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Effect of Electron Beam Welding and Heat Treatment on the Structure and Properties of Technical Titanium with an Alloying Dope of Boron

Abstract: The study discussed in the article included the analysis of features characterising the formation of an electron beam-welded joint made of a titanium alloy (Ti–TiB). The study also involved the investigation of the effect of heat treatment on structural-phase transformations in the weld metal and in the heat affected zone. The heat treatment of the welded joints resulted in the decomposition of the metastable phase, the distribution of boron particles in the structure as well as the increase in the structural homogeneity, leading to the improvement of mechanical properties.

Key words: titanium alloys, titanium boron, electron beam welding, welded joint, heat treatment, structure, mechanical properties

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Introduction

The dispersive hardening of titanium alloys with intermetallic compounds is the most advanced, prospective and sufficiently tested method enabling an increase in the mechanical and high-temperature properties of the aforesaid alloys. In addition to well-known titanium aluminides (Ti_3Al and TiAl), the properties of titanium alloys can also be improved using refractory and thermodynamically stable titanium silicide (Ti_5Si_3; T_{melt} = 2120°C, ΔF = -147 kcal/mol) and titanium borides (TiB and TiB_2; T_{melt} = 2060°C, ΔF = -35 kcal/mol) [1]. For a long time boron has been used as a modifier enabling the refinement of casting structures [2]. In addition, boron (poorly soluble in titanium) forms high-strength and refractory precipitates joined with the titanium matrix and leading to the significant hardening of grains [3]. The foregoing has led to the increased interest in using boron as an alloying element in such alloys.

The majority of advanced titanium alloys are characterised by the complex system of alloying and by the presence of rare and expensive chemical elements. For this reason, the formation of economically alloyed materials has always been a relevant issue. Presently performed research works are focused on the analysis and identification of prospective economical alloying systems providing the necessary complex of physico-mechanical properties of titanium alloys using domestic resources. This study aimed to examine the effect of the electron beam welding and subsequent heat treatment on the structure and properties of economically alloyed Ti – TiB.

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Tests and results

The test alloys were obtained through the doping of technical titanium with boron using the electron beam-induced melting [4]. The use of boron as an alloying element led to the refinement of grains and the precipitation of the hardening phase of TiB in the form of bar-like crystals undergoing refinement during subsequent thermal-strain treatment [4-6] (Fig. 1).

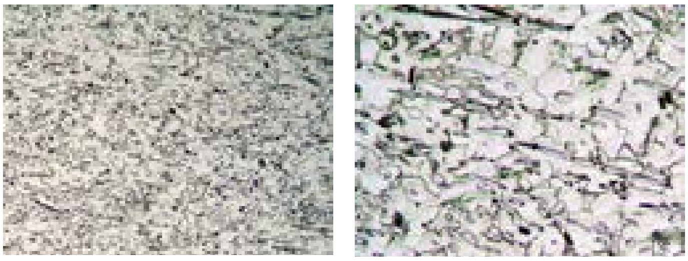


Fig. 1. Microstructure of the experimental specimen: a – 200x, b – 500x

The chemical composition (% by weight) of the test specimens was as follows:: Ti (base) – 0.112 Al – 1.11 B – 0.06 Cr – 0.20 Fe – 0.004 Nb – 0.003 Zr – 0.048 Ni – 0.004 V – 0.006 Sn.

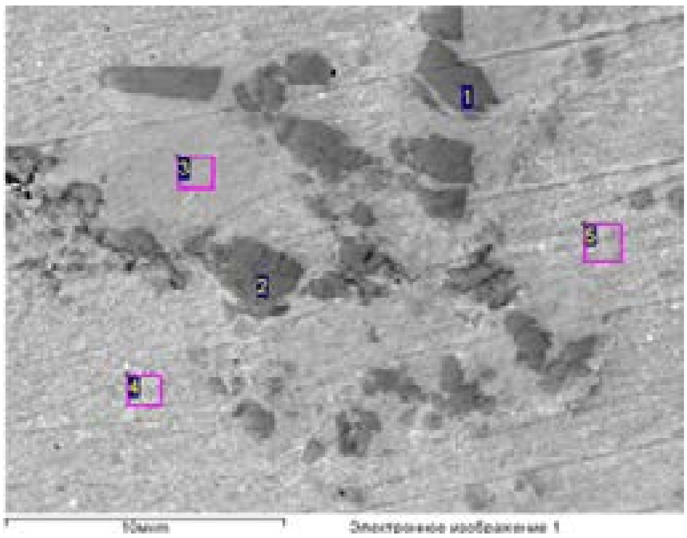
The results of X-ray phase analysis revealed the presence of two primary phases in the alloy, i.e. 89.15% of α-Ti and 10.85% of TiB. The energy dispersive spectrometry-based method (EDS) revealed that the matrix was composed of phase α grains and boron-enriched internal precipitates identifiable as titanium borides (TiB). The EDS analysis results are presented in Figure 2.

Technical titanium is known to be characterised by high plasticity and low strength. The results of the mechanical tests of the experimental specimens revealed that the doping with boron decreased plasticity and significantly increased mechanical properties. The test results concerning the mechanical properties of titanium alloys are presented in Table 1.

Table 1. Mechanical properties of the titanium alloys

Properties	Technical titanium [7]	Test specimen
Yield point $R_{0,2}$, MPa	500	631
Tensile strength R_m, MPa	560	812
Relative elongation A, %	25	11.8
Relative area reduction Z, %	55	15.2
Hardness, MPa	2000	3500

Electron beam welding is commonly used when making joints of titanium and its alloys. The locality and intensity of the process enable the obtainment of deep and narrow welds and narrow heat affected zones (HAZ). Before welding 9 mm thick specimens were preheated up to a temperature of 400°C and, next, welded using a UL-144 device provided with an ELA 60/60 welding power source. The welding process was performed in one run with full penetration. The welding process parameters were the following:



Spectrum	B	Ti	Fe	V
1	17.05	82.17	0.45	0.27
2	17.62	81.03	0.00	0.22
3	0.00	98.97	0.32	0.00
4	0.11	98.97	0.25	0.00
5	0.32	99.03	0.00	0.00

Fig. 2. Results of EDS-based analysis – analysis of the experimental specimen (% by weight)

- electron beam accelerating voltage – 60 kV;
- electron beam current – 90 mA;
- beam diameter on the joint surface – 2 mm;
- welding rate – 7 mm/s.

The observations of the welded joint performed using light and electron microscopy revealed that the weld contained the primary structure (Fig. 3a, b). Dendrites were not characterised by specific orientation in relation to the middle of the weld. Against the dendritic structure it was possible to notice small rounded inclusions, aciculae of phase α' and boride "chips" (Fig. 3c, d).

The dendritic structure was less clear closer to the HAZ. The HAZ structure (Fig. 4, a) contained grains of phase α, acicular phase α' and small rounded and fragmented inclusions. The areas closer to the base material (BM) revealed a greater amount of phase α and bar-like TiB crystals (Fig. 4, b).

The BM structure contained matrix grains of phase α, against the background of which it was possible to observe a significant amount of TiB borides both in the form of large and small (usually refined) bar-like crystals and as separate variously sized and shaped particles (Fig. 5).

It should be noted that in the BM, near the HAZ, where the amount of borides was lower, the volume of individual grains α revealed the presence of residues of acicular phase α' characterised by various etching degrees. Both in the BM and near the HAZ the borides were chip-shaped (Fig. 6).

The analysis of the EDS results revealed that, taking into

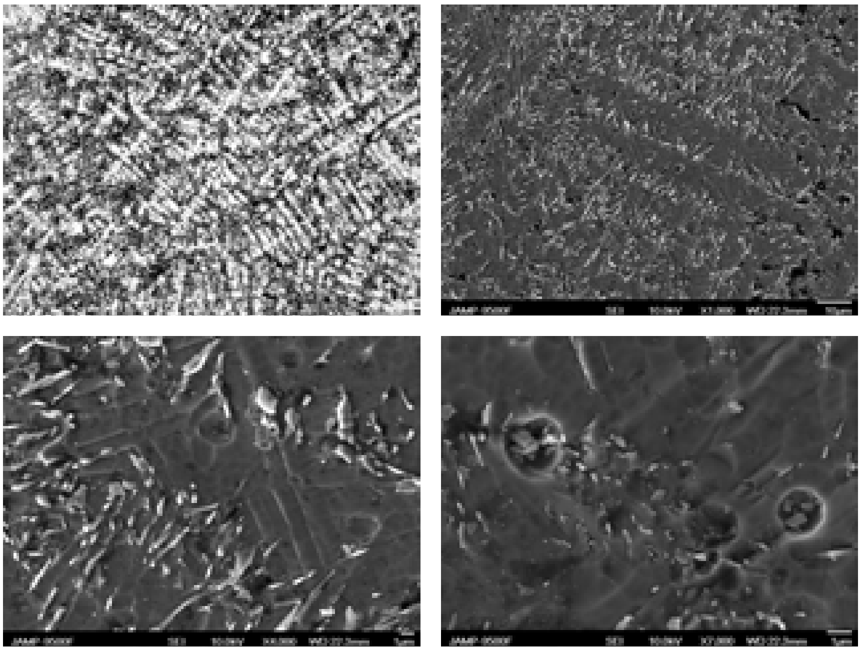


Fig. 3. Microstructure of the weld of test weld Ti-TiB: a – light microscopy (500x); b, c, d – electron microscopy (1000x, 4000x and 7000x)

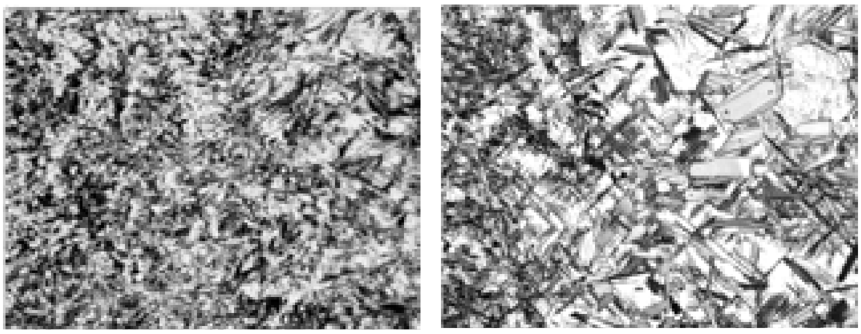


Fig. 4. Microstructure of the HAS and of the interface: a – SWC, b – HAZ – BM interface; (500x)

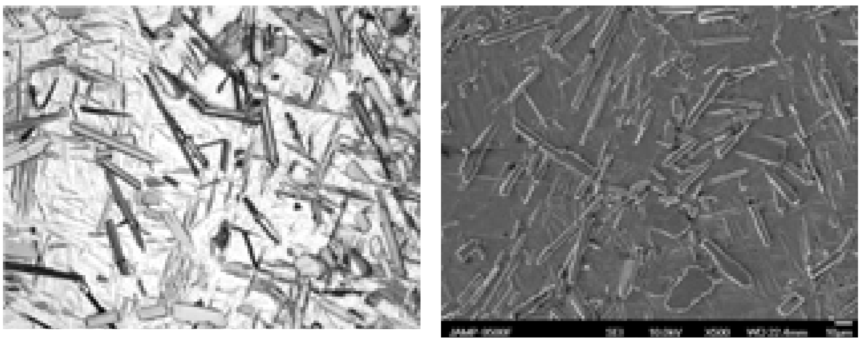


Fig. 5. Microstructure of the base material (BM): a – light microscopy (500x); b – electron microscopy (500x)

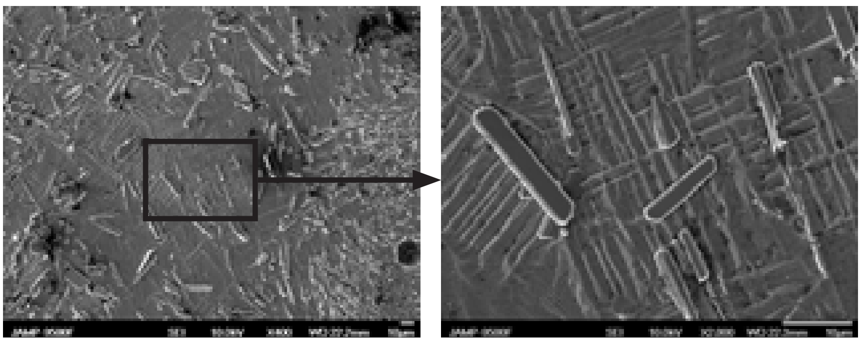


Fig. 6. Macrostructure of the BM–HAZ interface: a – 400x; b – 2000x

consideration its shape and composition, the acicular phase in the weld, HAZ and the BM zone adjacent to the HAZ could be identified as phase α' [7]. The small rounded and fragmented inclusions in the weld and in the HAZ were analysed as TiB (Fig. 7). The above-named location could be ascribed to the fact that borides refined as a result of high temperature-induced strain were arranged along the structure in the area heated during the welding process.

The analysis of the specimens subjected to the tests concerning strength and plastic properties revealed that during tension the rupture did not take place in the weld or HAZ (the weakest "points" of the welded joint) but in the base material. In view of the findings referred to in previous publication [5] it can be assumed that the distribution of small borides in the structure during welding led to the hardening of the welded joint. The mechanical test results are presented in Table 2.

To remove internal stresses generated during welding as well as to decompose the metastable phase, to equalise the composition and to obtain the optimum technological properties, the specimens were subjected to heat treatment (HT), i.e. annealing. Annealing was performed in a vacuum furnace in two variants: 1 - at a temperature of 800°C for 1.5 hours; 2 - at a temperature of 950°C for 2 hours. In both cases the specimens were cooled along with the furnace.

The metallographic tests revealed that if after annealing at 800°C the weld structure contained the fragments of casting structure (Fig. 8, a),

Spectrum	B	Ti
1	13.78	79.53
2	10.09	85.59
3	2.43	96.60
4	0.00	99.57

Spectrum	B	Ti
1	16.33	81.71
2	20.70	74.26
3	13.36	84.76
4	0.59	98.65
5	1.92	96.92

Fig. 7. EDS results – analysis of the welded joint, (% by weight.): a – rounded inclusions, b – chip-like inclusions

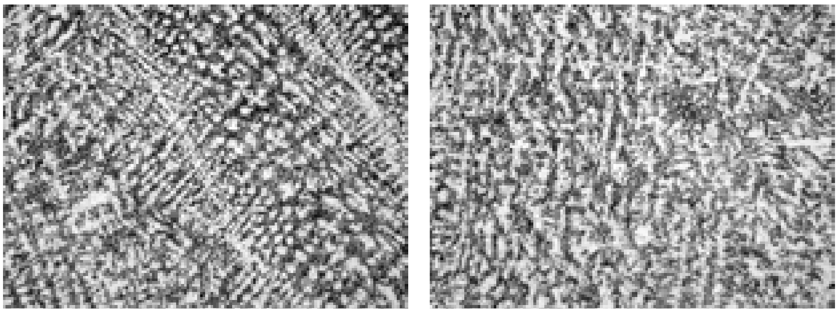


Fig. 8. Weld microstructure after annealing: a– 800°C, 1,5 h; b – 950°C, 2 h (500x)

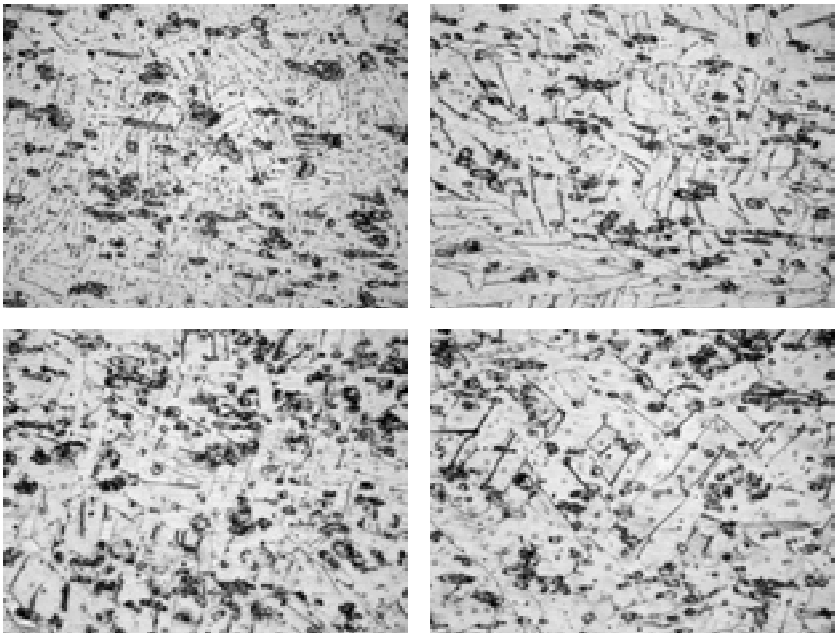


Fig. 9. Microstructure of the HAZ (a, c) and BM (b, d) of the joint welded after annealing: a, b – 800°C, 1,5 h; c, d – 950°C, 2 h (500x)

Table 2. Mechanical properties of the welded joint in the Ti–TiB titanium alloy before and after heat treatment

Properties	Welded joint	Welded joint + HT	
		800°C	950°C
Yield point $R_{0.2}$, MPa	686.0	773.5	789.3
Tensile strength R_m, MPa	742.0	911.0	910.0
Relative elongation A, %	5.4	7.0	6.0
Relative area reduction Z, %	9.8	12.9	12.9

after annealing at 950°C the weld did not contain the dendritic structure (Fig. 8, b).

The structure of the HAZ and that of the BM were identical in relation to annealing variants nos. 1 and 2. In both cases, the HAZ structure was slightly less refined than that of the BM. The boundary between the HAZ and the BM was not visible. The boundary constituted homogenous lamellar phase α containing variously shaped and sized TiB inclusions (Fig. 9). During the HT process the refined refractory borides were distributed uniformly in the fusible matrix [5]. The structural difference between HT regimes consisted only in the thickness of lamellas α (see Fig. 9).

The tension-triggered rupture took place in the BM (not in the weld or HAZ). The analysis of the mechanical test results related to the welded specimens before and after annealing (Table 2) revealed that the HT led to an increase in both strength and plasticity. In addition, the values of the above-named indications were approximately the same in relation to both modes. The foregoing led to the conclusion that the application of the longer hold time at the higher temperature was not useful.

Conclusions

1. The alloying agent of boron added to technical titanium (in the form of TiB_2) led to the refinement of grains and the precipitation of the TiB hardening phase in the form of bar-shaped crystals.
2. The precipitation of the refractory phase of TiB in the soft matrix of α-titanium significantly increased its strength and hardness.
3. The test titanium alloy proved to be characterised by satisfactory weldability.
4. The heating of surfaces remaining in contact during the process of welding resulted in the distribution of borides in the welded joint, leading to the hardening of the weld and HAZ.
5. The heat treatment of the welded joints led to the decomposition of the metastable phase, the distribution of boron particles in the specimen structure and the increase in structural homogeneity, translating into the improvement of mechanical properties.

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