10.1016/j.jallcom.2016.12.214
0925-8388/

modifications can be used. H. Clemens [7,11] reported that casting TiAl alloys based on Ti-(41–45)Al with an addition of Nb, Mo and B element exhibiting a very fine grained and texture-free microstructure with modest micro-segregations.

The dynamic recrystallization (DRX) and hot-deformation behavior of TNM TiAl alloy were investigated in-situ by means of high-energy X-ray diffraction (HEXRD) [13,14], It was found that the bcc β-phase recrystallizes dynamically, much faster than the α hcp-phase, which deforms predominantly through crystallographic slip underpinned by a dynamic recovery (DRV) process with only a small component of DRX. The excellent deformation behavior of TNM alloy is attributed to the rapid recrystallization dynamics of the β phase combined with the easy and isotropic slip characteristics of the bcc structure. The β and α phases deform to a very large extent independently from each other. For the microstructure, lamellae that buckled during deformation appear to have been the ones that were initially parallel to the loading axis. Recently, K.D. Liss [15] reported that the phase diagrams of stabilized β-phase in γ-based TiAl alloys under pressures up to 9.6 GPa and temperatures up to 1686 K by in situ synchrotron X-ray diffraction. Under high pressure of 9.6 GPa, the transition temperature $T_{\gamma,max}$, $T_{\alpha,min}$ (T_{eu}), $T_{\gamma,solv}$, $T_{\beta,start}$ and T_m are 1420 K, 1510 K, 1590 K, 1350 K and 1660 K, respectively. The ductile β-phase is present in three regions, namely $(\alpha_2 + \beta + \gamma)$, $(\alpha + \beta + \gamma)$ and $(\alpha + \beta)$, while the highly anisotropic phases α/α_2 show a minimum of 2.9%, which potentially allows for the adjustment of processing parameters to property requirements and optimization. The flow behavior and microstructure of TNM alloy have been studied using Gleebles 3500 device as reported in Refs [16,17]. The technique of hot processing map and microstructure observation of the compressive samples have to be conducted for further analysis regarding the deformation mechanism of the TNM alloy, and provide basis for the industrialized production.

In recent years, processing map is being developed to describe the dynamics of hot deformation since that describes the microstructural evolution in the work piece as a function of the processing variables viz., deformation temperature, strain rate and strain. Based on the principles of dynamic materials model (DMM) proposed by Prasad [18], the approach of the processing maps was utilized to study the deformation behavior of TNM alloy at elevated temperature in the paper. The DMM model considers mechanical processing as a system and work-piece as a power dissipater. At any given strain and temperature, the total power *P* consists of two complementary parts: *G* represents the power dissipation through plastic deformation, most of which is converted into the visco-plastic heat, and *J* represents the power dissipation through microstructure transition, such as DRV, DRX, superplastic flow, phase transformations, as well as damage of the material [19]. During plastic flow, *P* is described as follows [20]:

$$P = G + J = \sigma\dot{\varepsilon} = \int_0^{\dot{\varepsilon}} \sigma \, d\dot{\varepsilon} + \int_0^{\sigma} \dot{\varepsilon} \, d\sigma \tag{1}$$

where σ is the flow stress (MPa) and $\dot{\varepsilon}$ is the strain rate (s^(−1)). In this phenomenological model, the contents *G* and *J* can be related by the parameter *m* (the strain rate sensitivity), which is given as follows [11]:

$$m = \left(\frac{\partial J}{\partial G}\right)_{\varepsilon,T} = \frac{\partial P}{\partial G}\frac{\partial J}{\partial P} = \frac{\sigma \, d\dot{\varepsilon}}{\dot{\varepsilon} \, d\sigma} = \left[\frac{\partial(ln\sigma)}{\partial ln(\dot{\varepsilon})}\right]_{\varepsilon,T} \tag{2}$$

For the given strain and deformation temperature, the flow stress can be expressed as [21]:

$$\sigma = K\dot{\varepsilon}^m \tag{3}$$

At any deformation temperature and strain supplied, *J* can be gained by combining Eqs. (1) and (3) and is expressed by

$$J = \sigma\dot{\varepsilon} - \int_0^{\dot{\varepsilon}} \sigma \, d\dot{\varepsilon} = \frac{m}{m+1}\sigma\dot{\varepsilon} \tag{4}$$

For the ideal linear dissipating body, $m = 1$ and $J = J_{max} = \sigma\dot{\varepsilon}/2 = P/2$, and the power dissipation capacity of the material can be evaluated by the efficiency of power dissipation η is given by Ref. [22].

$$\eta = \frac{J}{J_{max}} = \frac{2m}{m+1} \tag{5}$$

With the change of deformation temperature and strain rate, η varies, which represents the characteristics of power dissipation through microstructure transition.

By utilizing the principle of the maximum rate of entropy production, a continuum criterion for the occurrence of flow instabilities is defined in terms of another dimensionless parameter, ξ [23].

$$\xi(\dot{\varepsilon}) = \frac{\partial \ln[m/(m+1)]}{\partial \ln\dot{\varepsilon}} + m \le 0 \tag{6}$$

The variation of the parameter with the deformation temperature and strain rate at a given stain constitutes the flow instability map, which denotes the flow instability in deformation at different deformation conditions.

In this paper, the processing maps at different strains are established based on the DDM, according to the corrected experiment data in the isothermal compression of TNM alloy with minor additions Si. The addition of Si element improves the creep strength and oxidation resistance of γ-TiAl alloys. Coupling with the microstructure evolution, the processability of TNM alloy is investigated through calculating the efficiency of dissipation and the instability parameter at different process parameters. The reasonable process parameters will provide the important guideline for the optimization of deformation techniques and the improvement of microstructure.

2. Experimental procedure

The investigated TNM alloy was produced by vacuum levitation melting (VLM) in a water-cooled copper crucible. The alloy was three times remelted and solidified by cylindrical ingot with 110 mm in diameter and 190 mm in length. Subsequently, the homogenization heat treatment was performed for 54 h at 950 °C and hot isostatic pressed (HIPed) was conducted for 4 h at 1250 °C and a pressure of 175 MPa in Ar atmosphere with furnace cooling. The alloy had actual chemical composition of Ti-44.5Al-3.8Nb-1.0Mo-0.3Si-0.1B, which was very close to the nominal one. Fig. 1 shows the as-HIPed microstructure of the TNM alloy, which exhibits a near lamellar structure with a colony size of about 100 μm. It can be found that the original microstructure is mainly composed of α_2/γ lamellar colonies (gray region), equiaxed γ grains (black region) and irregular β_0/B2 phases (bright region). The fraction of β_0/B2 phase is measured to be about 10%. The most of β_0/B2 phase is located at lamellar colony boundaries and triple junction, with a small amount of β_0/B2 phase distributes in the lamellar colony.

Compression specimens with a diameter of 10 mm and a height of 15 mm were cut by electric-discharge machining. Schematic illustration of the compressive deformation processes was shown in Fig. 2. Compression tests were conducted at a Gleeble 3500 simulator at temperature of 1100 °C, 1150 °C, 1200 °C, 1250 °C and