Intermetallics 44 (2014) 128–140

Contents lists available at ScienceDirect

Intermetallics

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

Microstructural design and mechanical properties of a cast and heat-treated intermetallic multi-phase γ-TiAl based alloy

Emanuel Schwaighofer [a,*], Helmut Clemens [a], Svea Mayer [a], Janny Lindemann [b,c], Joachim Klose [c], Wilfried Smarsly [d], Volker Güther [e]

[a] Department of Physical Metallurgy and Materials Testing, Montanuniversität Leoben, Roseggerstr. 12, A-8700 Leoben, Austria
[b] Chair of Physical Metallurgy and Materials Technology, Brandenburg University of Technology, Konrad-Wachsmann-Allee 17, D-03046 Cottbus, Germany
[c] GfE Fremat GmbH, Lessingstr. 41, D-09599 Freiberg, Germany
[d] MTU Aero Engines GmbH, Dachauer Str. 665, D-80995 Munich, Germany
[e] GfE Metalle und Materialien GmbH, Höfener Str. 45, D-90431 Nuremberg, Germany

ARTICLE INFO

Article history:
Received 21 May 2013
Received in revised form
12 September 2013
Accepted 16 September 2013
Available online 10 October 2013

Keywords:
A. Titanium aluminides, based on TiAl
B. Mechanical properties at ambient temperature
B. Mechanical properties at high temperatures
B. Phase transformation
C. Heat treatment
D. Microstructure

ABSTRACT

Advanced intermetallic multi-phase γ-TiAl based alloys, such as TNM alloys with a nominal composition of Ti–43.5Al–4Nb–1Mo–0.1B (in at.%), are potential candidates to replace heavy Ni-base superalloys in the next generation of aircraft and automotive combustion engines. Aimed components are turbine blades and turbocharger turbine wheels. Concerning the cost factor arising during processing, which – additionally to material costs – significantly influences the final price of the desired components, new processing solutions regarding low-cost and highly reliable production processes are needed. This fundamental study targets the replacement of hot-working, i.e. forging, for the production of turbine blades. But without forging no grain refinement takes place by means of a recrystallization process because of the lack of stored lattice defects. Therefore, new heat treatment concepts have to be considered for obtaining final microstructures with balanced mechanical properties in respect to sufficient tensile ductility at room temperature as well as high creep strength at elevated temperatures. This work deals with the adjustment of microstructures in a cast and heat-treated TNM alloy solely by exploiting effects of phase transformations and chemical driving forces due to phase imbalances between different heat treatment steps and compares the mechanical properties to those obtained for forged and heat-treated material.

1. Introduction

Recent publications underline the enormous potential and huge demand for novel β-solidifying multi-phase γ-TiAl based alloys for structural components like turbine blades and turbocharger wheels in modern high-performance combustion engines [1–7], such as the β-stabilized TNM alloy (TNM = TiAl–Nb–Mo) with a nominal composition of Ti–43.5Al–4Nb–1Mo–0.1B (in at.%) [8–10]. The main advantages of this alloy are a low density of about 4.1 g/cm^3, a high specific elastic modulus of about 28 GPa/(g/cm^3) and a high specific tensile yield strength of about 140 MPa/(g/cm^3) at 750 °C. This materials class also exhibits excellent oxidation resistance at service temperatures up to 800 °C due to the high content of Al and Nb [11,12]. Detailed information regarding the TNM alloying concept can be found in papers of Clemens et al. [8,9,13,14]. In general, the mechanical properties of TiAl alloys are determined by their chemical composition. However, for a fixed chemical composition balanced mechanical properties can be set only by an adjustment of appropriate microstructural features due to multiple heat treatments. In this context, the quantitative influence of various microstructural constituents on mechanical properties and, thus, the identification of critical processing parameters influencing the appearance of the final microstructure, are an essential knowledge for an application-oriented process and microstructure design.

In current TiAl technology, as-cast and hot-isostatically pressed (cast/HIP) material is the starting condition for thermomechanical processing to adjust specific microstructures by means of forging and/or ensuing heat treatments. In general, forging of γ-TiAl based alloys is conducted in a temperature range from 0.7 to 0.9·T_m, where T_m specifies the melting temperature in K, and requires a careful choice of processing parameters like temperature and strain rate [3,4,10]. After forging, which for TNM alloys can be either done under isothermal or near-conventional conditions, the material has

* Corresponding author. Tel.: +43 3842 4024204; fax: +43 3842 4024202.
E-mail address: emanuel.schwaighofer@unileoben.ac.at (E. Schwaighofer).

0966-9795/$ – see front matter
http://dx.doi.org/10.1016/j.intermet.2013.09.010

to be heat-treated via a multi-step heat treatment to ensure balanced mechanical properties at ambient as well as elevated temperatures. The major advantage of forging and subsequent heat treatments is the adjustment of small α_2/γ-colonies, which lead to an improved ductility of the final microstructure [15–17]. Recently, Wallgram et al. [18] have shown that grain refinement can be achieved by a combination of forging and post-forging recrystallization heat treatment, where phase transformations in interaction with recrystallization are taking place. This process leads to a homogeneous distribution of all phases within a fine-grained microstructure. Adversely, hot-forming procedures might imply the formation of undesired deformation textures, which lead to a more or less pronounced anisotropy of the mechanical properties. A forging texture, for example, cannot be fully removed by means of subsequent heat treatments. In addition, segregation effects arising from the solidification process cannot be completely compensated by hot-working and subsequent heat treatments.

In the last decade, process development and microstructural evolution of β-solidifying γ-TiAl based alloys were studied by several research groups for improving the mechanical properties. Mainly, the adjustment of desired microstructures was conducted by hot-forming operations and subsequent heat treatments starting from a cast/HIP ingot or powder metallurgically produced prematerial [9,19–24]. In these investigations, forming procedures, such as hot-extrusion and hot-forging, are playing a central role in respect to the evolution of the final microstructure. Thereby an increased dislocation density can help to refine coarse microstructural constituents by means of recrystallization processes. Throughout the employment of subsequent multi-step heat treatments, significant modifications of the microstructure can be set toward balanced mechanical properties of the final heat-treated material as reported in Ref. [14]. Furthermore, also experiments to study the influence of microstructural evolution starting from the cast/HIP condition were performed by means of single high temperature heat treatments with subsequent slow cooling [25]. Imaev et al. [26] showed an approach of grain refinement starting from an as-cast β-solidifying TiAl alloy via heat treatments in the single β-phase field followed by oil-quenching and subsequent isothermal annealing. Yang et al. [27] investigated the effect of discontinuous coarsening on grain refinement of cast/HIP peritectic TiAl alloys throughout the use of a cyclic heat treatment. However, in these studies the focus was put on grain refinement and not on the resulting mechanical properties and their optimization, i.e. high creep strength and sufficient ductility at room temperature (RT).

In the framework of the present study, a number of multi-step heat treatments were applied to a cast/HIP TNM alloy in order to achieve similar mechanical properties compared to forged and heat-treated material [14]. Thereby, heat treatments within the single β-phase field are playing a key role for obtaining chemical and microstructural homogeneity and, thus, to reach acceptable mechanical properties without a prior hot-forming operation. Additionally, the development of a cyclic heat treatment for obtaining microstructures from the cast/HIP condition with improved RT-ductility is a further step to address higher ductility requirements [28]. The characterization of final heat-treated TNM alloys on the nano-scale regarding lamellar spacing within the α_2/γ-colonies and the existence of ω-phase domains with $B8_2$ structure within the β_o-phase is reported in Refs. [14,29–31]. Based on these results, it is assumed that the observed "nanofeatures" are similar in our heat-treated microstructures, therefore TEM studies were neglected. Nevertheless, the present paper tries to identify the critical features for the design of microstructures by means of cost-effective and robust heat treatments starting from the cast/HIP condition in order to adjust balanced mechanical properties without hot-forming.

2. Material and experimental

The TNM material of the present investigation was produced by GfE Metalle und Materialien GmbH, Nuremberg, Germany, via the so called "advanced beta process". By this technique a powder metallurgically compacted electrode is vacuum arc remelted (VAR) for two times to achieve adequate chemical and structural homogeneity [32]. Detailed information on the applied melting technique can be found in Ref. [33]. Subsequently, the chemically homogenized electrode is melted in a VAR skull melter and cast by a centrifugal casting process [10]. The produced ingots had a diameter of 60 mm and a raw length of 297 mm. Due to the fast cooling rate during centrifugal casting a fine-grained cast microstructure is obtained and the deviation of the Al content along the ingot axis is smaller than ± 0.1 at.% [34]. The as-cast condition shows a small fraction of residual micropores, which are eliminated by the ensuing HIP step. Thereby, the material is heated up to 1200 °C, held for 4 h at 200 MPa and subsequently cooled via furnace cooling (<8 K/min) to RT. The chemical composition of the TNM material is shown in Table 1. As analytical methods X-ray fluorescence spectroscopy (XRF), inductively coupled plasma-optical emission spectroscopy (ICP-AES) and carrier gas hot extraction analysis were used (for elemental assignment see Table 1). Evidently, the deviation from the nominal TNM alloy composition is with Ti–43.67Al–4.08Nb–1.02Mo–0.1B rather small.

The phase transition temperatures and prevailing phase fractions at different annealing temperatures were primary characterized by means of *in situ* synchrotron heating experiments using the high energy X-ray diffraction (HEXRD) setup of the HZG beamline HARWI II at DESY in Hamburg, Germany. Detailed information regarding the experimental setup and evaluation of raw data can be found in Refs. [30,35]. Complementary, the phase transition temperatures were verified by means of differential scanning calorimetry (DSC) measurements with a heating rate of 20 K/min from RT to 1450 °C using a high-temperature DSC 404F3 from Netzsch, Germany. A sample size of 3 mm in diameter and approximately 1 mm in height, which corresponds to a sample mass of about 40 ± 3 mg, was used. The crucibles consisted of Al_2O_3. An Y_2O_3 suspension was used to improve the thermal contact between the samples and the crucible. The measurements were conducted under Ar-atmosphere with a gas flow of 50 ml/min. The temperature measurement of the DSC setup was calibrated by means of enthalpy standards. With both methods, HEXRD and DSC experiments, a temperature accuracy of about ±5 °C can be obtained. Furthermore, thermodynamic equilibrium calculations based on the CALPHAD

Table 1
Chemical composition of the investigated TNM alloy. The concentrations of Ti, Al, Nb, and Mo were obtained by means of X-ray fluorescence spectroscopy (XRF), whereas the amounts of B, Si, Fe, Cu, Cr, Ni, and C were determined by means of inductively coupled plasma-optical emission spectroscopy (ICP-OES). Carrier gas hot extraction analysis was conducted to quantify the impurity elements O, N and H.

	Ti	Al	Nb	Mo	B	Si	Fe	Cu	Cr	Ni	C	O	H	N
m.%	bal.	28.75	9.24	2.38	0.025	0.009	0.049	0.013	0.008	0.011	0.004	0.042	0.001	0.001
at.%	bal.	43.67	4.08	1.02	0.095	0.013	0.036	0.008	0.006	0.008	0.014	0.108	0.041	0.003