Journal of Alloys and Compounds 509 (2011) 7361–7367

Contents lists available at ScienceDirect

Journal of Alloys and Compounds

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

Tensile behaviour of boron modified Timetal 834 titanium alloy in the intermediate temperature range 400–500 °C

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ARTICLE INFO

Article history:
Received 26 March 2011
Received in revised form 18 April 2011
Accepted 20 April 2011
Available online 27 April 2011

Keywords:
Mechanical properties
Microstructure
High temperature alloys
Scanning electron microscopy

ABSTRACT

The tensile behaviour of boron modified Timetal 834 titanium alloy was studied in the intermediate temperature range 400–500 °C and compared with that of the base alloy. The yield and ultimate tensile strengths of the B modified alloy were found to be higher than those of the base alloy at all the temperatures investigated. The B modified alloy also exhibited only a marginally lower elongation to failure as compared to the base alloy at all the temperatures investigated. The B modified alloy exhibited dynamic strain aging in the temperature range 400–475 °C which is similar to the observed behaviour in the base alloy.

1. Introduction

In general, titanium alloys are widely used in aerospace gas turbine engines due to their relatively low density and attractive high temperature properties [1,2]. In recent past, many researchers have studied the influence of minor addition of boron (up to 0.5 wt.% B) on the mechanical properties of titanium alloys [3–9]. These studies have found that the boron modified titanium alloys exhibit higher strengths at room temperature without any loss in ductility. In a recent study [10], the effect of addition of 0.2 wt.% B on tensile properties of Timetal 834, a near α titanium alloy specifically developed for applications in compressor disks, blades, vanes and housings in modern aeroengines [11–13] was investigated. This study showed that the boron modified Timetal 834 alloy exhibited higher strengths than the base alloy at room temperature as well as at 600 °C, without any loss in ductility [10]. Unlike blades, which are relatively smaller components that are wholly exposed to a narrow range of high temperatures, compressor discs are large components and hence experience a spectrum of temperatures. These range from lower temperatures at the bore, intermediate temperatures in the web to higher temperatures at the rim. It is, therefore, essential that tensile behaviour of the B modified Timetal 834 alloy is understood at intermediate temperatures (400–500 °C) in addition to that at room temperature and its maximum service temperature (600 °C).

The temperature range of 400–500 °C is especially important because the base alloy (Timetal 834) is known to exhibit dynamic strain aging (DSA) in this temperature range. DSA is a strengthening mechanism which involves the interaction of moving dislocations with mobile point defects [14]. In Timetal 834 near α titanium alloy, DSA has been confirmed by observing various manifestations of DSA under tensile (appearance of serration in plastic region of flow curve, temperature insensitivity of flow stress, minimum ductility, maximum work hardening exponent and work hardening rate) [15] and cyclic (maximum peak stress ratio, increase in isotropic stress component, minimum half-life plastic strain range and lower fatigue life) [16–18] loading conditions. In previous studies [15,19], it has also been confirmed that the DSA effect was maximum at 450 °C at the strain rate of $6.7 \times 10^{-4}\ s^{-1}$.

In light of the above, the aim of the present study was to study the effect of minor addition of boron (0.2 wt.% B) on intermediate temperature range (400–500 °C) tensile properties of Timetal 834 titanium alloy.

2. Experimental procedure

Nominal chemical composition of the melted alloys is shown in Table 1. The alloys were prepared by consumable vacuum arc melting. While Ti, Al, Zr, Sn, Si, and B were added in elemental form, Mo and Nb were added as Mo/Al and Nb/Al master alloys. The details of the melting are given in our earlier study [9]. The cast ingots were subsequently forged at 1100 °C to 32 mm thick billets. Metallographic technique has been employed to determine the β-transus temperature (β_T) of the alloys. Small specimens were solution heat treated for 2 h at temperatures ranging from 975 °C to 1105 °C. The specimens were then water quenched and their microstructure was examined. β_T was taken as the temperature above which no primary α was seen. β_T of the base alloy and the boron modified alloy were determined to be 1045 °C ± 3 °C and 1075 °C ± 3 °C, respectively.

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doi:10.1016/j.jallcom.2011.04.111

Table 1
Nominal chemical composition of base and B modified Timetal 834 alloy.

Alloy/Elements	Al	Sn	Zr	Mo	Nb	Si	B	O	N	C
Base	5.78	4.01	3.71	0.72	0.55	0.30	–	0.09	0.007	<0.06
Modified	5.80	3.98	3.74	0.71	0.57	0.28	0.19	0.08	0.008	<0.06

Tamiriskandala et al. [8] have reported similar increase in β_T in B modified titanium alloy. The ingots were subsequently rolled in the $\alpha-\beta$ region at a temperature of (β_T – 25 °C) to 16 mm thick plates. In our previous study [10], a series of heat treatments, involving solution treatment and aging, were employed for the evaluation of tensile properties. Since solution treatment temperature of β_T – 20 °C was found to give a best combination of strength and ductility, it was chosen for carrying out the tensile studies in the present investigation in the temperature range 400–500 °C. All specimens were first solutionized at 1100 °C for 2 h followed by furnace cooling to room temperature in air environment and subsequently solution treated at β_T – 20 °C for 2 h, oil quenched and aged at 700 °C for 2 h and air cooled.

The microstructures after heat treatment were examined using a FEI quanta 400 scanning electron microscope (SEM). The microstructures were also examined using a transmission electron microscope (TEM, FEI Tecnai C^2) to study the effect of B addition on α-lath size. The tensile properties in the temperature range 400–500 °C were evaluated as per ASTM standard E – 8M [20] in laboratory air on a screw driven Walter + Bai Ag testing machine at a nominal strain rate of 6.7×10^{-4} s^{-1} at a temperature interval of 25 °C. Tensile tests were also conducted at 450 °C at four different strain rates (10^{-5} s^{-1} to 10^{-2} s^{-1}). In all cases, the specimens were heated to the desired temperature followed by 15 min soaking to homogenize the temperature within the gauge portion of the specimen. A tubular, three zone high temperature resistance furnace was employed for high temperature tensile testing which controls temperatures up to 1000 °C with an accuracy of ±1 °C. K type thermocouple has been used to measure the temperature along the gauge length of the specimen. A 25 mm gauge length and ±2.5 mm travel high temperature extensometer was used to record the strain during the tensile testing. Three specimens were tested for each test conditions.

Elemental mapping and compositional line profile analysis of the B modified Timetal 834 alloy was carried out using electron probe microanalysis (EPMA) in a CAMECA – SX100 instrument.

3. Results

3.1. Microstructure

Microstructures of Timetal 834 alloy under heat treatment condition (β_T – 20 °C/2 h/OQ followed by aging 700 °C/2 h/AC) are shown in Fig. 1a–c. It can be observed that the microstructure of the B modified alloy is similar to the base alloy (elongated primary α in a transformed β matrix), other than for the presence of elongated white precipitates. These precipitates can be clearly seen at higher magnification SEM micrograph in Fig. 1c. EDS analysis has confirmed that these precipitates contain Ti and B. Dimensions of the TiB has been measured using high magnification SEM micrographs and volume fraction through image analysis software. Average of minimum 10 measurements was taken from the SEM micrographs. The average length and width of these precipitates was measured to be 12.5 ± 1.4 μm and 2.0 ± 0.3 μm, respectively. The longest and shortest TiB was measured to be 19.5 ± 2.3 μm and 0.8 ± 1.2 μm, respectively. A representative TEM micrograph of one of these precipitates is shown in Fig. 2. Selected area diffraction pattern (SADP) from these precipitates confirmed that these precipitates are TiB (Fig. 2b). TEM was also used to examine the transformed β matrix and a representative TEM micrograph for 0.2 wt.% B containing alloy is shown in Fig. 3. It can be seen that the transformed β matrix consists of α laths separated by thin β films. SADP from α laths has also

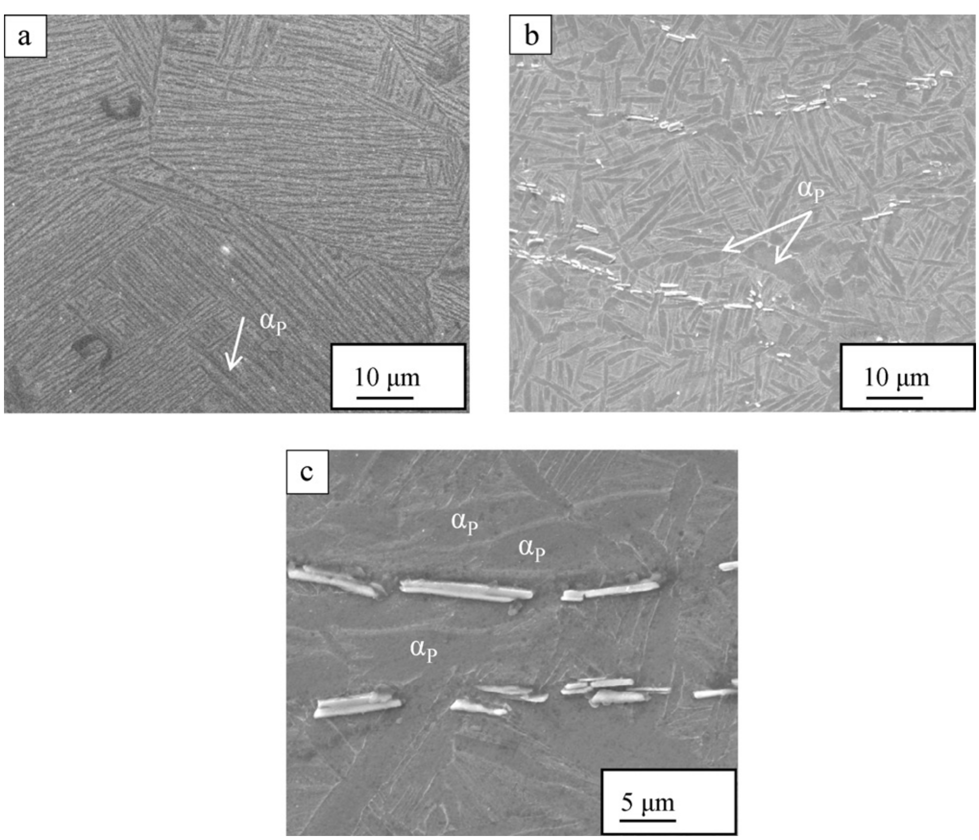

Fig. 1. SEM microstructures of (a) base alloy and (b and c) B modified Timetal 834 alloy showing elongated primary α and transformed β matrix. B modified alloy shows the presence of white TiB precipitates.

Table 2
Microstructural parameters of base and B modified Timetal 834 alloy.

Solution treatment temperature (°C)	Alloy	Alloy volume fraction of α_P (%)	Prior β grain size (μm)	α Lath thickness (μm)
β – 20	Base	16–19	51	2.1–2.25
	Modified	17–18	42	2.2–2.28

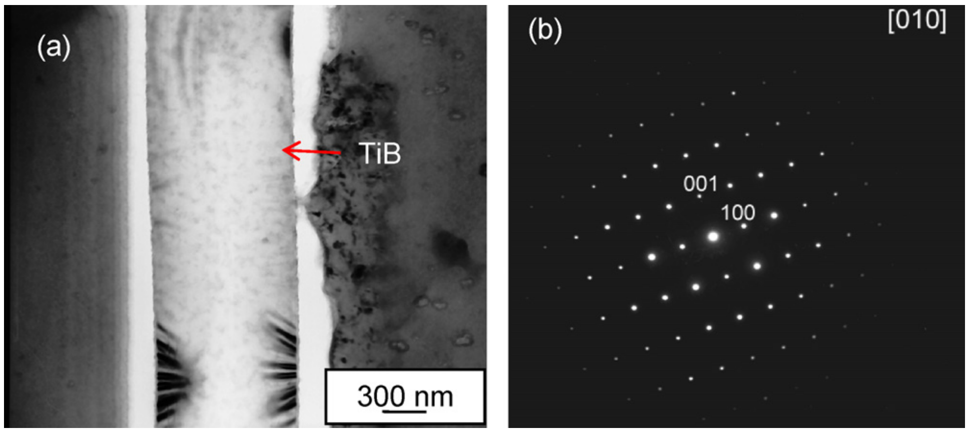

Fig. 2. Bright field transmission electron micrograph showing (a) TiB precipitate and (b) [0 1 0] diffraction pattern of TiB precipitate.

been shown in Fig. 3b. The microstructural parameters including α lath thickness, volume fraction of primary elongated α and prior β grain size are listed in Table 2. It is clear from Table 2 that the α lath spacing, volume fraction of primary elongated α and prior β grain size are similar for both the base and boron containing alloy.

3.2. Tensile properties

The plastic region of true stress–strain plots of the base and B modified Timetal 834 alloy at all five temperatures (400 °C, 425 °C, 450 °C, 475 °C, 500 °C) are shown in Fig. 4. Fig. 4 shows that both the alloys exhibit serrated flow behaviour in the temperature range between 400 °C and 475 °C. Interestingly, the types of serrations (see Table 3) observed are also similar in both alloys. The tensile properties in terms of 0.2% yield strength (YS), ultimate tensile strength (UTS), and percent elongation (%el) of the base and B modified alloy evaluated from 400 °C to 500 °C are listed in Table 4. The values listed are an average of three tests. The tensile properties at room temperature and 600 °C from our previous study [10] are also included in Table 4. It can be observed from Table 4 that the B modified alloy exhibits higher 0.2% YS and UTS as compared to base alloy at all temperatures in the temperature range investigated. The elongation to failure exhibited by the B modified alloy is also only marginally lower at all temperatures. However there is a

Table 3
Types of serrations manifested by the base and B modified alloy at different test temperature.

Test temperature (°C)	Alloy	Type of serrations
400	Base	A + B
	Modified	A + B
425	Base	A + B + E
	Modified	A + B + E
450	Base	B + C_A
	Modified	B + C_A
475	Base	A + C_B
	Modified	A + C_B
500	Base	–
	Modified	–

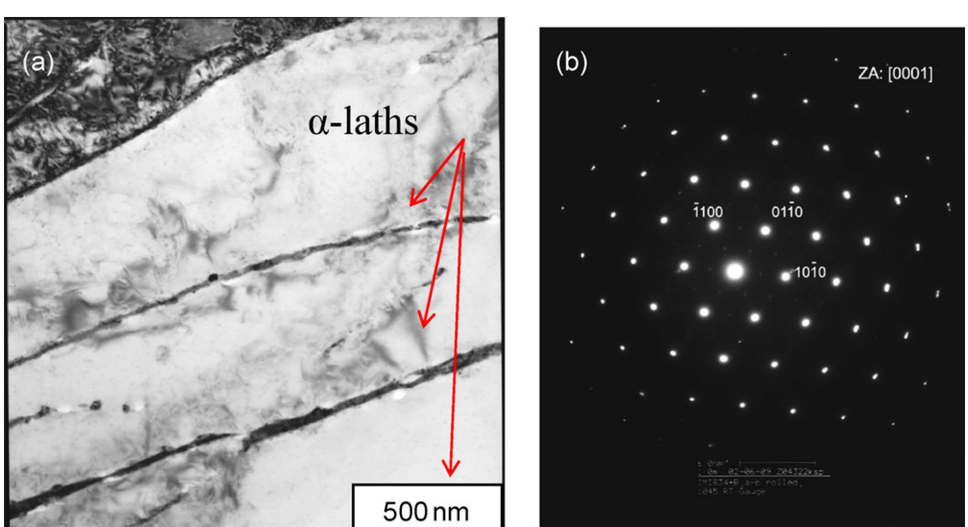

Fig. 3. Transmission electron micrograph taken from the matrix of modified alloy showing (a) alternate lamellae of α and β and (b) [0 0 0 1] diffraction pattern of α phase.

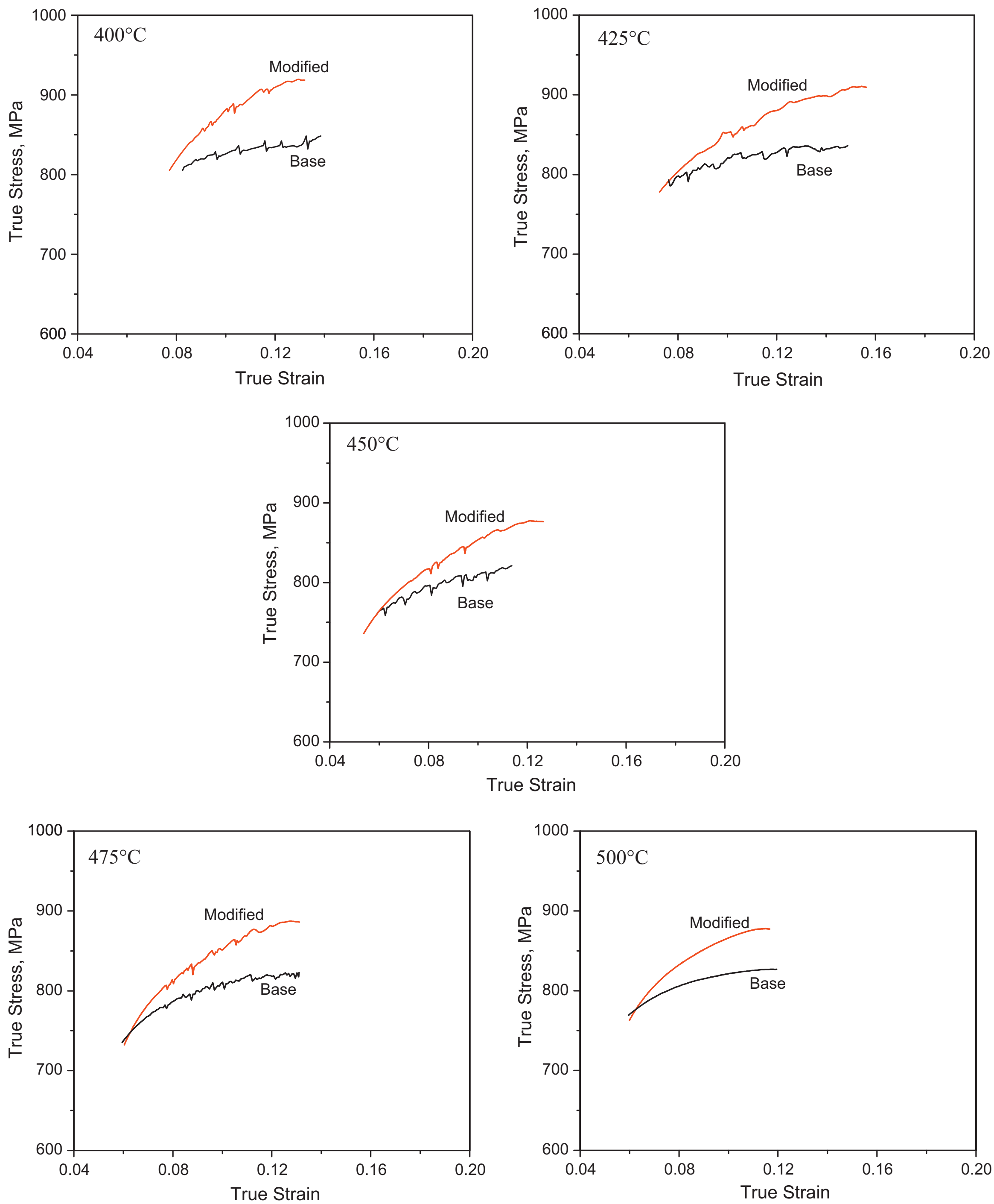

Fig. 4. Comparison of flow curves at various test temperature.

significant drop in elongation to failure for both alloys at 450 °C. Fig. 4 and Table 4 also shows that the B modified alloy exhibit higher strain hardening (as evident from the ratio of UTS/0.2% YS) at all the temperatures tested.

3.3. Dynamic strain aging

In order to determine and compare the temperature range in which DSA occurs, the 0.2% YS and UTS as well as % elongation of both alloys are plotted as a function of temperature in Figs. 5 and 6, respectively. Fig. 5 shows that decrease in strength remains nearly insensitive to increase in temperature from 425 to 475 °C in both the base as well as B modified alloy. Fig. 6 clearly shows that elongation to failure decrease as temperature is increased above 400 °C and exhibits a minima at 450 °C for both the alloys. Both the alloys exhibit negative strain rate sensitivity (γ) and showed the same value of γ (−0.01) at 450 °C as shown in Fig. 7. All these observations confirm that the DSA occurs in the same temperature range (400–475 °C) in both the B modified alloy as well as in the base alloy.

Table 4
Tensile properties of base and B modified Timetal 834 titanium alloy from 400 °C to 600 °C.

Test temperature (°C)	Alloy	0.2%YS (MPa)	UTS (MPa)	(UTS/0.2% YS)	%El (25 mm GL)
400	Base	692	867	1.25	9.3
	Modified	722	917	1.27	8.8
425	Base	683	845	1.23	8.9
	Modified	720	901	1.25	8.2
450	Base	675	842	1.24	6.1
	Modified	710	896	1.26	5.8
475	Base	671	832	1.24	7.6
	Modified	703	887	1.26	6.9
500	Base	660	817	1.23	8.2
	Modified	690	870	1.26	7.8
600	Base	617	721	1.16	9.2
	Modified	641	753	1.17	8.3

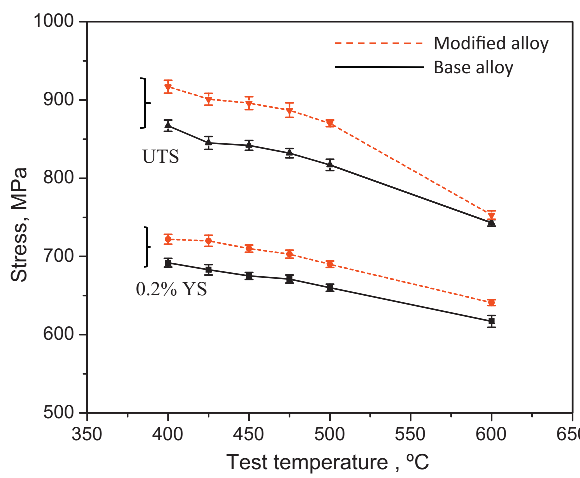

Fig. 5. Variation of 0.2% yield strength and ultimate tensile strength with test temperature.

4. Discussion

4.1. Tensile properties

In the present study, irrespective of the test temperature, the B modified alloy exhibited higher strength than the base alloy even though B addition does not affect the prior β grain size or the α lath size in the transformed β microstructure (see Table 2). In our previous study, the increase in strength due to B addition in Timetal 834 at room temperature and 600 °C were attributed to the load sharing by the strong and stiff TiB whiskers. A model proposed by Curtin and Zhou [21] and modified by Boehlert et al. [22] was used to predict the ultimate tensile strength of the B modified alloy from the properties of the base alloy and the TiB whiskers. The equation used is given below:

$$\sigma_{\mathrm{UTS}} = f\sigma_C\xi(\bar{\rho}_0, m) + (1-f)\sigma_m(\varepsilon_{\mathrm{UTS}}) \quad (1)$$

where f is the volume fraction of TiB, σ_C is the characteristic TiB strength, $\xi(\bar{\rho}_0, m)$ is a numerical factor that depends only on the dimensionless initial TiB length $\rho_0 = \delta_C/L = r\sigma_C/L\tau$ and the Weibull modulus (m).

Boehlert et al. [22] estimated that the in situ TiB whisker strength (σ_C) is 8.0 GPa with a Weibull modulus $m = 2$. If one assumes the same strength characteristics for the TiB whiskers in the present study and substitutes the other parameters measured experimentally such as r (radius of whisker) = 1.3 µm, L (average length of whisker) = 12.5 µm and f (volume fraction of TiB) = 1.48% and the appropriate τ and σ_m (ε_u) values for each tested temperature one can predict the UTS of the B modified alloy. These values are enumerated in Table 5. It can be observed that the calculated UTS values for the B modified alloy are in reasonable agreement with the experimentally measured values. The observation of only a marginally lower ductility in the modified alloy as compared to the base alloy is also consistent with the above model. The analysis of the Boehlert et al. [22] shows that the elongation to failure is very sensitive to the whisker strength statistics and the initial whisker length relative to the critical length, i.e., ρ_0. High elongation to failure is obtained as long as ρ_0 is greater than a critical value of ρ_0^* which for TiB whiskers with a strength of 8 GPa and Weibull

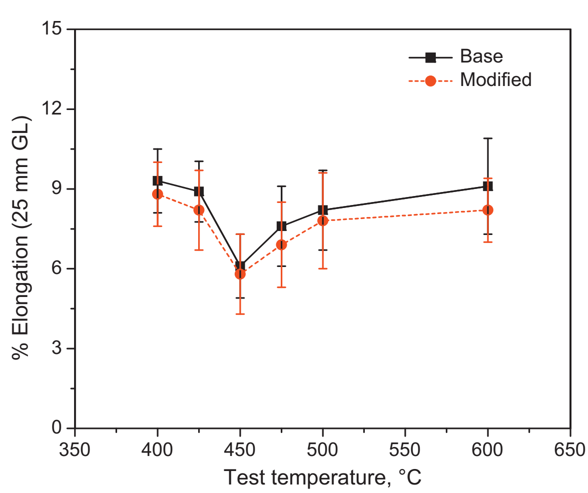

Fig. 6. Variation of ductility with test temperatures.

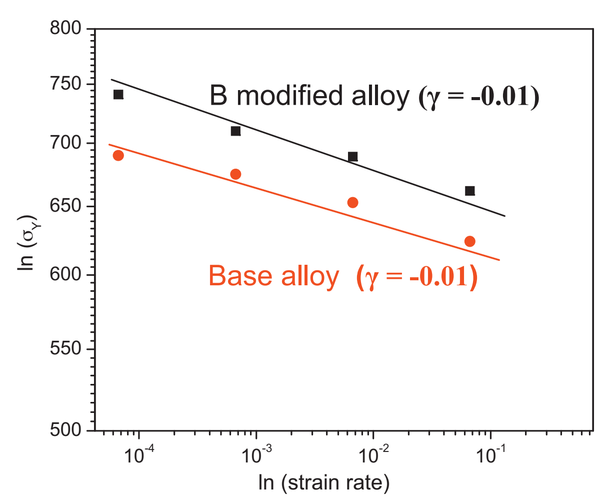

Fig. 7. Variation of yield strength with strain rate showing negative strain rate sensitivity (γ) at 450 °C.

Table 5
Predicted UTS (σ_{UTS}) for B modified alloy using load sharing model (Eq. (1)).

Test temperature (°C)	$\rho_0 = (r \times \sigma_C)/(L \times \tau_C)$	$\xi(\bar{\rho}_0, m)$	$\sigma_m(\varepsilon_{UTS})$ (MPa)	$\sigma_{UTS} = f\sigma_C\xi(\bar{\rho}_0, m) + (1 - f)\sigma_m(\varepsilon_{UTS})$ (MPa)	Experimentally obtained σ_{UTS} (MPa)
400	1.69	0.384	860	893	917
425	1.73	0.379	837	870	901
450	1.74	0.378	835	867	896
475	1.76	0.376	834	856	887
500	1.79	0.372	802	834	870
600	2.03	0.346	712	742	753

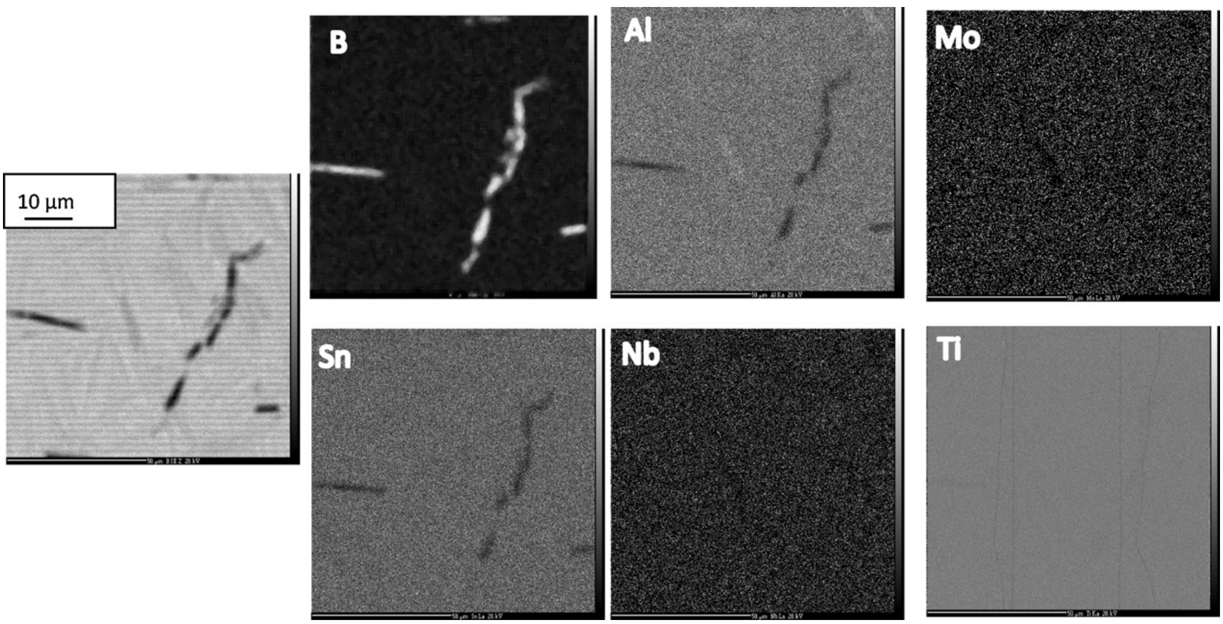

Fig. 8. Elemental mapping of boron modified Timetal 834 around TiB precipitates.

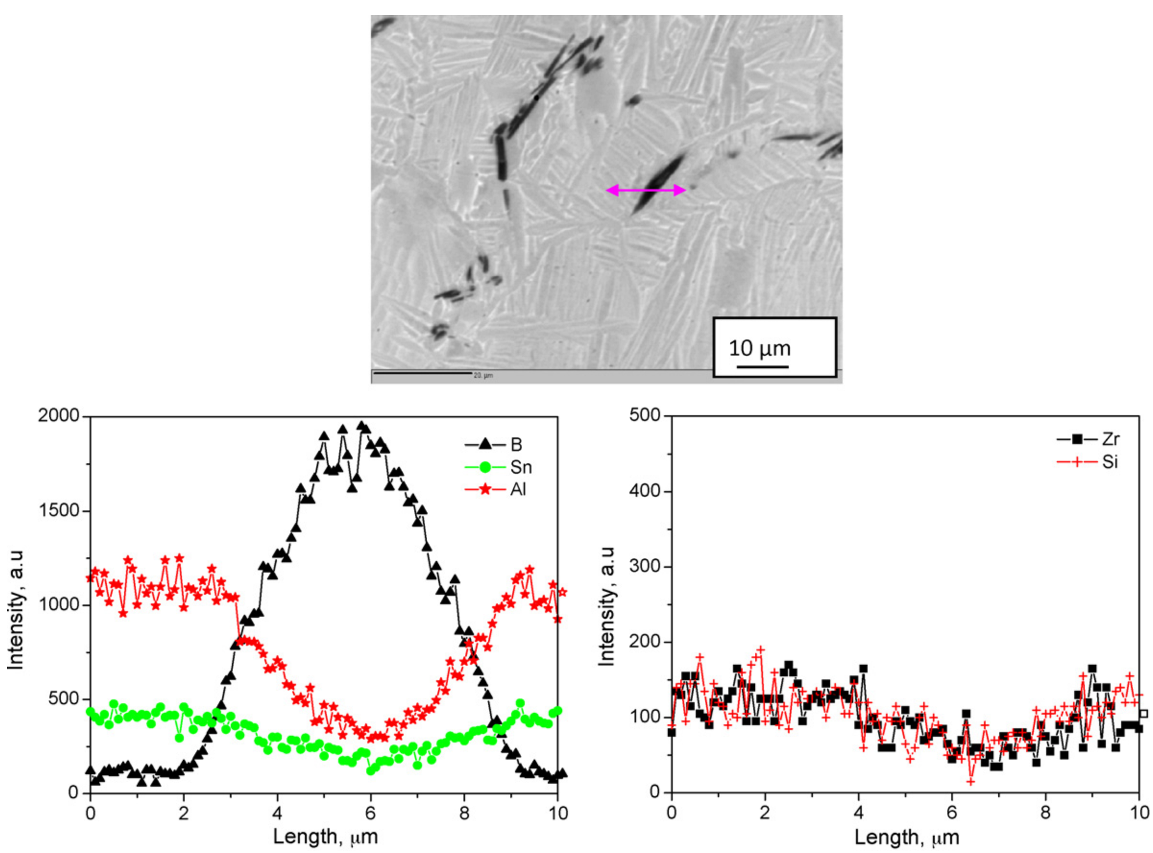

Fig. 9. Line profile compositional analysis of modified Timetal 834 along TiB precipitate.

modulus of 2 is ~0.5. In the present study, the ρ_0 in all cases is >1.0 (see Table 5) and hence the obtained ductility is also consistent with the prediction of the above model.

4.2. Dynamic strain aging

As mentioned earlier, the B modified alloy also exhibits DSA like the base alloy by showing the various manifestations of DSA [14] (appearance of serrations in stress–strain curves, temperature insensitivity of strength values, minima in ductility and negative strain rate sensitivity). Interestingly, the temperature range in which DSA is observed is also same for both which indicates that B plays no role in DSA in this alloy. Elemental distribution map of B modified alloy along TiB precipitate is shown in Fig. 8. It is clear from Fig. 8 that nearly entire boron has been precipitated in form of TiB whiskers. This is further confirmed by the compositional line profile of boron across different phases as shown in Fig. 9. Thus the EPMA analysis confirms that there is a very small amount of boron, if any, in the solid solution of B modified Timetal 834 alloy. This is also supported by the earlier studies [23,24] which shows that B has very low solubility (<0.02%) under equilibrium conditions. In the present study, the observation of no effect of B on DSA in B modified Timetal 834 alloy can be attributed to the absence of B in solid solution.

The cause of DSA in Timetal 834 near α Titanium alloy has not been yet established clearly. In recent past, it has been suggested that the presence of Silicon (Si) increases the strength of DSA in Timetal 834 near α titanium alloy [25] which is mainly caused due to interstitial solute atoms [15,26,27]. Ramchandra et al. [28] has also reported the enhancement of DSA in Timetal 685 titanium alloy due to Si as a substitutional solute atom. The author has reported [15] that during the evolution of near α titanium alloy from Timetal 679 to Timetal 834, the percentage of silicon has been increased to optimize the high temperature mechanical properties. Since, Si atom is 21% smaller than titanium atom and produces considerable strain in the crystal lattice [29], this may lead to the enhancement of DSA, which is mainly caused by interstitials through the mechanism proposed by Winstone [26] and Sasano [27]. Winstone [26] has reported that in a perfect hexagonal crystal the interstitial atom introduces a spherical distortion, which can only interact strongly with the edge components, and hence the effect of dynamic strain aging is weak. If small silicon atoms are introduced into the crystal, close to the interstitials, the interstitial site loses its symmetry and a shear component is introduced into the distortion, which may interact with the screw component and therefore increase the strength of strain aging.

5. Conclusions

Tensile properties (0.2% YS, UTS, elongation to failure) of base and B modified Timetal 834 alloy were evaluated and compared in the intermediate temperature range between 400 °C and 500 °C and can be summarized as:

1. The B modified alloy shows higher strength (0.2% YS, UTS) and only a marginally lower elongation to failure as compared to base alloy at all the temperatures investigated. The strength was estimated on the basis of the load sharing model proposed by Curtin and Zhou [21] and modified by Boehlert et al. [22].
2. The B modified alloy shows dynamic strain aging in the same temperature range as that exhibited by the base alloy.

Acknowledgements

The authors would like to acknowledge Dr. G. Malakondaiah, DMRL for his encouragement and guidance in this research activity. The authors also thank Mr. A. Sambasiva Rao for the help with the EPMA. The authors are grateful to Defence Research and Development Organization for providing the funding and facilities to carry out this work.

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