Journal of Alloys and Compounds 663 (2016) 217–224

Contents lists available at ScienceDirect

Journal of Alloys and Compounds

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

Extraordinary superplastic properties of hot worked Ti–45Al–8Nb–0.2C alloy

V. Imayev [a,*], R. Gaisin [a], A. Rudskoy [b], T. Nazarova [a], R. Shaimardanov [a], R. Imayev [a]

[a] *Institute for Metals Superplasticity Problems of Russian Academy of Sciences, Ufa, Russia*
[b] *St. Petersburg State Polytechnical University, St. Petersburg, Russia*

ARTICLE INFO

Article history:
Received 18 July 2015
Received in revised form
18 November 2015
Accepted 30 November 2015
Available online 8 December 2015

Keywords:
Intermetallics
Hot working
Microstructure
Grain boundaries
Superplasticity
Electron backscattering diffraction

ABSTRACT

Superplastic behavior of the Ti–45Al–8Nb–0.2C alloy in ultrafine-grained condition has been investigated. The ultrafine-grained condition was produced via hot extrusion at $T \approx 1250$ °C followed by unidirectional isothermal forging at $T = 950$ °C. The produced material showed extraordinary superplastic elongations ($\delta = 770$–1342%) at $T = 850$–1050 °C and enhanced values of the strain rate sensitivity coefficient, $m > 0.3$ at $\varepsilon' \sim 10^{-4}$–$10^{-3}$ s^{-1}. The obtained superplastic properties and the results of microstructural examination of the tensile strained specimens suggest that the grain boundary sliding was the predominant deformation mechanism during superplastic flow. In spite of a low content of the α_2–Ti_3Al phase and absence of the β(B2) phase, the produced ultrafine-grained microstructure showed surprisingly slow dynamic grain growth during superplastic flow at $T = 850$–1050 °C. The activation energy was defined to be $Q = 303$ kJ/mol suggesting that the predominant deformation mechanism during superplastic flow was grain boundary sliding controlled by volume diffusion of equally aluminum and titanium in γ-TiAl.

1. Introduction

Superplastic forming is considered as one of the promising processing route with respect to hard-to-deform intermetallic alloys based on γ-TiAl+α_2–Ti_3Al (hereafter γ+α_2 alloys). From a general point of view, the main prerequisites for achieving high superplastic characteristics are a fine- (d~1 μm) or ultrafine-grained (d < 1 μm) microstructure with predominantly high-angle grain boundaries, a high microstructural homogeneity and a high stability of the grain size against dynamic growth during superplastic flow [1,2].

In respect of γ+α_2 based alloys, it has been documented that superplastic properties are improved: i) with refining the microstructure down to ~0.1 μm, ii) with increasing the α_2-Ti_3Al phase content, iii) at transition from "conventional" alloys to β-solidifying ones, which are chemically more homogeneous, iv) with appearance of the β(B2) phase, which is regarded to be favorable for superplasticity (Table 1) [3–15]. In addition, the transition from "conventional" to β-solidifying alloys containing a large amount of the β(B2) phase allows reducing a number of hot working steps during fabrication of fine-grained products. As was demonstrated, superplastic properties were even attained in as-cast β-solidifying alloys containing 20–30 vol.% of the β(B2) phase without any prior hot working (Table 1). That is, superplastic behavior in γ+α_2 based alloys may be related not only to the fine-grained microstructure but also to the beneficial effect of the β(B2) phase during superplastic flow. Particularly, outstanding superplastic properties were obtained in the as-cast high chromium alloy [12]. Note that the soft β phase enables producing components from alloys like Ti–42Al–5Mn [16] and Ti–43Al–4Nb–1Mo–0.1B [17,18] using near conventional or isothermal hot forming.

At the same time, superplastic forming should be considered as an intermediate processing stage, which is to be followed by final heat treatment restoring high-temperature capability of a γ+α_2 based alloy. Therefore, high superplastic characteristics are of great interest in γ+α_2 based alloys, in which high creep resistance might be restored by final heat treatment.

Reasoning from the aforesaid, the goal of this work was to reach superplastic properties in the Ti–45Al–8Nb–0.2C alloy, which belongs to "TNB-family" and is considered to be one of the promising creep resistant γ+α_2 alloys [19,20]. Superplastic forming might help in fabrication of complex shaped parts made of this high

* Corresponding author. Institute for Metals Superplasticity Problems of Russian Academy of Sciences, Ul. Khalturina 39, 450001 Ufa, Russia.
E-mail address: vimayev@mail.ru (V. Imayev).

http://dx.doi.org/10.1016/j.jallcom.2015.11.228
0925-8388/

Table 1
Superplastic elongations attained in different ingot-metallurgy γ-TiAl+α_2–Ti_3Al based alloys.

Alloy	Processing	Microstructure/β(B2) phase	Superplastic properties			Ref.
			T, °C	ε', s^{-1}	δ, %	
Ti–50Al	MF	UFG	850	8.3×10^{-4}	260	[3]
Ti–48Al–2Nb–2Cr	MF	UFG	800	8.3×10^{-4}	355	[4]
Ti–46.8Al–2.2Cr–0.2Mo	2F	Near UFG	900	2×10^{-4}	425	[5]
Ti–46.5Al–3Nb–2Cr–0.2W	MF	FG	950	1×10^{-3}	600	[6]
Ti–44.2Al–3(Nb,Cr,B)	2F	Near FG	1000	8.3×10^{-4}	775	[7]
Ti–45.5Al–2Nb–2Cr	1F + rolling	FG + lamellae remnants	1200	10^{-3}	980	[8]
Ti–45Al–6(Nb,Mo)–0.2B	1F	Near FG/5% β(B2)	1000	8.3×10^{-4}	1000	[9]
Ti–43Al–4Nb–2Mo–0.5B	1F	Near FG/10% β(B2)	950	1×10^{-4}	405	[10]
Ti–43Al–4.5Nb–2Mo–0.2B	As-cast	LG/20% β(B2)	1050	1.7×10^{-4}	310	[11]
Ti–46Al–8Cr–2Nb–0.15B	As-cast	LG/30% β(B2)	850	1×10^{-4}	628	[12]

MF – multiple forging, 1F and 2F – one and two-step forging, respectively, FG and UFG – fine- and ultrafine-grained, LG – lamellar/globular.

temperature alloy and seems to be an effective approach to enhance the overall performance of TNB alloys. The achievement of superplastic properties in the alloy specially designed as creep-resistant and high-strength alloy seems also to be interesting from a materials science point of view. To refine the as-cast microstructure of the Ti–45Al–8Nb–0.2C alloy, the hot working consisting of hot extrusion and forging has been utilized in the present work. Mechanical behavior and microstructural changes resulted from superplastic deformation were studied by electron microscopy and possible mechanisms of superplasticity were discussed.

2. Material and experimental

The starting material with the nominal composition of Ti–45Al–8Nb–0.2C (in at. %) was produced by vacuum arc remelting and supplied from GfE Metalle und Materialien, Germany as extruded rods of ⌀48 × 90 mm. It is known that the ingot material was preheated at $T = 1250$ °C and extruded to a ratio of 7:1, then subjected to machining and cutting. After that, the cylindrical workpieces were subjected to unidirectional forging under isothermal conditions at $T = 950$ °C, $\varepsilon' = 5 \times 10^{-4}$–$10^{-3}$ s^{-1} to a strain of around 80% and ageing at $T = 800$ °C (3 h) followed by furnace cooling. A glass lubricant was used to decrease friction forces and to protect the workpiece surface against oxidation during forging. Using the described technique a sound forging free of any cracks with approximate dimensions of 115 mm in diameter and 16 mm in thickness was manufactured. The degree of the hot work imparted to the material can be evaluated by calculating the true strain as follows: $e = \ln(H2/H1)+\ln(h1/h2)$ (1), where H1 and H2 are the lengths of the workpiece before and after hot extrusion, h1 and h2 are the heights of the workpiece before and after hot forging. The calculation gives $e \approx 1.95 + 1.61 = 3.56$. For the sake of simplicity, the alloy condition obtained via hot extrusion and unidirectional forging followed by ageing is hereafter called as the hot worked condition.

Flat specimens with a gauge size of $10 \times 5 \times 2$ mm^3 were tensile tested at temperatures in the range of $T = 800$–1050 °C with an initial strain rate of $\varepsilon' = 8.3 \times 10^{-4}$ s^{-1}. Two or three specimens per point were tested at each temperature. The tensile tests were performed in air without any protection against oxidation. An elongation to rupture, δ, and true stress-true strain curves σ-e were determined. The strain rate sensitivity coefficient, m, was defined at different strain rates by changing the strain rate employed. To plot the dependence of $\ln(\sigma)$ on $1/T$, the σ_{30} values corresponding to 30% of elongation were taken into consideration.

The microstructure examination was carried out using scanning in backscattering electron mode (SEM, BSE) and transmission (TEM) electron microscopy. Before SEM studying, the specimen surfaces were polished. Electron backscattered diffraction (EBSD) technique was applied to evaluate the microstructure before and after superplastic deformation. EBSD analysis was conducted using the CHANNEL 5 processing software. A scan step size was taken as 0.1 μm. The grain boundaries having misorientation angle less than 2° were excluded from the consideration taking into account the measurement accuracy. The boundaries with misorientation angle higher than 15° were taken into account as high-angle grain boundaries. For the sake of simplicity, only γ-TiAl phase orientations were taken into consideration in the EBSD study although the alloy contains a small amount of the α_2-Ti_3Al phase. BSE images and EBSD data were used to define the mean grain size, d in the grips and the gauge areas of tensile tested specimens. The alloy composition was measured by energy dispersive X-ray (EDX) analysis system calibrated using ternary TiAl–Nb based alloy standard. The specimens for SEM examination were prepared from the grip area and near the fracture zone of the tensile tested specimens. EBSD analysis was also used to obtain inverse pole figures.

3. Results and discussion

3.1. Initial hot worked condition

The alloy composition measured from different parts of the hot worked workpiece was at the average defined as Ti–45.37Al–8.35Nb (carbon was not taken into consideration). Fig. 1a,b represents BSE images of the Ti–45Al–8Nb–0.2C alloy after hot extrusion and forging followed by ageing. A near fully fine-grained microstructure with a grain size of $d = 3$–30 μm, as a result of dynamic recrystallization, was produced in the extruded material. A striped microstructure with stripes parallel to the extrusion axis was observed after extrusion. Lamellae remnants elongated along the extrusion axis were sometimes distinguished. The β(B2) phase was not detected in the obtained condition that is consistent with our previous work [21]. SEM and TEM examinations showed that the hot forging led to formation of a homogeneous near fully recrystallized ultrafine-grained microstructure with a mean grain size of $d = 0.9$ μm (Fig. 1b,c). Annealing twins were sometimes observed in relatively coarse grains; apparently, the twins were formed immediately after completing the hot forging processing.

Fig. 2 represents the EBSD orientation map and the corresponding grain boundary misorientation-angle distribution obtained for the alloy in the ultrafine-grained condition. The fraction of the α_2-Ti_3Al phase was found to be around 3 vol. % and, therefore,