IMPACT TOUGHNESS OF ELECTRON BEAM WELDS OF INDIGENOUSLY DEVELOPED Ti6Al4V (ELI GRADE)

By
Ch. Radhakrishna
Defence Metallurgical Research Laboratory, Hyderabad
and
K. Prasad Rao
Indian Institute of Technology, Madras.

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INTRODUCTION

When section thickness, increases more than 5mm, high energy density process like Electron Beam Welding (EBW) is advantageous than conventional Gas Tungsten Arc Welding (GTAW). The inherent vacuum conditions of EBW process make welding of Ti6Al4V more appropriate. However, it is generally observed that certain alpha/beta alloy of titanium welds made by EBW tend to exhibit lower values of toughness compared to their base metal counterparts (1) which is attributed to the alpha prime martensitic structure formed due to higher weld cooling rates.

Slower weld cooling rates may reduce alpha prime content and may encourage nucleatron and growth of alpha phase. In order to attain equilibrium phase composition, post weld heat treatments are tried on Ti6Al4V welds. Several temperatures and techniques have been reported like duplex, triplex heat treatments. There is no optimum heat treatment suggested to improve the toughness of Ti6Al4V welds in general and EB welds in particular. Attempts have also been made (2) to use in-situ PWHT using defocused electron beam. Not many studies are available on the effect of the techniques like bead-over-bead (to reduce weld cooling rate) and in-situ post weld heat treatment using defocused beam and also different post weld heat treatments on the impact toughness of Ti6Al4V (ELI) EB weld metals. Therefore, a study has been taken up in this regard and results of the same are presented and discussed. The study becomes all the more important because the Ti6Al4V studied was indigenously produced at MIDHANI, Hyderabad.

Experimental

12mm thick hot rolled and annealed plate of Ti6Al4V (ELI grade) was used in the present study. (Chemical composition (%wt) Al - 6.7%; V-4.4%; 0-827 ppm; N — 84 ppm; H-34 ppm; C-0.01%; Fe-0.05%; Ti-Balance). Electron Beam welding (EBW) of the plates (100*60*12 mm) was carried out using Hawker Siddeley Dynamics Ltd, U.K. (Torvac/Wentage) make machine at DRDL, Hyderabad. No filler was used and full penetration welds were obtained (parameters - 130 KV, 95 MA, 143 cm/min). Two sets of samples were welded using these weld parameters.

1. Single Bead
2. Bead-over-Bead

(First bead or weld was made and immediately second weld was made over the same, remelting the first. The heat of the first weld made gave a preheating effect which reduces the weld cooling rate.)

In order to post weld heat treat in-situ, in the first set, defocused electron beam was traversed several times (for 5 minutes) over the surface. The first set of weld coupons were subjected to different post weld heat treatments (PWHT) in a tubular furnace which are as follows.

(1) 1020°C/1hr/AC and FC (AC-Air Cooled and FC-Furnace Cooled)

(2) 930°C/3hr/AC and FC

(3) 930°C/1hr/AC and FC

(4) 850°C/1hr/AC and FC

(5) 700°C/1hr/AC

(6) 850°C/1hr/WQ + 550°C/3hr/AC (STA1)

(7) 930°C/1hr/WQ + 550°C/3hr/AC (STA2)

(8) 550°C/3hr/AC.

Titanium welds were coated with high temperature antioxidation coatings prior to PWHT. To ensure further freedom from contamination, samples were machined to 10mm from 12mm. Optical metallography was carried out after etching with Kroll's reagent. Transmission Electron Microscope (TEM) (Philips CM 12-120 KV) was used to study the samples which were jet polished (using Fischione twin jet electro polisher machine) at -40°C, using 92% Ethyl alcohol and 8% sulfuric

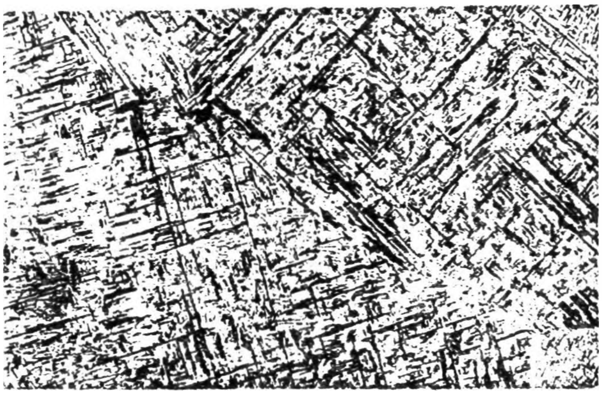

Fig. 1a : As-weld microstructure (Optical) 200 X

Fig. 1b : As-weld microstructure (TEM) 9000X

acid. X-ray diffration analysis was done using Cu K_{alpha} radiation with nickel filter. Charpy specimens were prepared as per ASTM standard E-23. Instrumented charpy impact testing was carried out using Wolpert, German make machine. Vickers macro hardness measurements were taken using a load of 20 Kg. Hardness value is taken as criterion to compare the strength of weld metals. Fractured specimens were subjected to Scanning Electron Microscopical examination.

RESULTS AND DISCUSSION

Microstructures

As weld microstructure basically contained alpha prime martensitic structure, (**Fig. 1a** (optical) **1b** (TEM)). Though insitu PWHT did not show any appreciable change in the optical microstructure, it did show significant precipitation in TEM micrographs (**Fig.2**)

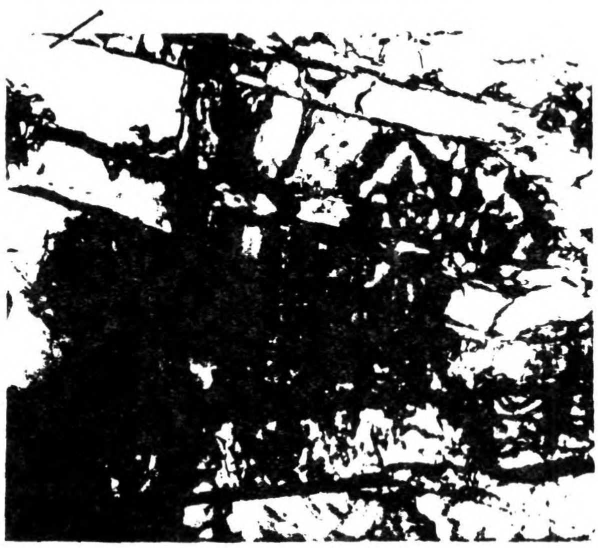

Fig. 2 : In-situ PWHT weld metal (TEM) 19000X

As for weld metals exposed to temperatures just above beta transfer (1020°C), the general feature was that of nucleatron of continuous grain boundary alpha. It was thin in the case of air cooled specimen and quite coarser in the case furnace cooled specimen. (**Fig. 3, 4**).

In weld metals exposed to 930°C (temperature below beta transus), the morphology of alpha changed quite significantly and it depended on temperature, time and cooling rate. Furnace Cooling after 1hr or 3hr exposure at 930°C resulted in continuous grain boundary alpha which was very coarse, where as air cooling resulted in discontinuous and relatively thinner grain boundary alpha. TEM mirograph of Furnace cooled sample showed precipitation of beta in between coarser alpha

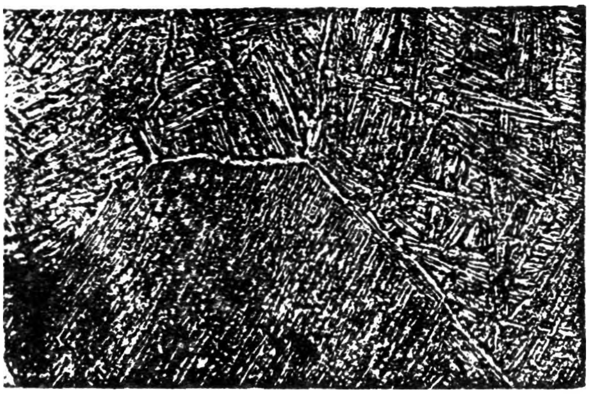

Fig. 3 : Weld metal PWHT, 1020°C, air cooled (optical) 599X

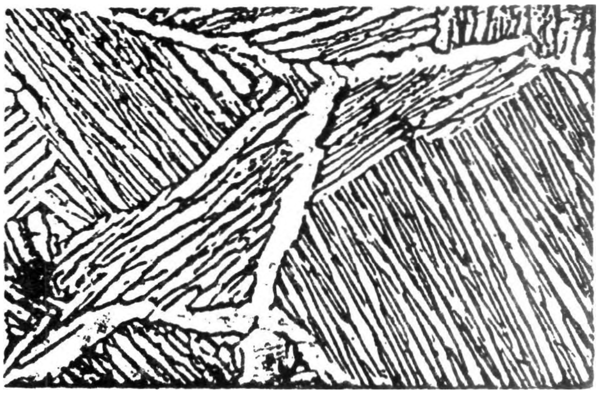

Fig. 4 : Weld metal PWHT, 1020°C, furnace cooled (optical) 500X

plates (**Fig.5**) which was confirmed by X-ray diffraction results. Ageing after solutionising treatment at 930°C did not change the optical metallography of samples significantly.

Impact Toughness

Impact Toughness results are presented in the following order.

(1) Effect of welding temperature.

(2) Effect of PWHT temperature.

(3) Effect of cooling rate.

(4) Effect PWHT time at a particular temperature.

(5) Effect of direct ageing and soultion Treatment and Ageing (STA).

Fig. 5 : Weld metal PWHT, 930°C, 3hr, furnace cooled (TEM) 9000X

1 Effect of Welding Techniques (Table 1)

(a) Bead Over Bead (BOB)

(b) In-situ local PWHT using defocused electron beam (IHT)

It can be observed that the two pass BOB technique has significantly improved the as-weld RT weld metal toughness from 24 Joules to 33 Joules, close (85%) to that of base metal toughness (38 Joules). WM toughness with IHT technique is almost equal to as-weld toughness and there is no change. **Fig.6** which shows finer dimples indicates its high toughness. **Fig.7** which is a fractograph of insitu PWHT weld metal indicates steps and flatness indicating its relatively less ductile features.

Table 2 shows the effect of above techniques on WM macrohardness. It can be seen that the as-weld hardness is higher by about 25 VHN compared to base metal. BOB and IHT techniques have not resulted in reduction in hardness. Hence for applications which require combination of strength and toughness BOB technique is effective.

Table 1 : Impact Toughness Values, (Joules) of Weld Metals[1]														
Sl. No.	Time at Temp. hr.	As Weld Single bead	Post weld heat treatment											
			Bead-over bead	In-situ	1020°C		930°C		850°C		700°C	550°C	STA1(4)	STA2(5)
					AC(2)	FC(3)	AC	FC	AC	FC	AC	AC		
1.	0	24	33	22	-	-	-	-	-	-	-	-	-	-
2.	1	-	-	-	30	29	38	25	23	17	19	-	-	-
3.	3	-	-	-	-	-	23	27	-	-	-	22	16	13

2. *Effect of* PWHT Temperature (Table 1)

PWHT conditions :

(a) As-Welded + 700°C/1h/AC (typical stress relieving in the alpha-beta field).

(b) As-welded + 850°C/1h/AC (solutionising in alpha-beta field)

(c) As-welded + 930°C/1h/AC (solutionising in alpha-beta field)

(d) As-welded + 1020°C/1h/AC (beta field)

It can be observed that solutionising PWHT at 700°C has resulted in marginal reduction in the RT weld metal impact toughness compared to AW toughness. Of all the above PWHTs, PWHT at 930°C has significantly increased the WM impact toughness and the WM toughness is equal to that of as-received BM (38 joules). PWHT at 850°C has neither resulted in degradation nor improvement in toughness of WM. PWHT in the beta field at 1020°C could partially help. (30 joules). Fractograph of 930°C PWHT weld metal showed dimples while lower temp. PWHT resulted in relatively less ductile features.

Table 2 shows the effect of PWHT temperature on WM peak hardness of EB welded Ti-6Al-4V. Welds heat treated at 700°C showed higher hardness (351) than the base metal, as-weld metal (340 VHN) and welds heat treated at 850°C (341 VHN), 930°C (312 VHN) & 1020°C (285 VHN). There is no marked change in the BM hardness with the above heat treatments. Therefore, for applications, where toughness and not strength is the criterion, PWHT at 930°C can be used.

3. Effect of Cooling rate (Table 1)

PWHT conditions :

(a) At 850°C - 850°C/1h/AC and 850°C/1h/FC

(b) At 930°C - 930°C/1h/AC and 930°C/1h/FC

(c) At 1020°C - 1020°C/1h/AC and 1020°C/1h/FC

Table 1 shows the effect of cooling rate (Air cooled-AC, Furnace cooled-FC) at various PWHT temperatures on RT WM impact toughness. The PWHT temperatures ranged from alpha-beta field (850°C & 930°C) to beta field (1020°C). It can be seen that, samples AC from temperatures in the alpha-beta field exhibited higher RT impact toughness than the

Table 2 : Macro Hardness Values VHN of Weld Metals[1]														
Sl. No.	Time at Temp. hr.	As Weld Single bead	Post weld heat treatment											
			Bead-over bead	In-situ	1020°C		930°C		850°C		700°C	550°C	STA1(4)	STA2(5)
					AC(2)	FC(3)	AC	FC	AC	FC	AC	AC		
1.	0	340	341	341	-	-	-	-	-	-	-	-	-	-
2.	1	-	-	-	285	285	312	312	341	341	351	-	-	-
3.	3	-	-	-	-	-	315	310	-	-	-	351	351	362

(1) Baser metal Toughness - 38J; Hardness - 315 VHN
(2) AC - Air Cooled, (3)FC - Furnace Cooled (4) STA1 - 850°C/1h/WG+550°C/3h/AC
(5) STA2 - 930°C / 1h / WQ+55°C / 3h/AC

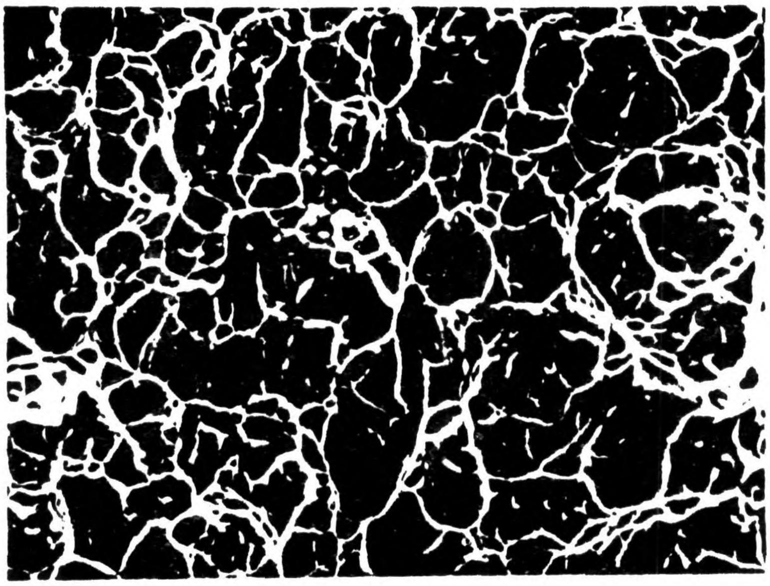

Fig. 6 : Base metal fractograph (SEM), 500X

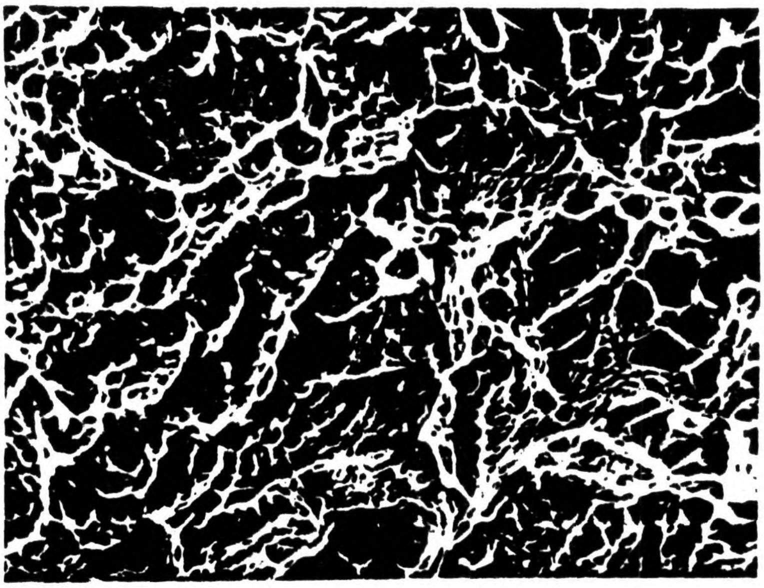

Fig. 7 : In-situ PWHT weld metal fractograph (SEM), 500X

FC samples. This degree of increase in toughness in the alpha-beta field increased with increase in temperature. In fact the increase is more pronounced at temperatures close to beta-transus. At 850°C AC resulted in WM toughness of 23 joules, while this got reduced to 17 joules with FC. Samples AC at 930°C exhibited 38 joules, while the weld metal toughness reduced to 25 joules for FC samples. The above trend of increase in RT WM toughness with AC compared to FC as evident in the alpha-beta field is not noticed for samples heat treated in the beta field at 1020°C. There is no effect of cooling rate above beta-transus and both AC & FC samples exhibited almost same RT impact toughness values. The trend noticed in toughness values, was not found in hardness values.

4. Effect of PWHT time at a particular temp (Table 1)

PWHT conditions :

(a) AC - 930°C/1h/AC and 930°C/3h/AC

(b) FC - 930°C1h/FC and 930°C/3h/AC

Increase of PWHT time at 930°C from 1hour to 3 hours with AC is not effective in improving the RT weld metal impact toughness and in fact degraded the toughness significantly. While the samples PWHT for 1 hour with AC could restore the toughness (38 joules) to that of BM, the increase of time from 1 hour to 3 hours has not resulted in any increase in the WM toughness compared to AW. However, there is an increase in toughness with FC at930°C when PWHT time is increased from 1 hour to 3 hours. The sample heat treated for 3 hours showed increase in toughness (28 joules) compared to sample heat treated for 1 hour (22 joules).

No significant change in WM hardness was observed with increase of time from 1 hour to 3 hours at 930°C and the WM hardness was comparable to that BM. No marked change in the BM hardness occured with increase of time from 1 hour to 3 hours with both AC & FC at 930°C.

5. **Effect of Direct Ageing and STA PWHT (Table 1)**

PWHT Conditions :

(a) As-welded + Direct ageing (550°C / 3h / AC)

(b) As-welded + (850°C / 1h / WQ + 550°C / 3h / AC) - STA1

(c) As-welded + (930°C / 1h / WQ + 550°C / 3h / AC) - STA2

It can be observed that the direct ageing treatment at 550°C has not resulted in any improvement in RT WM impact toughness compared to AW toughness. Both STA1 and STA2 PWHTs after welding have exhibited significantly lower WM toughness compared to AW toughness. Of the two heat treatments, solutionising at 930°C is more detrimental from the toughness point of view. The WM toughness reduced by about 36% as a result of 850°C solutionising, the reduction was almost half when solutionising was carried out at 930°C.

Table 2 shows the effect of direct ageing and two STA PWHTs on peak hardness of weld metals. The WM hardness of direct aged PWHT sample at 550°C is more compared to both as-weld and base metal, the difference being more with base metal. While base metal hardness was 315 VHN, the WM hardness after 550°C direct ageing PWHT has increased to 351 VHN. Both the STA PWHTs have increased the hardness of WM, the increase being more for the ST2A (930°C) PWHT and there was no difference between WM and BM hardness after PWHT. Hence direct ageing at 550°C PWHT should be used with caution if the as-received BM is in annealed condition. This is because of the fact that there is an improvement in strength with no degradation in WM toughness, the BM hardness/strength is unaffected by this PWHT. Due to this there is a large strength difference between WM and BM. However, this treatment may be effective if the as-received BM is in fully heat treated (i.e STA) condition since the difference in strength and toughness between WM and BM will be narrowed.

For applications which demand high strength and moderate toughness, STA PWHTs can be used. Low temperature solutionising treatments (850°C) in alpha-beta file are preferable as they result in trade-off between strength and toughness. Higher solutionising temperatures result in high strengths with reduced toughness. The BM can be welded in annealed condition and strengthened by suitable STA treatment after welding so that both WM and BM develop similar strength and toughness to the extent possible. However, if toughness is criterion, both the STA PWHTs are detrimental, as they result in lower toughness values at the expense of strength.

Overall, it can be noted that attempts by various PWHTs to improve toughness of weld metals will not, in general, go together with retaining their strength as obtained after welding. Even the PWHT which was attempted, in-situ, also proved to be not so effective in improving toughness of weld metal. Though PWHT at 930°C (AC), increased toughness of weld metal to significant level (almost close to that of base metal), the strength has been decreased. Attempts to increase Strength by direct aging at 550°C and solutionising (at 930°C or 850°C) followed by aging at 550°C, resulted in decrease of toughness. The beneficial effect appears to be stress relieving by exposing welds to such high temperatures. The very interesting feature of the present study is the beneficial effect noted by adopting bead-over-bead technique. It has shown both high ductility and strength and hence this technique is strongly recommended in the strength and of components made of Ti6Al4V. As mentioned earlier, the heat retained by the first pass, will reduce cooling rate of the final pass. Though X-Ray diffraction studies could not differentiate between beta and alpha prime phase, it is highly probable that some amount of beta would have resulted in the as weld metal structure because of relatively slow cooling rates. Imam et.al. (3) also suggest the same because the interplanar spacings in the two Structures would be nearly the same, and for each beta peak there is an alpha prime peak at essentially the same angle. Detailed TEM studies using Selected Area Diffraction techniques are necessary for further analysis. Analysis of microchemistry of these in the as weld and PWHT condition would also help in understanding the behaviour of these weld metals.

CONCLUSIONS

1. Bead-over-Bead technique was found to be the best in obtaining relatively tougher and stronger weld metals compared to all other techniques and PWHTs.
2. In-situ PWHT is found to be not useful in improving toughness.
3. PWHT at 930°C is ideal to get tougher weld metals but at the cost of Strength. Stress relieving will be an additional advantage.
4. Furnace cooling from below beta transsus temperatures deteriorates toughness, while air cooling is not.

5. Prolonged timings at a particular temp is not effective in improving weld metal toughness.

6. For applications where stress relieving combined with high strength and moderate toughness are the requirement, Solutionising followed by aging PWHTs can be used.

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