Materials and Design 67 (2015) 50–63

Contents lists available at ScienceDirect

Materials and Design

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

Effect of boron and carbon addition on microstructure and mechanical properties of metastable beta titanium alloys

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ARTICLE INFO

Article history:
Received 14 August 2014
Accepted 3 November 2014
Available online 10 November 2014

Keywords:
β-Titanium alloys
Boron and carbon
Solution treatment
Ageing
Electron microscopy
Tensile testing

ABSTRACT

Effect of boron and carbon on microstructure and mechanical properties of β titanium alloys Ti–15V–3Cr–3Mo–3Sn, Ti–10V–2Fe–3Al, and Ti–5V–5Mo–5Al–3Cr has been studied in detail. The addition of boron and carbon results in refinement of β grain size and α-precipitates during ageing. While the hardness and tensile strength increase with the addition of boron and carbon, the elongation to failure deteriorates. The increase in strength is attributed to a synergistic effect of grain refinement and load sharing by TiB and TiC particles; whereas decrease in elongation is due to the brittleness of these hard particles. Ageing results in increase in strength and decrease in elongation as compared to solution treatment condition. In this case, the effect of boron and carbon is marginal. Further enhancement in the properties can be achieved by fine tuning heat treatment parameters. Multiple slopes are observed in log–log plots of true stress–true strain thereby implying different deformation mechanisms over a large range of plastic deformation.

1. Introduction

Beta titanium alloys have been extensively used for aerospace structural applications [1,2]. It is primarily because of three attributes [3]: (1) relatively lower density as compared to steels and nickel base super alloy, (2) reasonable balance of modulus, strength, ductility and fracture toughness, and (3) excellent corrosion resistance. Additionally, the alloy can be heat treated to obtain a range of mechanical properties depending upon the application [4]. In a very recent study carried out by Srinivasu and co-workers [5], the effect of thermo-mechanical processing on tensile and fracture toughness of a high strength beta titanium alloy has been clearly shown.

Some of the applications of β-titanium alloys include landing gears, slat and flap tracks, springs, brackets and so on [1]. Since the use of β-titanium alloys results inconsiderable weight saving and, therefore increased fuel efficiency of an aircraft, there is a continuous drive towards increasing use of these alloys. This is possible by improving the mechanical properties (especially the strength and fracture toughness) of these alloys. The alloys are used at room temperature as well as moderately high temperatures. Therefore, any attempt to improve the properties of the alloy should address both low and high temperature (25–500 °C) properties. In recent times, additions of boron and carbon in beta titanium alloys have been attempted with beneficial effects. Small addition of carbon leads to significant refinement in the microstructure of an aged β-titanium alloy [6]. Similarly fine microstructure with boron addition has been obtained in pure titanium [7] and titanium alloys such as Ti–6Al–4V and Ti–6Al–2Sn–4Zr–2Mo [8]. Grain boundary pining effect of TiB whiskers has also been shown by Cherukuri and co-workers [9]. A study on synergistic effect of boron and carbon on Ti–15V–3Al–3Sn–3Cr has shown similar results [10]. While the addition of boron results in substantial refinement in beta/prior beta grain size, carbon addition is associated with refinement in the aged microstructure. Additionally these additions also lead to nucleation of undeformable particles such as TiB and TiC. Thus, refinement in microstructure and the presence of undeformable particles lead to strengthening of these alloys. Extensive work carried out on the effect of boron addition in near alpha and alpha–beta alloys has clearly established the beneficial effect of boron on both room and high temperature properties [12]. Ranganath and Mishra [13] also showed beneficial effects of B_4C addition in Ti–6Al–4V alloy.

Therefore in the present investigation, the effect of boron and carbon addition in three beta titanium alloys namely Ti–15V–3Cr–3Al–3Sn (Ti-15333), Ti–10V–2Fe–3Al (Ti-1023) and Ti–5V–5Mo–5Al–3Cr (Ti-5553) has been studied. The alloys with B and

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http://dx.doi.org/10.1016/j.matdes.2014.11.004
0261-3069/

Table 1
Chemical composition of the selected titanium alloys (wt.%).

Titanium alloy	V	Cr	Al	Fe	Mo	Sn	B	C	N	O	Ti
Ti–15V–3Cr–3Al–3Sn (Ti-15333)	14.2	2.7	3.2	–	–	2.2	–	–	0.004	0.102	Bal.
Ti–15V–3Cr–3Al–3Sn–0.1B–0.1C (Ti-15333BC)	14.9	3.1	3.1	–	–	2.3	0.07	0.11	0.005	0.12	Bal.
Ti–10V–2Fe–3Al (Ti-1023)	9.50	–	3.1	2.3	–	–	–	–	0.003	0.110	Bal.
Ti–10V–2Fe–3Al–0.1B–0.1C (Ti-1023BC)	9.70	–	3.2	1.8	–	–	0.08	0.11	0.006	0.13	Bal.
Ti–5V–5Al–5Mo–3Cr (Ti-5553)	4.00	2.4	3.9	–	3.5	–	–	–	0.006	0.105	Bal.
Ti–5V–5Al–5Mo–3Cr–0.1B–0.1C (Ti-5553BC)	5.00	2.8	4.6	–	4.4	–	0.07	0.11	0.007	0.12	Bal.

Fig. 1. As forged pancakes (diameter: 130 mm, thickness: 7 mm) of some selected titanium alloys.

C designated as Ti-15333BC, Ti-1023BC and Ti-5553BC along with base line compositions (Table 1) have been investigated. While Ti-15333 and Ti-1023 are earlier generation alloys used for a variety of aerospace applications [14], Ti-5553 is a relatively recent alloy mainly developed for landing gear applications [15]. The effect of these additions on microstructure of solution treatment and solution treated plus aged conditions have been studied first. This is followed by the evaluation of hardness and tensile properties in single phase beta and aged beta structure (comprising fine alpha in a beta matrix). Structure–property correlation has been carried out to understand: (1) the effect of ageing on mechanical properties in a given composition and (2) the effect of boron and carbon addition on microstructure and properties of the alloys in both solution treatment and solution treatment plus aged conditions.

2. Experimental procedure

The alloys were melted by non-consumable vacuum arc melting to obtain 600 g pancakes. The melting was repeated four times to get a homogenous pancake. While V was added as V-Al master alloy, elements such as Al, Sn, Cr, C and B were added in pure elemental form. The alloys without boron and carbon were also melted to generate base line microstructures and mechanical property data. Chemical analysis of Al, Sn, Cr, V and B was carried out using Inductively Coupled Plasma-Optical Emission Spectroscope (ICP OES) instrument and O, N, and C were analysed using Leco analyser. Chemical analysis results are shown in Table 1. The alloys were hot forged to about 7 mm thickness from 10 mm initial thickness thereby giving an overall deformation of 30%. Fig. 1 shows as-forged pancakes of some alloys.

The hot forged alloys were given two different heat-treatments: (1) solution treatment (ST) for 1 h followed by water quenching and (2) solution treatment plus aging (STA) at 500 °C for 8 h followed by air-cooling. This was done to generate two different microstructures, namely, single-phase β and aged β (containing fine α in retained β matrix) respectively. The details of forging and heat treatment are given in Table 2.

Standard metallographic polishing techniques were employed for microstructural observation using optical and scanning electron microscope (SEM) and finally etching was carried out with Kroll's reagent (2 ml of HF, 4 ml of HNO_3, 94 ml of distilled water). Etched samples were examined under optical and SEM. For transmission electron microscopy, specimens were prepared by mechanically polishing the discs of 3 mm dia up to 100 μm and then electro-polishing in twin jet electro polisher (FISCHIONE Instrument, Model: 110). Electro-polishing was done using 5% H_2SO_4 solution in methanol as electrolyte at 223 K. During polishing, the voltage was maintained at 20 V. A Tecnai G^2 20 T Transmission Electron Microscope (TEM) was used for the examination of the foils.

Hardness of all selected materials, both in solution treated and solution treated plus aged condition, was measured by using Shimadzu microhardness tester (model HMV 2000), applying a load of 500 g with a dwell time of 15 s. Room temperature tensile tests were performed on flat tensile specimens. During tensile specimen preparation, 1 mm layer was machined out from both top and bottom surfaces in order to remove the oxide layer formed during forging and heat treatment. A screw driven Instron machine (5500R) was used for the tests at a strain rate of 10^3 s^1. Engineering stress–strain data were extracted from the load–elongation curves recorded during the tests. The tensile tests were carried out according to ASTM: E8M-142 in flat type fixer digital control INSTRON 5500R test system in order to obtain the stress-strain curves. Fracture surfaces of the failed specimens were observed using scanning electron microscope.

3. Results

3.1. Chemical composition and microstructure

Optical microstructures of the alloys in solution treatment conditions are shown in Fig. 2. Equiaxed microstructure is seen in all

Table 2
Beta-transus temperature, forging temperature and heat treatment details of titanium alloys investigated.

Titanium alloy	Ti-15333	Ti-15333BC	Ti-1023	Ti-1023BC	Ti-5553	Ti-5553BC
Forging temperature (°C)	900	900	950	950	1000	1000
Solution treatment	810 °C/1 h/WQ		850 °C/1 h/WQ		900 °C/1 h/WQ	
Ageing	500 °C/8 h/AC					