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Electron Beam Welding of Butt Joints in Titanium Grade 2

Abstract: Titanium's excellent mechanical and physical properties make it a popular structural material commonly used in industry. However, the high chemical activity of titanium at high temperature necessitates the use of high-quality shielding gases during the welding process. The study discussed in the article aimed to assess the effect of welding parameters on the structure and mechanical properties of 3 mm thick butt joints in titanium Grade 2 (3.7035) made using the electron beam welding method under vacuum conditions without the filler metal (511). The verification of joint quality involved the performance of hardness measurements, tensile tests, bend tests as well as macro and microscopic metallographic examinations. The tests results revealed the obtainability of joints characterized by appropriate penetration depth and geometry as well as by optimum mechanical properties.

Key words: electron beam welding, titanium, titanium Grade 2

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1. Introduction

The constantly developing industry of the 21st century is constantly looking for new technological and material solutions to speed up production, reduce labour costs and obtain higher quality. The use of titanium as a structural material constitutes one of possible solutions. Titanium and its alloys play a key role among engineering materials. This chemical element is characterised by extraordinary properties, making it a nearly perfect structural material applicable in many areas [1–5].

Titanium and its alloys are characterised by very good mechanical and physical properties as well as by excellent corrosion resistance. Other advantages of titanium and its alloys include high resistance to corrosion in air, sea water, tap water and organic acids. However, titanium alloys are not resistant to hydrofluoric acid as well as concentrated sulphuric and nitric acids. The titanium application areas include the aviation, medical, automotive and power industries. Because of their high biocompatibility and the aforementioned corrosion resistance, titanium and its alloys are often used in the production of all types of implants and medical prosthetic devices. A high strength-to-weight ratio (i.e. specific strength) is a very attractive feature in the production of aircraft engine components, such as housing parts or engine blades [1–6].

The welding of titanium and its alloys faces a significant challenge connected with intense chemical reactivity. Above 300 °C, titanium begins to oxidise, where the intensity of oxidation process increasing along with growing temperature. In addition, oxidation is accompanied by diffusion processes, resulting in the dissolution of nitrogen, oxygen and hydrogen in titanium. The aforesaid phenomena improve the strength and hardness of the metal, yet, at the same time, reduce its plastic properties. Other difficulties related to the welding of titanium include its low thermal and electrical conductivity [1, 6].

Presently, the primary methods applied industrially for welding titanium and its alloys include non-consumable electrode inert gas welding (i.e. TIG welding) and, to a lesser extent, metal inert gas welding (i.e. MIG welding). A solution to the potential problem of oxidation and deterioration of plastic properties could involve the use of electron beam welding. Although the technology has been known for approximately 7 decades, only the recent years have seen a growing interest in the method, both from research and industrial points of view. The method has many advantages, including the possibility of welding metals which are poorly weldable by means of other methods, the obtainment of narrow welds with deep penetration and the unnecessity of bevelling the edges of sheets/plates (aimed to obtain the full penetration of materials when making butt welded joints). In respect of reactive metals, such as titanium and its alloys, the electron beam welding method offers an important advantage, i.e. the possibility of welding under vacuum conditions. The aforesaid advantage effectively prevents the negative impact of harmful chemicals from the environment during exposure to high temperatures [5–8].

The tests discussed in the article aimed to assess the quality of welded joints made of titanium Grade 2 applying the electron beam welding process under vacuum (511) without using the filler metal. The scope of the tests included the adjustment of parameters, the making of welded joints as well as the performance of macro and microscopic metallographic examinations, tensile strength tests, bend tests and hardness measurements.

2. Tests and results

2.1. Materials materials

The tests involved titanium Grade 2 (3.7035), i.e. pure titanium α, widely used in industry. Tables 1 and 2 present the chemical composition and mechanical properties of the titanium grade in accordance with the ASTM-B-265 standard [9].

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The elements subjected to joining were 3 mm thick sheets placed next to each other (200 mm × 80 mm × 3 mm). The preparation of elements plays an important role in electron beam welding. For this reason, before welding, the edges of the sheets were subjected to milling at an angle of 90 ° so that the gap created after joining would not exceed 0.1 mm.

Table 1. Chemical composition of titanium Grade 2 [9]

Chemical composition [%]					
Ti	**C**	**O**	**N**	**H**	**Fe**
Bal.	<0.080	<0.250	<0.030	<0.015	<0.30

Table 2. Mechanical properties of titanium Grade 2 [9]

R_m [MPa]	R_e [MPa]	HV	A [%]
345	275	145	20

2.2. Electron beam welding process

The electron beam welding tests, performed at the Łukasiewicz Research Network – Upper-Silesian Institute of Technology (Welding Centre) in Gliwice, involved the use of an EB 756 electron beam welding machine (Cambridge Vacuum Engineering) featuring a high-voltage generator having a maximum power of 30 kW, a directly heated cathode and the stepless adjustment of accelerating voltage up to 150 kV. The operating pressure in the chamber was restricted within the range of 10^{-4} mbar to 10^{-5} mbar.

The welding of final joints was preceded by the making of test joints (in order to identify the optimum welding current in relation to welding rates applied in the tests). Before welding, the sheets were cleaned using abrasive cloth and acetone. The ultimate number of welded joints amounted to four. Individual joints were made using various, previously specified welding rates and welding current values (determined during the tests). Table 3 presents technological parameters and linear welding energy values (calculated using formula 1). The welding parameters (the same in relation to all the tests joints) were the following:

- accelerating voltage – 120 kV,
- focusing lens current – 655 mA,
- cathode heating current – 22 A,
- working distance – 420 mm,
- pressure in the working chamber – 10^{-4} mbar.

$$E = \frac{q}{V}\left[\frac{\text{kJ}}{\text{mm}}\right]$$

Where $q = UI$ – welding heat source energy [W]
V – welding rate [mm/s]
U – arc voltage [V]
I – current [A]

Before welding, the sheets were cleaned using abrasive cloth and acetone. Afterwards, the sheets were set up on a work table and pressed using appropriate clamps (see Fig. 1).

2.3. Test sheet properties

The welding process was followed by sampling the joints for test specimens. Metallographic specimens were subjected to grinding, polishing and etching in Kroll's reagent. The

Table 3. Welding parameters

Joint designation	Electron beam current [mA]	Welding rate [mm/min]	Linear welding energy [kJ/mm]
A	5.25	100	0.378
B	8	500	0.115
C	9	1000	0.065
D	18	4000	0.032

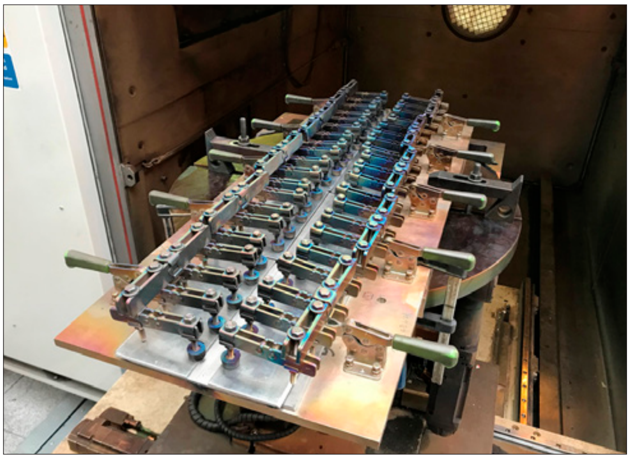

Fig. 1. Test sheets fixed before welding

metallographic tests were performed in accordance with the requirements of the PN-EN ISO 17639:2022-07 standard [10], using an Eclipse MA200 microscope and a DS.-Fi2 camera (Nikon). Macrostructural photographs were used to measure and assess joint imperfections in accordance with the criteria provided in the PN-EN ISO 13919-1:2020-04 standard [11]. The subsequent stage involved Vickers hardness tests performed under a load of 0.98 N (HV 0.1), in accordance with the PN-EN ISO 9015-2:2016-04 standard [12]. The hardness tests involved the use of an automatic hardness tester (Prüftechnik), performing measurements every 100 μm along a line parallel to the sheet surface in mid-cross-section. The results of metallographic examinations and hardness measurements are presented in Figures 2 through 5. Tensile tests were preceded by the preparation of specimens characterised by the same cross-section within the joint (in accordance with the PN-EN ISO 4136:2022-12 standard [13]), using a Criterion Model 45 testing machine (MTS). Bend tests were performed using an individually made roller bending machine, in accordance with the requirements specified in the PN-EN ISO 5173:2010/A1:2012 standard [14]. The bending pin diameter amounted to 10 mm, whereas the bend angle was 180 °. The sizes of the test specimens were the same. Each specimen was subjected to 2 transverse face bend tests (TFBB) and 2 transverse root bend tests (TRBB). Table 4 contains the results of the tensile and bend tests. In turn, Figure 6 shows a diagram presenting tensile strength values along with a reference (control) specimen, representing the strength of the base material.

3. Discussion

The results of analyses concerning the macro and microstructures presented in Figures 2 through 5 revealed the width of the heat affected zone extending along with increasing linear energy. The joints were characterised by clearly visible grain growth within the weld and HAZ. The weld contained coarse-grained phase α’. The interface and HAZ were characterised by the presence of coarse-grained phases α (granular) and α’ (acicular). In turn, the base material contained fine-grained phases α, typical of technical titanium.

Welding imperfections detected during the tests included, among other things, intermittent undercut (5012), excess weld metal (excessively large reinforcement on the weld face) (502), linear misalignment (507) and angular misalignment (508). The imperfections (mostly) satisfied the criteria of quality level B, exceptions being the linear misalignment (508) in joints A and D (representing quality level C) and intermittent undercut (5012) in joint B (representing quality level C).

The results of hardness measurements (presented in Figures 2 through 5) were similar in all the joints. In addition, the measurement values along the measurement line were similar in relation to the entire welded joint area. The weld area in joint C was characterised by a significant hardness increase of 20 HV.

All the test joints were characterised by similar tensile strength, restricted within the range of 432.5 MPa to 442.6 MPa. The values obtained were above the previously adopted acceptance criterion (i.e. R_m≥345 MPa). The lowest tensile strength values were identified in the specimens sampled from joint A (100 mm/min) as only in their cases the rupture took place outside the weld area. The maximum

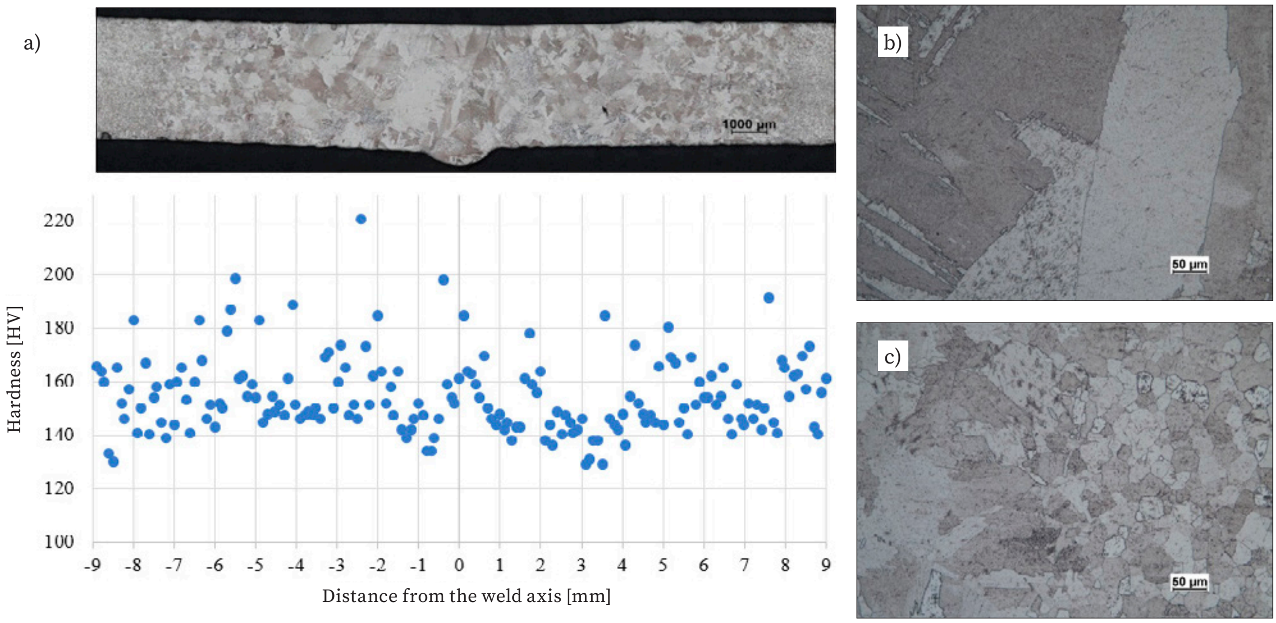

Fig. 2. Joint A: a) joint cross-section and hardness distribution, b) weld microstructure and c) HAZ microstructure

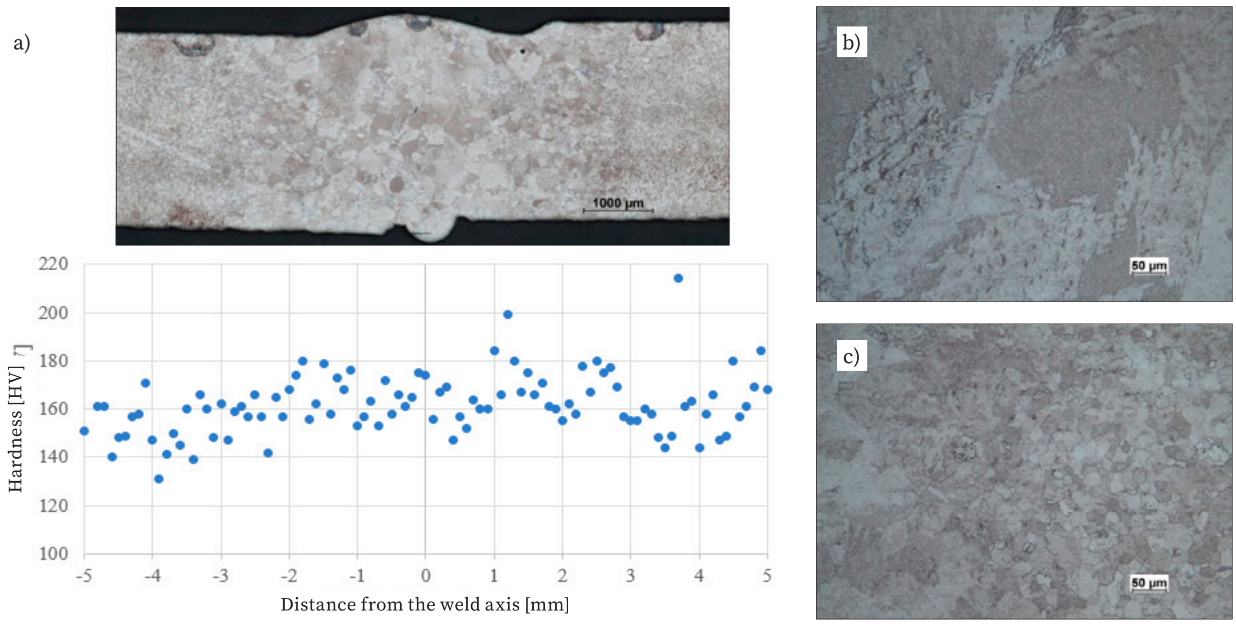

Fig. 3. Joint B: a) joint cross-section and hardness distribution, b) weld microstructure and c) HAZ microstructure

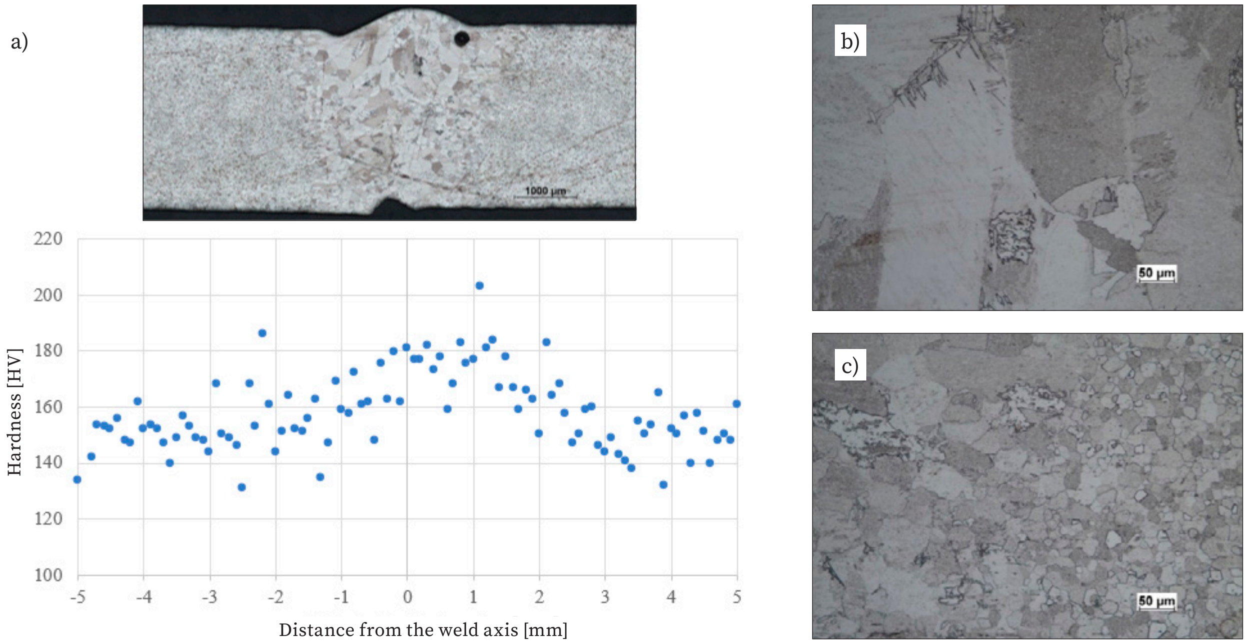

Fig. 4. Joint C: a) joint cross-section and hardness distribution, b) weld microstructure and c) HAZ microstructure

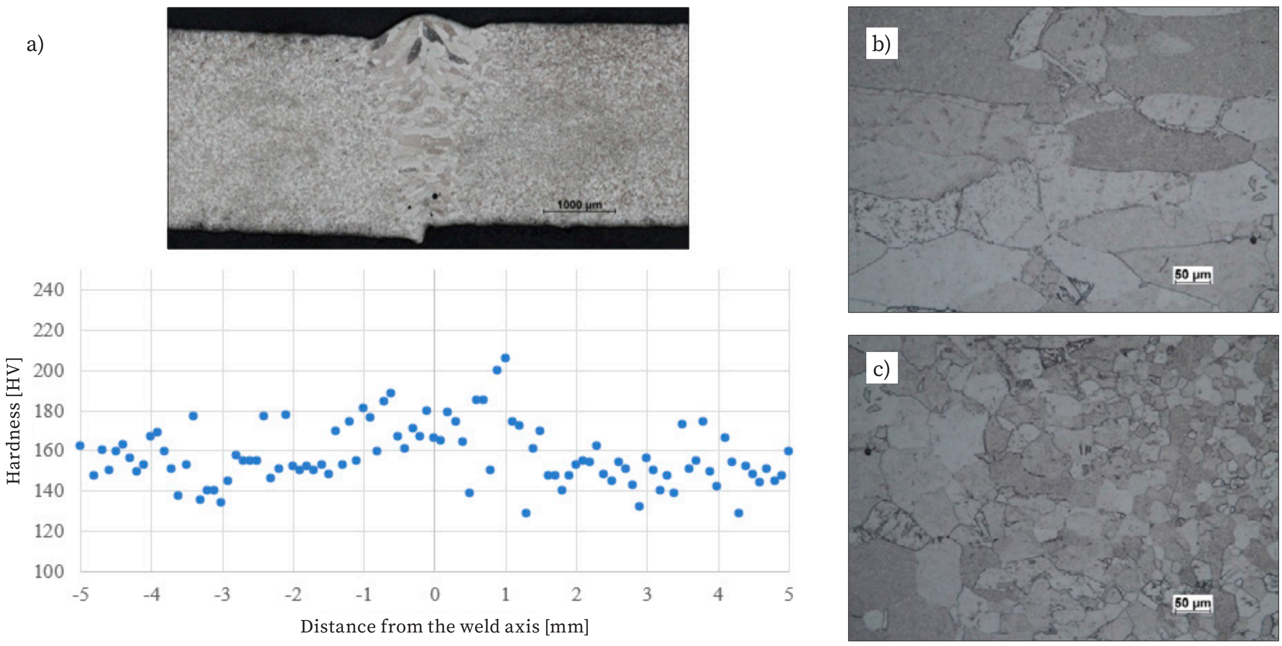

Fig. 5. Joint D: a) joint cross-section and hardness distribution, b) weld microstructure and c) HAZ microstructure

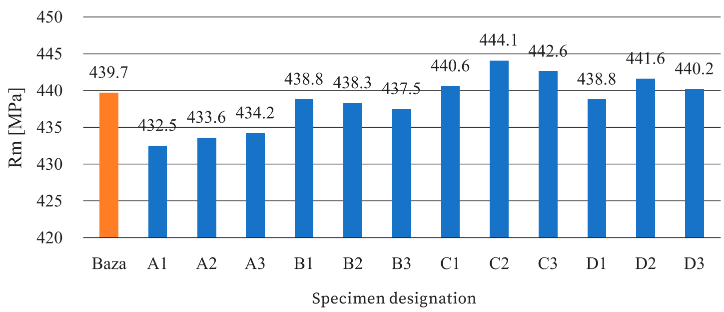

Fig. 6. Tensile test measurement results

Table 4. Tensile and bend test results

Specimen designation	R_m [MPa]	Rupture	Specimen designation	Bend test results
A/R/1	432.5	outside the weld	A/TFBB/1	no cracks
A/R/2	433.6	outside the weld	A/TFBB/2	no cracks
A/R/3	434.2	outside the weld	A/TRBB/1	no cracks
B/R/1	438.8	outside the weld	A/TRBB/2	no cracks
B/R/2	438.3	outside the weld	B/TFBB/1	cracks in the weld
B/R/3	437.5	outside the weld	B/TFBB/2	cracks in the weld
C/R/1	440.6	in the weld	B/TRBB/1	no cracks
C/R/2	444.1	in the weld	B/TRBB/2	no cracks
C/R/3	442.6	in the weld	C/TFBB/1	no cracks
D/R/1	438.8	outside the weld	C/TFBB/2	no cracks
D/R/2	441.6	in the weld	C/TRBB/1	cracks in the weld
D/R/3	440.2	in the weld	C/TRBB/2	no cracks
–	–	–	D/TFBB/1	no cracks
–	–	–	D/TFBB/2	no cracks
–	–	–	D/TRBB/1	cracks in the weld
–	–	–	D/TRBB/2	cracks in the weld

tensile strength, identified in specimen C/R/2, amounted to 444.1 MPa. In turn, the lowest tensile strength, identified in specimen A/R/1, amounted to 432.5 MPa.

The analysis of Table 4, concerning bend tests, revealed positive results in relation to all the specimens sampled from joint A (100 mm/min), both in terms of the transverse face bend test (TFBB) and transverse root bend tests (TRBB). In the remaining specimens it was possible to observe one or two cracks along the entire weld. The PN-EN ISO 15614-11 standard [15] states that test specimens should not contain any welding imperfections (in any direction) having a length in excess of 3 mm.

4. Concluding remarks

The tests concerning the electron beam welding of titanium Grade 2 under vacuum and without using the filler metal (511) enabled the obtainment of joints characterised by appropriate geometry and penetration depth. The hardness values identified during the tests were similar both in all the specimens and within the individual areas of the welded joints. The mean values of all the measurements amounted to 157.3 HV, with a standard deviation being 14.2 HV. In terms of the tensile and bend tests, the most favourable result was obtained in relation to joint A (100 mm/min; 5.25 mA), which ruptured outside the weld and did not contain post-bend cracks. The foregoing implies the application of an optimum linear welding of energy 0.378 kJ/mm, ensuring the obtainment of appropriate welded joint plasticity. The test results also revealed the necessity of rejecting excessively high welding rates and the need for applying lower linear welding energy values.

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