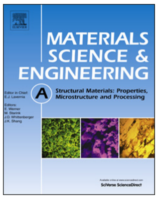
Materials Science & Engineering A 612 (2014) 456–461

Contents lists available at ScienceDirect

Materials Science & Engineering A

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



Effect of Zr and Si addition on high temperature mechanical properties of near-α Ti–Al–Zr–Sn based alloys

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ARTICLE INFO

Article history:
Received 14 May 2014
Received in revised form
13 June 2014
Accepted 22 June 2014
Available online 28 June 2014

Keywords:
Ti alloy
Compression test
Microstructure
Transmission electron microscopy (TEM)
Yielding strength

ABSTRACT

The mechanical properties and microstructural evolution of Ti–Al–Zr–Sn based near α-Ti alloys with various amounts of Zr and Si have been systematically investigated. The compression test results reveal that higher contents of Zr and Si can improve the yielding strength both at room temperature and high temperature (650 °C). The enhanced yield strength was found to be contributed mainly by fine silicide precipitates (Ti_5Si_3). Zr was enriched in the silicide formed at α-lath boundaries. The microstructural characterization of the alloys with various alloying elements has been studied using transmission electron microscopy (TEM).

1. Introduction

High temperature titanium alloys, especially near-α titanium alloys are extensively used in jet engines as compressor discs and blades due to their light weight and superior fatigue and creep properties at elevated temperatures up to 600 °C [1–6]. Above 600 °C, the strength of the conventional near-α titanium alloys like Ti-1100, IMI834 and VT18U, drastically reduced [1–3,6]. For the past 20 years numerous research works have been carried out to find suitable strengthening additives to improve the high temperature strength. However, the effective strengthening method to improve high temperature properties of near-α titanium alloys has yet to be identified.

Alloying is one of the fundamental methods to improve the high temperature mechanical properties of titanium alloys [6–13]. Most of the high temperature titanium alloys are based on a typical near-α Ti–Al–Sn–Zr based alloy [2,7,14]. Aluminum element works as an effective α stabilizer and increases high temperature strength [6,15,16]. However, addition of high amounts of aluminum leads to embrittlement at room temperature and microstructural instability at high temperature, due to the precipitation and coarsening of brittle α_2-Ti_3Al phase [16]. Tin works as a neutral stabilizer and as a solid solution strengthener, often in conjunction with aluminum to achieve the higher strength without causing embrittlement [6]. Zirconium is a neutral stabilizer, exhibiting unlimited solubility in titanium and is one of the important solid solution strengtheners in titanium alloys [17–21]. In addition to that, Zr also improves corrosion and oxidation resistance of titanium alloy [22–24]. However, it has been reported that the use of Zr is limited to only 5 wt%, as Zr reduces the solubility of silicon in titanium [22]. Excess amount of Zr addition might favor the formation of large silicide, which degrades the ductility and fatigue properties [25]. However, no detailed investigations have been available in open literature about the effect of high Zr content in titanium alloys.

In the present study, the effect of increasing Zr content together with various amounts of Si in a commonly used high temperature titanium alloy system, i.e., in Ti–Al–Zr–Sn based near-α titanium alloys on mechanical properties and microstructure have been investigated using compression test and transmission electron microscope.

2. Experimental procedures

Four Ti–7.7Al–*x*Zr–0.5Ta–0.5Mo–2Sn–*xx*Si alloy ingots with two different Zr contents ($x=4$ and 6 wt%) and two different Si contents ($xx=0.05$ and 0.3 wt%) were prepared from pure Ti, Al, Sn, Zr, Mo, Ta and Si ($\geq 99.5\%$ purity) by using an arc-melting method, under an argon atmosphere. The composition of ingots is listed in Table 1. Each ingot was melted six times to ensure compositional homogeneity. The ingots were solution treated at 1100 °C for 2 h and air cooled to room temperature, followed by ageing at 750 °C for 4 h and air cooled to room temperature.

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http://dx.doi.org/10.1016/j.msea.2014.06.078

Compression tests at room temperature and at 650 °C were carried out at a strain rate of 5×10^{-3}/s using a cylindrical specimen of diameter 3 mm and height 6 mm, in Shimadzu testing machine equipped with a split type electric furnace. For the compression test at 650 °C, the test was carried out inside the furnace, maintained at 650 °C. The specimens were held at 650 °C for 10 min before the compression test at 650 °C. To check the reproducibility of the compression test results, for each condition compression tests were done for three samples. The error percentage was less than 0.6%.

Microstructural characterizations were carried out using X-ray diffraction (XRD), optical microscope (OM) and transmission electron microscope (TEM). The XRD measurement was carried out on RINT2500 X-ray diffractometer using Cu Kα radiation, operated at 40 kV and 300 mA. The specimens for OM observation were mechanically polished on emery papers of GRIT 240 to 2000 grades. Final polishing was carried out on sylvet cloth, mounted on a smooth rotating polishing wheel using water suspensions of alumina powder of 0.5 µm. Polished samples were etched with a solution of 2% HF+10% HNO3+88% distilled water (volume%) at room temperature.

TEM observations were carried out on JEOL 2000FX TEM and JEOL 2100F TEM. The specimens for TEM observation were prepared by electrolytic polishing of thin discs of ∅3 mm, punched from thin sections of ~50 µm thickness. Electro polishing was carried out in an electrolyte containing 10% perchloric acid, 30% n-butyl alcohol and 60% methanol at 20 V, using a twin jet polisher. The temperature of the electrolyte was maintained at −40 °C to −30 °C, using liquid nitrogen, throughout the process of electro thinning.

3. Results and discussion

The compression test results (at room temperature and at 650 °C) of the four alloys in solution treated and aged conditions are shown in Fig. 1(a) and (b), respectively. A summary of the compressive yield strength is given in Table 2. As seen from Table 2, in the alloy Ti–7.7Al–4Zr–0.5Ta–0.5Mo–2Sn–0.05Si with an increase in Zr content from 4 wt% to 10 wt%, the room temperature and high temperature compressive yield strength were increased from 850 MPa to 900 MPa and from 490 MPa to 550 MPa, respectively. In the alloy Ti–7.7Al–4Zr–0.5Ta–0.5Mo–2Sn–0.3Si with an increase in Zr content from 4 wt% to 10 wt%, the room temperature and high temperature compressive yield strength were increased from 950 MPa to 1120 MPa and from 605 MPa to 620 MPa, respectively.

In the alloy Ti–7.7Al–4Zr–0.5Ta–0.5Mo–2Sn–0.05Si with an increase in silicon content from 0.05 wt% to 0.3 wt%, the room temperature and high temperature compressive yield strength were increased from 850 MPa to 950 MPa and from 490 MPa to 605 MPa, respectively. In the alloy Ti–7.7Al–10Zr–0.5Ta–0.5Mo–2Sn–0.05Si with an increase in silicon content from 0.05 wt% to 0.3 wt%, the room temperature and high temperature compressive yield strength were increased from 900 MPa to 1120 MPa and from 550 MPa to 620 MPa, respectively. The increase of both Zr and Si contents can improve the yielding strength at both room and high temperatures.

The XRD results of the four alloys are shown in Fig. 2. All the investigated alloys reveal only one crystalline phase (α-Ti). Optical microstructures of the Ti–7.7Al–4Zr–0.5Ta–0.5Mo–2Sn–0.3Si and Ti–7.7Al–10Zr–0.5Ta–0.5Mo–2Sn–0.3Si alloys in solution treated and aged conditions are shown in Fig. 3(a) and (c), respectively. The prior-β grain sizes in these alloys are approximately in the range of 600–800 µm. Fig. 3(a) and (c) reveal a basket weave configuration of Widmanstatten plates of α phase, which is the common microstructure obtained for near-α titanium alloys during air cooling from β phase [26]. Fig. 3(b) and (d) are the higher magnification of a local area in Fig. 3(a) and (c), respectively. In both the alloys under high magnification, dark spots, which might correspond to silicide precipitates, were observed mainly at the α-lath boundaries. Both alloys with the lower and higher Zr contents have quite similar microstructures to the OM observation.

TEM images of the above two alloys (Ti–7.7Al–4Zr–0.5Ta–0.5Mo–2Sn–0.3Si and Ti–7.7Al–10Zr–0.5Ta–0.5Mo–2Sn–0.3Si) in solution treated and aged condition are shown in Fig. 4. Fig. 4(a) and (b)

Table 1
Chemical composition of the ingot.

S. No	Alloy (wt%)
1	Ti–7.7Al–4Zr–0.5Ta–0.5Mo–2Sn–0.3Si
2	Ti–7.7Al–10Zr–0.5Ta–0.5Mo–2Sn–0.3Si
3	Ti–7.7Al–4Zr–0.5Ta–0.5Mo–2Sn–0.05Si
4	Ti–7.7Al–10Zr–0.5Ta–0.5Mo–2Sn–0.05Si

Table 2
Effect of Zr and Si on compressive yield strength.

Alloy (wt%)	Compressive yield strength (MPa)	
	Room temperature	At 650 °C
Ti–7.7Al–4Zr–0.5Ta–0.5Mo–2Sn–0.3Si	950 (±5)	605 (±3)
Ti–7.7Al–10Zr–0.5Ta–0.5Mo–2Sn–0.3Si	1120 (±6)	620 (±4)
Ti–7.7Al–4Zr–0.5Ta–0.5Mo–2Sn–0.05Si	850 (±4)	490 (±3)
Ti–7.7Al–10Zr–0.5Ta–0.5Mo–2Sn–0.05Si	900 (±5)	550 (±3)

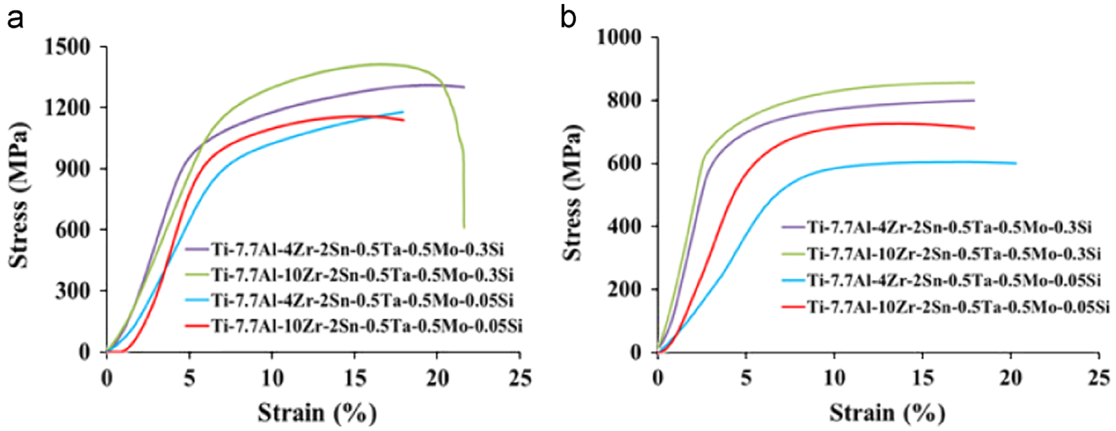

Fig. 1. Compression test (a) at room temperature (b) at 650 °C.