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Welding Studies on a Near-alpha Titanium Alloy

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ABSTRACT

The mechanical properties and microstructures of electron beam and friction welds of a near-alpha titanium alloy IMI 834 (presently TIMET 834) have been evaluated. Electron beam welds that contain micro pores and friction welds are free from such solidification-related defects. Porosity index in electron beam welds shows a decreasing trend with an increase in the welding speed. Electron beam welds contain coarse prior β grains and fine transformed β microstructure while, friction welds contain fine prior β grains and coarse transformed β microstructure. Electron beam welds with fine transformed β microstructure exhibited higher strength as compared to friction welds with coarse transformed β microstructure. The impact toughness of both the welds is comparable. Drastic reduction in impact toughness was observed when the welds were subjected to post-weld ageing as a result of inter-lath precipitation. Coarse-grained electron beam welds exhibited better creep and stress rupture properties as compared to friction welds.

Keywords: Electron beam weld, friction weld, mechanical and metallurgical properties

1. INTRODUCTION

Titanium and its alloys are characterised by their moderate strength, light weight, and outstanding corrosion resistance[1]. Titanium exhibits hexagonal crystal structure (α) at room temperature and undergoes allotropic transformation to body-centered cubic structure (β) at 882 °C. This temperature where transformation from α to β occurs, is called β transus. Hexagonal crystal structure is favourable in creep-critical applications owing to its low diffusivity. Addition of alloying elements can either stabilise α or β depending on the nature of the alloying element. By suitable additions of the alloys, the room temperature phase can be retained at high temperature, and similarly, high temperature phase can be retained at low temperature. The compositions of the alloys can be tailored to contain different proportions of α or β phases to meet different property requirements. The compositions of the alloys, that are employed in engineering applications, are tailored to meet specific application requirement and contain different proportions of α and β phases. Alloys that contain 2-3 per cent β phase are classified as near α alloys and these exhibit superior creep properties among all the titanium alloys. The microstructure of the titanium alloys can be manipulated by thermomechanical working and heat treatment. When near α and α + β titanium alloys with sufficient retained strain energy from the thermo mechanical working are heat treated below the β transus, a portion of α re-crystallises as equiaxed α and the remaining β undergoes transformation to acicular/lath α with retained β in between. Such bimodal microstructures exhibit best combination of creep, fatigue, and toughness properties[2]. For fruitful commercial exploitation, the alloy should exhibit wide heat treatment window over which the microstructure obtained does not show appreciable variation. Research in this direction led to the development of IMI 834 (presently TIMET 834), a-near-alpha titanium alloy that contains carbon as one of the alloying elements to widen the heat treatment window. IMI 834 was developed to meet the need for the high temperature, weldable, *Ti* alloy with improved creep strength, fatigue performance and fine defect-tolerant microstructure for compressor stage of jet engines, both as disc and as blade component[3-6].

Bimodal microstructure fulfills the need of optimum combination of properties at service temperature[7] of about 600 °C. The ideal microstructure is fine (β) grain size with high volume fraction of transformed β. IMI 834 is typically heat treated to give ~7.5 to 15.0 per cent volume fraction of primary equiaxed α phase in fine-grained lamellar transformed β matrix to meet optimum combination of properties[4,5]. Primary α volume fraction is controlled by heat treatment on the solution in the two-phase (α+β) region below the β transus and lamellar spacing (alternate layers of α and β) is governed by quenching rate[8].

Joining of *Ti*-alloys is mainly carried out by fusion welding processes like gas tungsten arc welding (GTAW), gas metal arc welding (GMAW), plasma arc welding, laser beam welding (LBW) and electron beam welding (EBW)[1]. Fusion welds of titanium are reported to be prone to gas-related microporosity[9-14] that have an adverse impact on fatigue properties[14,15]. Solid state welding processes like friction welding are reported to be free from such problems[14]. Keeping aforementioned in view, a comparative evaluation of electron beam welding and friction welding has been done.

2. EXPERIMENTAL METHOD

2.1 Parent Metal

Rods of 22 mm dia hot rolled in the sub-transus region were employed for friction welding studies. The material used for electron beam welding was 15 mm thick plate obtained

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by hot rolling at 1000 °C of forged billet of 30 mm thickness forged at 1000 °C. Major alloying elements in wt percentage of the material studied are *Al*-5.75, *Sn*-4.37, *Zr*-3.8, *Mo*-0.58 and *Si*-0.42. The β transus of the material was 1055 °C. The material in the as forged and rolled condition consists of un-stabilised microstructure. To stabilise the microstructure, the material was subjected to a solutionising treatment at 1020 °C/2 h/OQ followed by ageing at 700 °C/2 h/AC. After this heat treatment microstructure contains equiaxed primary α + transformed β. Heat treatments at different temperatures were carried out to have the optimum volume fraction of primary α (20-22 per cent), as shown in Fig.1.

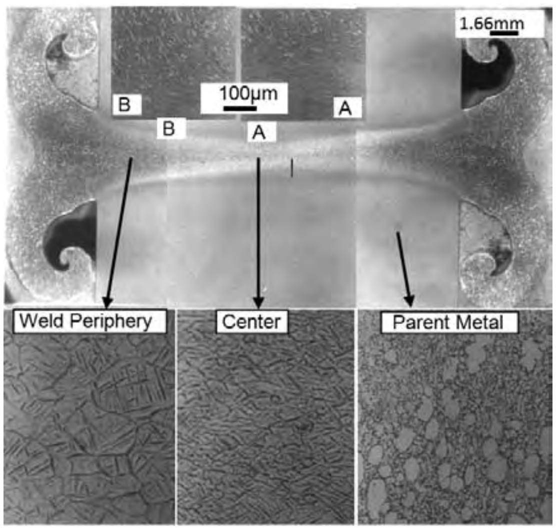

Figure 1. Microstructure of AR+AW of friction weld.

2.2 Welding

Friction welding was carried out in the atmosphere on a continuous-drive friction welding machine of 150 kN capacity at 10 mm burnoff (length loss) and at constant friction and forge forces of 7.9 kN and 38 kN, respectively, at 1200 rpm speed.

Electron beam welding was carried out on a low kV electron beam welding machine of 60 kV and 80 kW capacity of Technometa make. 15mm thick plates were butt-welded at a constant beam voltage of 55 KV and 105 mA beam current at three speeds namely, 0.75, 1.00 and 1.25 m/min.

Table 1. Heat treatment designations

Material	Heat Treatment	Designation*
Parent	1020 °C/2 h/OQ	STA (OQ)
Parent	1020 °C/2 h/OQ (Solution treatment) + 700 °C/2 h/AC(ageing treatment)	STA (AC)
Weld	Weld+700 °C/2 h/AC(ageing)	STA (OQ) PWA
Weld	Weld+700 °C/2 h/AC(ageing)	STA (AC) PWA

***Note:** ST- Solution treated, STA- solution treated and aged, PWA-post-weld aged, AC-air cooled, OQ-oil quenched, STA (OQ) PWA-parent metal in STA (OQ) + post-weld ageing of weld, STA (AC) PWA-parent metal in STA (AC) + post-weld ageing of weld

2.3 Heat Treatment

The parent metal was subjected to two types of heat treatments (Table 1) namely: (i) solution treatment at 1020 °C/2h and subjected to air cooling followed by ageing at 700 °C/2 h and air cooled [STA (AC)], (ii) solution treatment at 1020 °C/2 h and subjected to oil quenching followed by ageing at 700 °C and air cooled [STA (OQ)]. The welds were subjected to post-weld ageing only (PWA).

2.4 Metallography and Mechanical Properties

Macro and Microstructural examinations were carried out after conventional metallographic sample preparation. Microporosity measurement was carried out using optical microscope at a magnification of 100X. Pores were assumed to be spherical for carrying out required calculations. Porosity was quantified by size of the pores, number of pores per unit area and area fraction of the pores[10, 12, 15], (Table 2). The welds were examined by TEM to investigate the microstructural changes that occured during STA and ageing treatments. Notch tensile testing was carried out as plain tensile specimens failed outside the weld[16]. Testing was performed employing standard specimen configurations with gauge length of 25 mm and notch located at weld centre. In the case of welds the observations on NTS are based on one test. Charpy V notch specimen of 10 mm x 10 mm x 55 mm were employed with the notch located at the weld centre. Impact test observations are based on at least two test specimens. Testing was carried out at room temperature.

Creep and stress rupture tests were performed at constant load with a single arm ratio of 50:1. Creep test was conducted at a stress of 150 MPa at 600 °C while stress rupture was carried out at a stress of 220 MPa and at a temperature of 650 °C. In creep test the percentage creep strain was recorded for 100 h as well as after fracture of the specimen. In stress rupture test, the time taken for fracture was obtained.

3. RESULTS

3.1 Friction Welding

3.1.1 Metallography

Weld bead configuration and microstructures of weld, deformed zone and parent metal regions are compared in Fig. 1. The weld region contains very fine prior β grains and transformed β structure with lath martensite. Prior β grain size is coarser in the peripheral region of the weld as a consequence of higher temperature that prevails in the peripheral region due to higher peripheral speed. More heat generation at the peripheral region results in the wedge shape of the weld. Adjacent to the weld primary equiaxed α experienced deformation that is predominant in the peripheral region possibly due to higher speed in that region (Fig.1). Post-weld ageing did not show any microstructure changes at optical level.

3.1.2 Mechanical Properties

The effect of starting parent metal processing history and post-weld heat treatments on notch tensile strength, impact toughness, creep and stress rupture properties are given in Table 3. Influence of cooling rate after solutionizing of the parent metal at 1020 °C on the mechanical properties of the welds forms part of the data provided in Table 3.

Table 2. Porosity parameters

Nomenclature	Definition	Designation
Size of pore	Diameter	D
Maximum size of pore	Diameter of largest pore	$D_{max.}$
Average pore area	Sum of the areas of pores/number of pores	$(A_p / N)=A_{av}$
Porosity index	Area of pores/observed area (A_p/A_0)	P
Number of pores/unit area	Number/area observed	N/A_0

Notch Tensile Strength : Notch tensile strength (NTS) of the welds in the as welded condition matches with that of the parent metal in solution treated and aged condition (Table 3). Post-weld ageing led to reduction in NTS. Fractograhic examination revealed that, the fracture was ductile in the as welded condition and PWA resulted in cleavage like fracture [Figs 2(a) and 2(b)].

Impact Toughness: In the as-welded condition, the impact toughness was about 12 J. Post-weld ageing treatment resulted in drastic reduction in toughness to as low as 6 J. Fracture features changed from ductile in the as-welded condition to cleavage like appearance after PWHT [Figs 2(c) and 2(d)]. In the as-welded condition, shear lips were evident and the same were absent in post-weld aged condition. This difference in the behaviour is possibly due to ductility reduction as a result of ageing.

Creep and Stress Ruptures: Creep and stress rupture properties improved when the welds were subjected to ageing treatment. It was observed that welds of air-cooled parent metal after solution treatment [STA (AC)] resulted in better creep and stress rupture properties as compared to that after oil quenching [STA (OQ)] (Table 3). Cooling rate effects on creep properties are as per trends reported in near-alpha[17] and $\alpha + \beta$ titanium alloys[15].

3.2 Electron Beam Welding

3.2.1 Metallography

From the microstructures shown in Fig. 3, it was found that the welds contain microspores. The occurrence of these pores is predominant in the root portion of the weld. The weld microstructure consisted of lath martensite.

Influence of welding speed on porosity in welds has been presented in Fig. 4. Size of pores, average area of pores, and number of pores were found to be maximum at intermediate welding speed and low at both lower and higher welding speeds. Porosity index was found to decrease with increase in the welding speed.

3.2.2 Mechanical Properties

The influence of prior processing history of the parent metal, welding speed, and post-weld ageing on the mechanical properties of electron beam welds is presented in Table 4.

Notch Tensile Strength : In general, the tensile strength was marginally higher at high welding speeds. Post-weld ageing of low-speed welds led to reduction in strength while an increase in the strength was observed in respect of high-speed welds. Fracture features were ductile in the as-welded condition while, brittle fracture was observed after PWA [Figs 5(a) and 5(b)]. Welding speed showed marginal influence on fracture behaviour.

Impact Toughness: Speed of welding did not exhibit noticeable influence on impact toughness in the as-welded condition except that large scatter was noticed at the highest speed. This could be due to possible defective notch preparation. However, PWA resulted in drop in impact toughness (Table 4). The failure mode changed from ductile in the as-welded condition to brittle after post-weld ageing [Figs 5(c) and 5(d)]. Shear lips, an indication of ductility, were found in the as-welded condition and the same were absent in post-weld aged condition. Welding speed exhibited very little influence on fracture features.

Creep and Stress Rupture: From Table 4, it is seen that creep strains are low at higher welding speeds in the as-welded condition. Post-weld ageing results in a reverse trend, possibly due to higher propensity of precipitation during ageing of the

Table 3. Mechanical properties of parent material and friction-welded joint

Parent materials condition	Condition of testing	Impact toughness (J)	NTS (MPa)	Creep 600 °C/150 MPa			Stress rupture life 650 °C/ 220 MPa (h)
				100 h Strain (%)	Life (h)	Strain to fracture (%)	
STA (OQ)	Without welding	7, 8, 8	1502	0.20-0.26	-	-	84-85
STA (OQ)	AW	12, 12, 13	1506	0.361	140 h	0.455	14.9
STA (OQ)	Post-weld aged	6, 6, 6	1386	0.35	160 h	0.498 (Test interrupted)	18.8
STA (AC)	Post-weld aged	-	-	0.32	212.2 h	0.503 (Test interrupted)	19.1

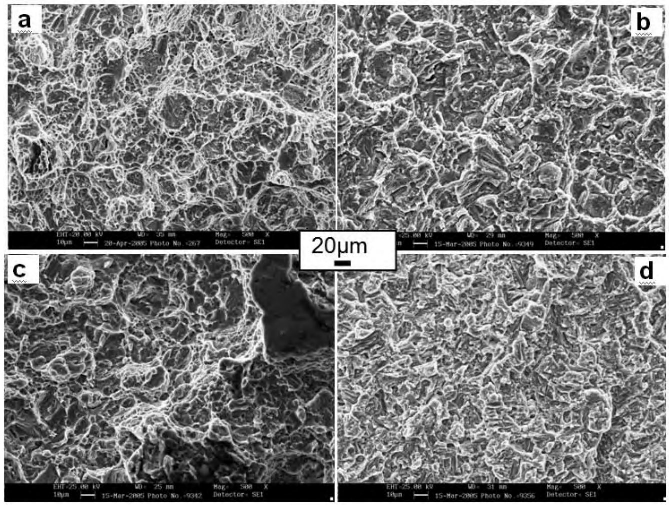

Figure 2. Fractographs of friction welds (a) STA (OQ) +AW notch tensile, (b) STA (OQ) +PWA notch tensile, (c) STA (OQ) +AW impact toughness, and (d) STA (OQ) +PWA impact toughness.

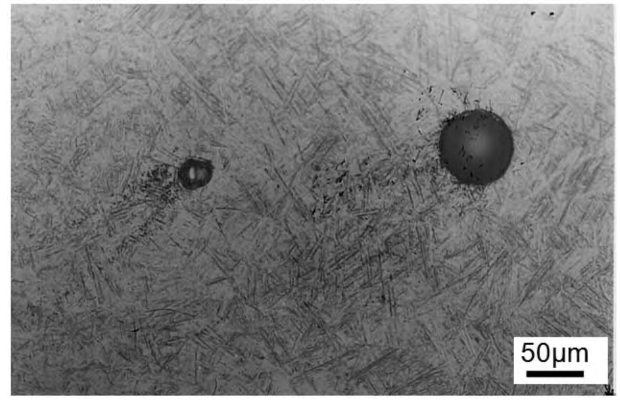

Figure 3. Microstructure of electron beam-welded joint showing micro porosity.

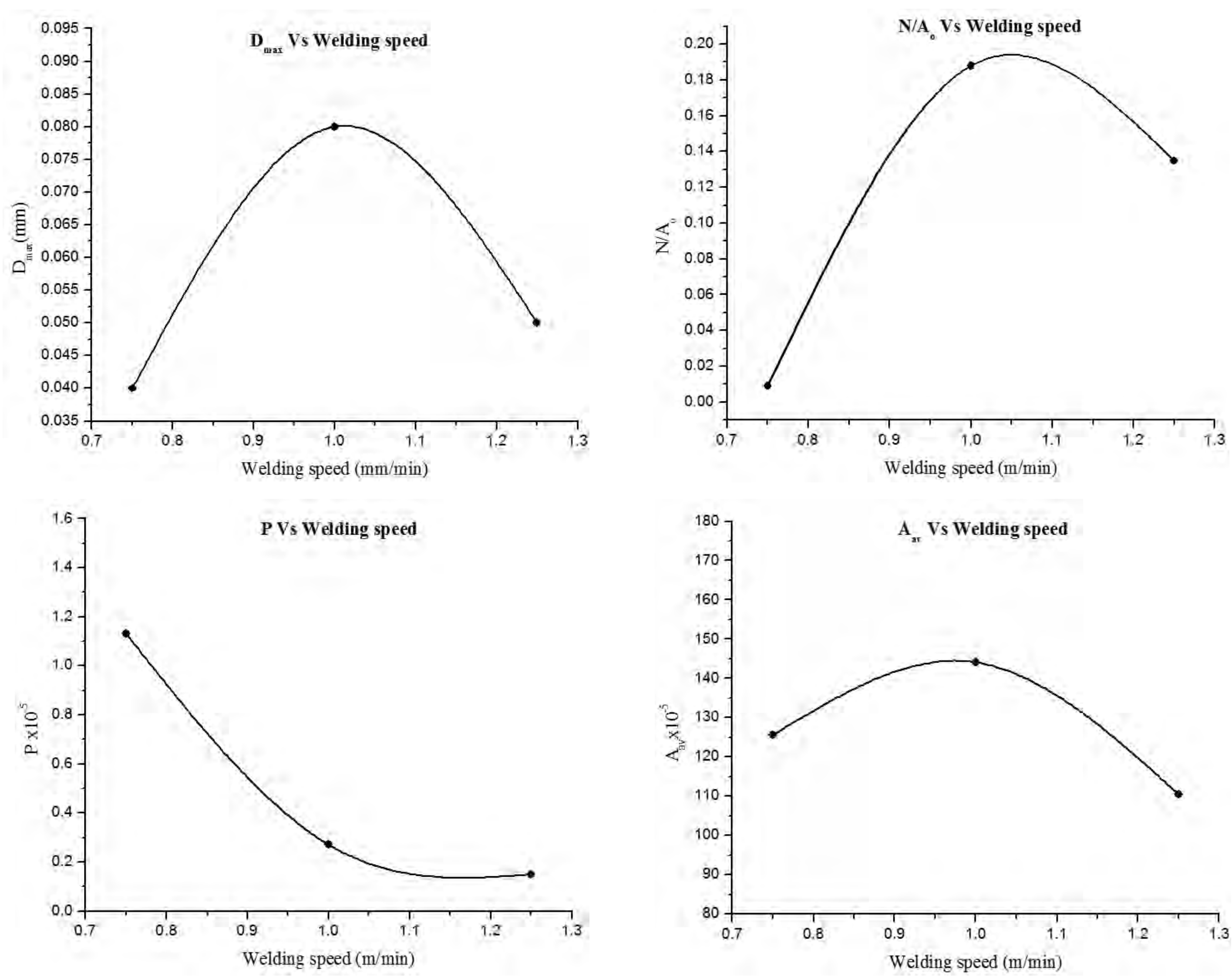

Figure 4. Effect of welding speed on porosity parameters of electron beam-welded joints.

Table 4. Mechanical properties of electron beam welds

Parent material condition	Heat treatment condition	Welding speed m/min	Impact toughness (J)	NTS (MPa)	100 h Creep strain (%)	Creep life (h)	Stress rupture life (h)
STA (OQ)	AW	0.75	10,13	1611	0.24,0.256	140,160	23.5,43.8
		1.00	10,12	1638	-		-
		1.25	06,14	1674	0.137-0.15	140,160	19.2,24.9
STA (OQ)	PWA	0.75	04-06	971	0.173,0.222	-	20.5,29.6 -
		1.25	06,07	1455	0.202,0.248	-	22.2,25.2 -

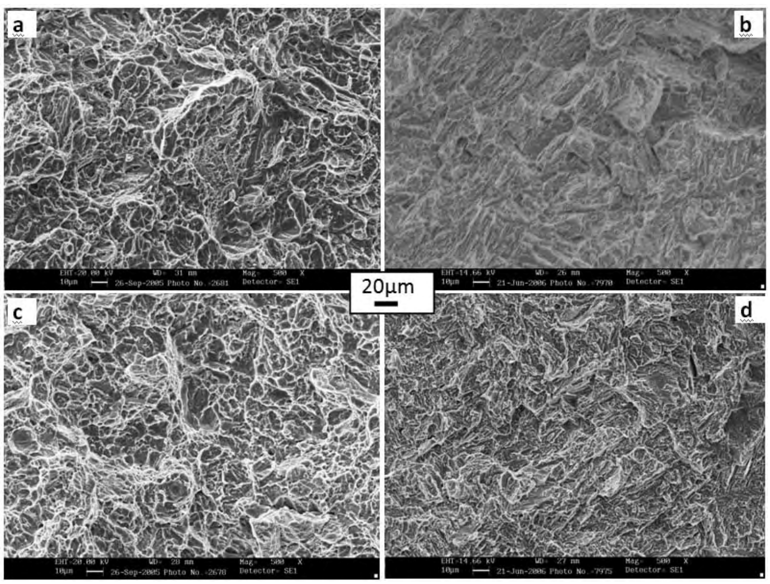

Figure 5. Fractographs of electron beam welded a) STA (OQ) +AW Notch tensile, (b) STA (OQ) +PWA Notch tensile, (c) STA (OQ) +AW Impact toughness, and (d) STA (OQ) +PWA Impact toughness.

high speed welds due to greater meta-stable nature of these welds as a consequence of higher cooling rate at higher welding speeds. It was found that welds in general exhibited nearly similar stress rupture life in the as-welded and post-weld aged conditions excepting scatter in low-speed welds in the as-welded condition.

4. DISCUSSION

Friction welds contain very fine prior β grains not achievable by any conventional welding as well as thermo-mechanical processing and heat treatments. These welds are free from solidification-related defects such as microporosity. The fine β grain size coupled with freedom from micro porosity is likely to impart better fatigue properties as has been reported in some of the near-alpha and α + β alloys[13,15] as compared to electron beam welds.

A comparison of mechanical properties of electron beam and friction welds is given in Table 5. The notch tensile strength of electron beam welds is higher than friction welds. Post-weld ageing leads to reduction in strength values. The higher strength of electron beam welds could be due to the fine transformed β microstructure of electron beam welds. Another possibility for the lower strength of friction weld is the aligned microstructure in friction welds due to unidirectional flow of the material.

Impact toughness of electron beam and friction welds are comparable taking into account the scatter that can be expected in impact properties. Post-weld ageing has resulted in drastic reduction in impact toughness and the same is reflected in brittle fracture features (Fig. 2). This behaviour is attributed to possible aligned micro precipitation of β[15,18-20] coupled with silicides along the martensite lath boundaries[15] as reported in some of the titanium alloys and observed in this study [Figs 6(a) and 6(b)] These precipitates undergo coarsening after ageing treatment. Reduction in impact toughness is more pronounced than that in notch tensile strength. The parent metal in the bi-modal microstructure, when subjected to ageing, does not results in such drastic reduction in impact toughness as that observed in welds. This difference in the behaviour could be attributed to the difference in the microstructure of the two in that, base metal contains bi-modal microstructure (Fig. 1) while, welds contain transformed β structure comprising acicular /lath α (Fig. 1 and Fig. 3). In the event of precipitation along the lath interfaces, such a microstructure is likely to provide easy crack path as was evident from tortuous crack path before ageing and straight crack path after ageing. In general the low toughness of welds is in conformity with the low toughness of the parent metal[6] as it contains α stabilizers to a maximum permissible limit and such compositions exhibit low toughness[21].

Friction welds exhibit lower creep and stress rupture properties in the as-welded and post-weld aged condition as compared to electron beam welds.

In electron beam welding porosity index (P) decreases with an increase in the welding speed, while all other porosity parameters exhibit maximum values at intermediate welding speeds and a decreasing trend at low as well as high welding speeds. These trends are in conformity with those reported in

Table 5. Comparison of properties of friction and electron beam welds

Property	Condition	Friction weld	Electron beam weld
NTS (MPa)	AW	1506	1567-1674
	PWA	1386	1455-1620
Impact Toughness (J)	AW	12-14	10-14
	PWA	6	4-7
Creep (100 h % strain)	AW	0.361	0.137-0.256
	STA(AC)PWA	0.32	-
	STA (OQ)PWA	0.35	0.173-0.248
Stress rupture life (h)	AW	18.8	19.2 – 43.8
	STA(AC)PWA	19	22-25
	STA (OQ)PWA	14.9	-

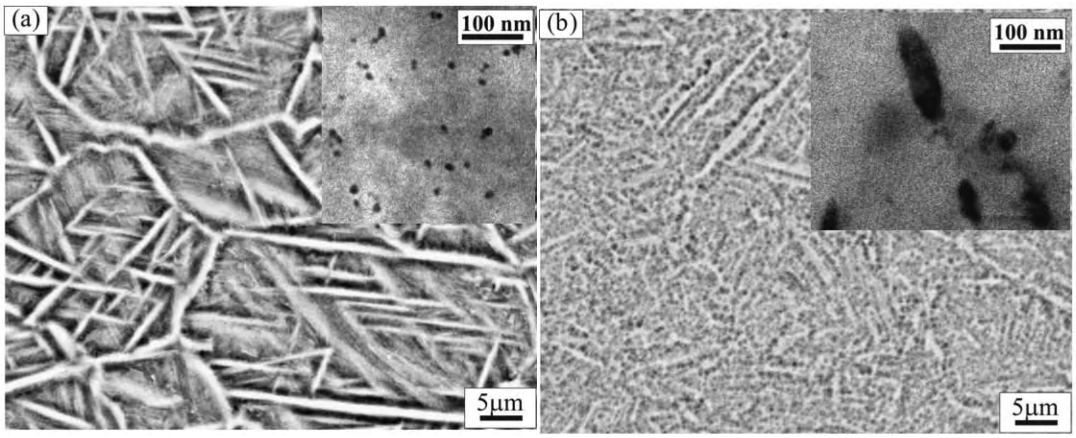

Figure 6. SEM, BSE : (a) As-welded friction welds (b) post-weld aged friction weld showing formation of precipitates along the lathe boundaries.

other titanium alloys[13, 17]. A decrease in the porosity index with an increase in the speed could be due to very little time available for porosity nucleation as a consequence of high cooling rates at high welding speeds. Welding speed has a marginal influence on the mechanical properties of electron beam welds.

5. CONCLUSION

A comparative evaluation of friction welds and electron beam welds has been carried out. Friction welds contain very fine prior β grain size and are free from porosity. In electron beam welding, porosity index decreased with an increase in the welding speed. Electron beam welds exhibited better notch tensile strength; creep, and stress rupture properties as compared to friction welds due to finer transformed β structure and coarser prior β grain size. Post-weld ageing of the welds deteriorated the impact toughness possibly due to aligned micro precipitation of β grains in conjunction with silicides along martensite lath boundaries.

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