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THE EFFECT OF TIG WELDING ON MICROSTRUCTURE AND MECHANICAL PROPERTIES OF A BUTT-JOINED-UNALLOYED TITANIUM

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Microstructures, properties and technical parameters of welding specimen of 3 mm thick sheets of commercially pure titanium have been studied. The results indicate that the TIG welding process is suitable for commercially pure titanium, full penetration and the welding seam without defects can be obtained. The tensile, bending and hardness properties of the joints are corresponding to matrix structure. The mechanical properties of the three welded joints are similar to each other and comparable to those of the base material.

Key words: *Ti, TIG welding, mechanical properties, microstructure*

Utjecaj TIG zavarivanja na mikrostrukturu i mehanička svojstva sučeljeno zavarenog nelegiranog titana. U radu su prikazani rezultati ispitivanja mikrostrukture, mehaničkih svojstava i tehnički parametri zavarivanja limova debljine 3 mm iz titana komercijalne čistoće. Rezultati su pokazali da je TIG postupak zavarivanja pogodan za zavarivanje komercijalno čistog titana, te da se može postići potpuna penetracija i zavareni spoj bez defekata. Svojstva dobivena razvlačenjem i savijanjem kao i tvrdoća odgovaraju svojstvima osnovnog materijala.

Ključne riječi: *Ti, TIG zavarivanje, mehanička svojstva, mikrostruktura*

INTRODUCTION

Titanium and its alloys offer control of their processing history and microstructure and a wide range of properties [1]. Pure titanium undergoes an allotropic transformation at 883 °C from a hexagonal close packed crystal structure (α phase) to body centred cubic structure (β phase). The transformation temperature is strongly influenced by alloying elements that raise or lower it. Elements that raise the transformation temperature are termed as α stabilisers and those that lower it, β stabilisers. Interstitial elements; oxygen, nitrogen and carbon are α stabilisers and hydrogen is a β stabiliser; metallic alloying elements or impurities can be either of them. Depending on their microstructure, titanium alloys are classified as (i) unalloyed or commercially pure titanium (ii) α and near- α alloys, (iii) α-β alloys and (iv) metastable β alloys [2]. Good high temperature strength and creep resistance properties are usually obtained with near α-Ti alloys containing Al, Zr, Mo, Sn and Nb in variable amounts [3]. However, welding of Ti and its alloys is difficult because, Ti is extremely chemically reactive at high temperatures. During welding, Ti picks up oxygen (O), hydrogen (H) and nitrogen (N) from the atmosphere easily. Studies have shown that an increase in O and H in the welding zone, increases its strength but at the expense of toughness [4, 5]. Nitrogen is agglomerated around grain boundaries at about 500 °C. This causes dramatic decrease in toughness and tensile strength. Also, in the microstructure of the Ti, over 0,2 % C may results in formation of TiC that causes the early micro crack formation of the hard particles. The permissible rate of the H is 0,02 % and O is 0,16 % after welding process [6]. If contamination levels exceed a certain amount, cracking may result from the stress generated during welding.

With the development of titanium industries, many welding methods such as beam welding, resistance welding and diffusion welding and gas tungsten arc welding (TIG) have been developed [7].

In the present study, commercially pure titanium was welded by gas tungsten arc welding (GTAW or TIG) technique using a filler metal of similar chemical composition to the parent metal. The present article is a contribution to the understanding of the weldability of commercially pure titanium (C. P. Ti). This study aims to examine how different arc welding currents influence the microstructure and mechanical properties. The results were discussed in the light of microstructure and mechanical behaviour of the titanium.

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EXPERIMENTAL PROCEDURES

The specimens used in the investigation were extracted from butt joints of commercially pure titanium. A schematic diagram of the test plate is shown in Figure 1. Shape

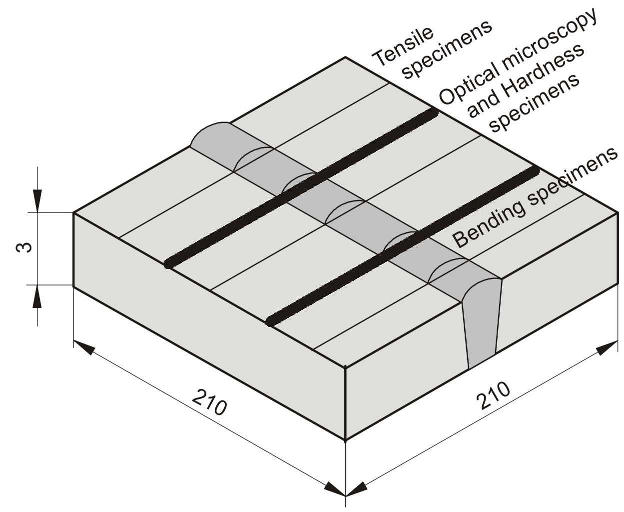

Figure 1. **Schematic picture of the welded material and extracted specimens**
Slika 1. **Shematski prikaz zavarenog materijala i mjesta uzimanja uzoraka**

of the specimens which are used in the present study and their dimensions are given in Figure 2. All specimens were

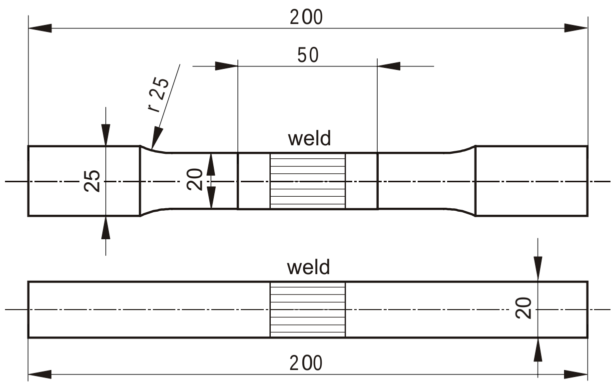

Figure 2. **The tensile and bending specimens and their dimensions**
Slika 2. **Oblik i dimenzije uzoraka za ispitivanje razvlačenjem i savijanjem**

obtained in the same orientation from the flat position welded joints. The C. P. Ti plate was 3 mm thick, so single welding pass was deposited. Chemical composition for the parent metal and filler rod are shown in Table 1. The filler rod has a diameter of 1,6 mm. Pre-welding cleaning procedures and steps to protect the molten weld zone were carried out to avoid contamination of the weld. High purity argon (99,9 %) was used as shielding gas during welding and as trailing gas right after welding to prevent absorption of oxygen and nitrogen from the atmosphere. During welding, welding parameters, gas flow, and welding speed were measured. The welding machine characteristics and other parameters are given in Table 2. Tensile, face, root and side bending tests were performed at room temperature and three specimens were used for each condition. Vickers micro hardness measurement was taken for the base metal, heat affected zone and weld metal by a diamond pyramid intender under 300 g loading with the "Instron Wolpert" micro hardness tester. In all cases, the space between indentations was 1mm. The specimens produced using the TIG process were sectioned transverse to the weld direction for general micro structural characterisation. A metallographic technique was developed for preparing the titanium samples for microscopy. This involved grinding with various grades of silicon carbide papers followed by polishing using 15 μm diamond grit. A final polishing was carried out with colloidal silica containing 2 % hydrogen peroxide and 2 % ammonia. The specimens were examined using the optical microscopy (Olympus PME 3). Etching was carried out in a solution of 5 % HF, 20 % HNO_3, and 75 % glycerol for approximately 90 s.

Table 1. **Chemical composition of the parent plate and welding filler rod.**
Tablica 1. **Kemijski sastav polaznog lima i dodatne žice za zavarivanje**

Element Weight / %	C	O	H	N	Fe	Ti
Material						
C. P. Titanium (99 %)	0,10	0,16	0,015	0,030	0,2	Balance
Filler Rod	0,03	0,10	0,005	0,012	0,1	Balance

Table 2. **Details of the welding process variables**
Tablica 2. **Tehnički parametri zavarivanja**

Material	C.P.Ti [A]	C.P.Ti [B]	C.P.Ti [C]
Current / A	80	90	100
Voltage / V	12	12	12
Filler rod diameter / mm	1,6	1,6	1,6
Tungsten electro diameter / mm	6	6	6
Gas flux / (lt / min)	18	18	18
Welding speed / (mm / s)	8	8	8

RESULTS AND DISCUSSION

Table 3. shows the quality of the welded seam using three different arc currents. The welded joints by TIG method are bright, silvery colour, smooth and they show little deformation. A bright, silvery weld indicated that the shield-

ing gas used was free from contamination; weld coloration ranging from straw through blue, purple and grey indicated increasing level of contamination in the shielding gas [8]. However, the backs of welded joints are light blue and show more deformation. Although the precautions are used during welding processing, the back of welded joints might be oxygenated. Table 3. shows that the front width of the specimen A is less than (3,6 mm) but, the specimen C is (4,2 mm). This shows that full penetrations can be obtained with an increase in arc current but, the size of heat affected zone is also increased. It is clear that the specimen B has excellent back and front width and height of the weld seam. One of the most important observations was that welded joints were absolutely defect free this indicates the good penetration and shielding of the melting pool.

Table 3. **Quality of the welded seam**
Tablica 3. **Kvaliteta zavarenog spoja kod različitih struja zavarivanja**

Material	A	B	C
Gap / mm	1,6	1,6	1,6
Curent / A	80	90	100
Front hight / mm	0,6	0,89	0,6
Back hight / mm	0,3	0,67	0,52
Front width / mm	3,5	3,7	4,2
Back width / mm	2,7	3,7	4,0
Defect	Nothing	Nothing	Nothing

Figure 3. shows the low magnified structures of Ti sheets by various welding currents. The penetration of weld seam appeared to be low by the specimen A, mid level in the specimen B and showed more penetration in the specimen C. For weld which is produced at high arc energy input, a significant increase in the depth of weld penetration has been observed.

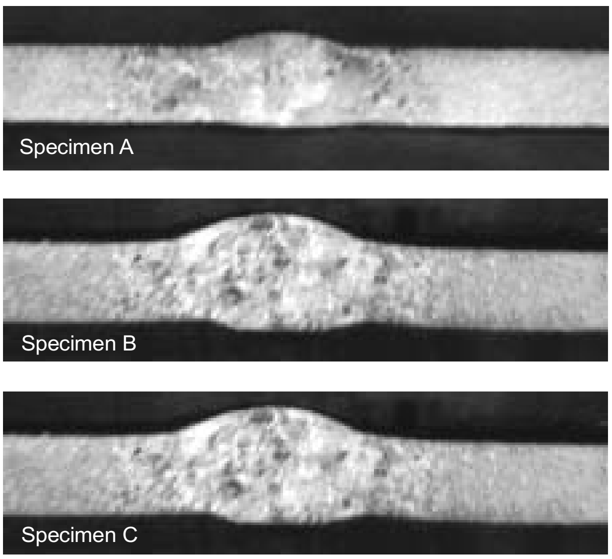

Figure 3. **Weld seam macrostructure of C. P. Ti welding specimens**
Slika 3. **Makrostruktura zavarenog spoja titana komercijalne čistoće**

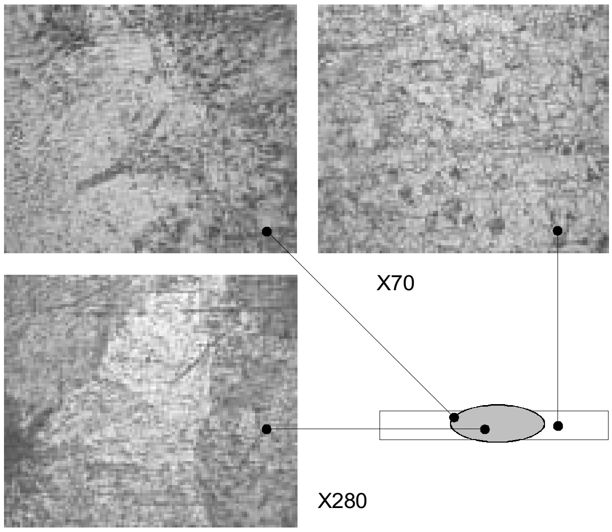

Figure 4a. **Microstructure of the C. P. Titanium welded at current 80 A**
Slika 4a. **Mikrostruktura zavarenog titana komercijalne čistoće kod struje od 80 A**

Figure 4. a to c show the joint surface photographs by various welding currents. The equi-axed grains are appeared at the matrix. The fine α structures are observed.

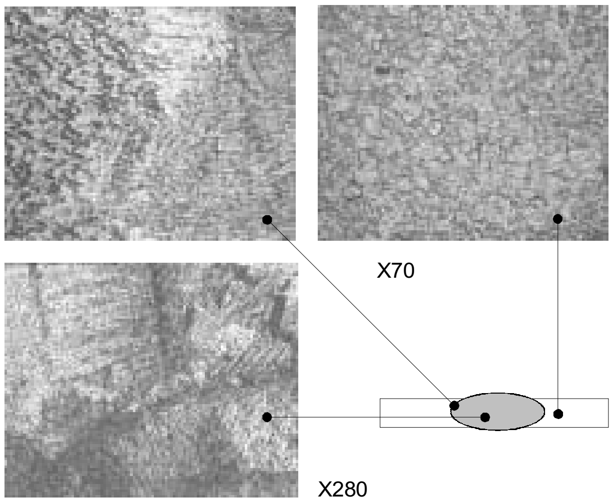

Figure 4b. **Microstructure of the C. P. Titanium welded at current 90 A**
Slika 4b. **Mikrostruktura zavarenog titana komercijalne čistoće kod struje od 90 A**

The surfaces of the welded joints indicate typical casting structures composed of equi-axed grains in the centre and the dendritic grains in the outside of welded seam. The size of grains by specimen C is the largest, while the size by specimen A is the smallest in fusion-zone. The grain size by specimen B is intermediate. The centre of welded joints is clean. The differences of the grain size in the centre and outside of the welded seam are three times greater in specimen C than that in specimen B, and four times greater in specimen A due to the high temperature in long term and low welding speed of specimen C. The grains would grow from outside to inside, arc current has the lowest degree in specimen A and the grains are finer than the others. Also, the serrate and regular plate shaped, columnar martensitic structures are appeared in the specimen A, while more regular plate shaped structure is appeared in specimen B and the coarse serrate and columnar α structures are appeared in the specimen C. Within each grain, parallel striations are evident which terminate at the grain

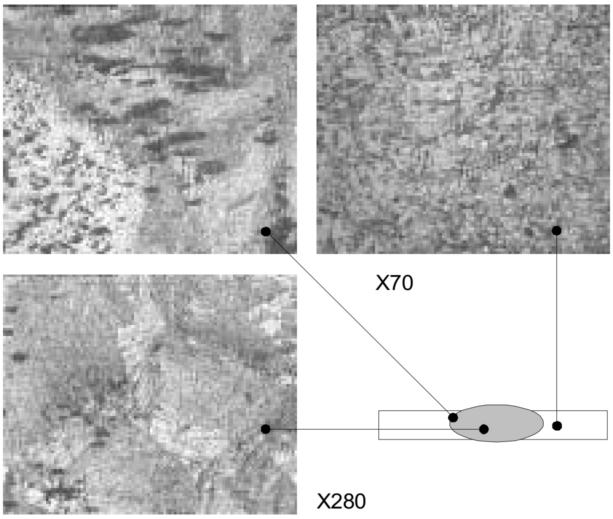

Figure 4c. **Microstructure of the C. P. Titanium welded at current 100 A**
Slika 4c. **Mikrostruktura zavarenog titana komercijalne čistoće kod struje od 100 A**

boundary; the striations take on a different orientation at an adjacent grain. It is seen that significant grain coarsening has occurred in the heat-affected zone (HAZ) adjacent to the base material. The degree of grain coarsening increases as one moves to the fusion zone. The HAZ undergoes strong thermal cycles involving rapid heating and cooling. Because the kinetics of the grain growth depend on temperature, the evaluation of the grain structure in the HAZ which is different from isothermal processing of metals and alloys. Thus decreasing the heat input provides a steeper distribution of peak temperatures in the HAZ. Increasing the heat input increases the width of the HAZ and the time of exposure to temperatures and reduces the cooling rate [10]. It is clear that the three specimens in the welded joints have different microstructures due to the temperature variation during welding and cooling processes. Additional current and voltage result in more vaporized metal and fumes. The TIG welding arc exerts heat flux, current density and pressure distribution on the surface of the weld pool. Surface tension gradients play a dominant role in determining the maximum velocity of the fluid flow in the weld pool [11]. Thus, optimising the parameters for welding speed, quality and low fume formation, increase the mechanical properties and provide better microstructures [12].

Titanium alloys are technologically important structural materials, so there have been many researches on their welding and properties of the welded joints. Zhou and Chew [13] studied impact toughness of TIG welded Titanium alloys. They showed that the HAZ and weld metal contain lower volume percentage of primary α grains than the base metal. The primary α grain boundaries were favourable nucleation sites for microcracks, and that the microcracks coalesced with the main propagating crack during impact. Therefore, the optimum structure of the specimen B has influence on ductility and mechanical responses of C.P. Ti, but an increase in the welding current is harmful for welded seam formation and HAZ, maybe the coarse structure and more intermetallics of the specimen C (Figure 3.) has a delitarous effect on mechanical properties and ductility.

Figure 5. shows the microhardness of weldments. The microhardness decreases from centre of welded joint to matrix for specimen A while the microhardness of fusion zone is 1,5 times greater than that of matrix. Similar trend

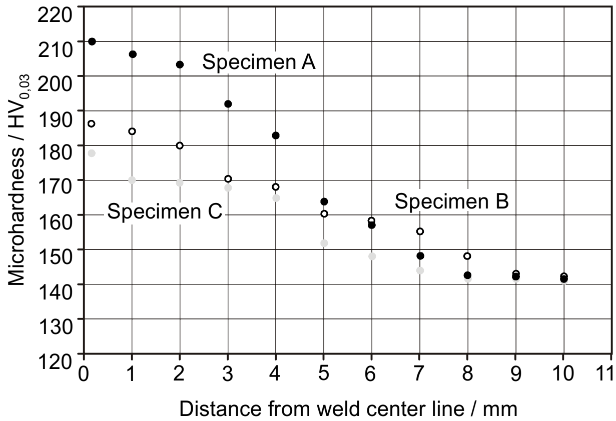

Figure 5. **The effect of arc currrent on the hardness in TIG welds of C. P. Titanium**
Slika 5. **Učinak struje zavarivanja na mikrotvrdoću TIG zavara titana komercijalne čistoće**

has also been observed for the specimens B and C. An increase in arc current resulted in decreased hardness. The highest value of the hardness is obtained in specimen A due to the low heat input and fast cooling rate which caused more columnar, acicular and fine α structures. It is also clear that the lowest hardness values are obtained in the specimen C that consists of the tensile and bending response of the specimens.

The fracture location of the specimens and tensile data of the three arc currents are listed in Table 4. Yield and tensile strengths increase in the order of α and β microstructures while elongation decreases in the order of coarse microstructure due to the increased heat input. The middle range of arc current causes excellent grain formation and orientation of the fine α and β phases. Also, The yield strength and ultimate tensile increase can be attributed to solid-solution strengthening by the formation of titanium carbonitrides, titanium oxides and titanium carbure that are also believed to be responsible for the grain refinement [14]. Moreover, specimens were fractured in the base metal, because of low percentage of the O, C, N and H in the chemical composition of the filler rod. As in all materials, the mechanical properties of the weldments are strongly related to their microstructures. The microstructural development in weld fusion zone and HAZ is controlled by the phase transformation characteristics of the material, and the peak temperature distribution and thermal cycles associated with the welding process parameters. The peak temperature and the rates of heating and cooling are maximum at the weld centre line and decrease rapidly with increasing distance from the weld centre line.

Table 4. **Tensile and bending properties of the commercially pure titanium**
Tablica 4. **Svojstva razvlačenjem i savijanjem komercijalno čistog titana**

Material	A	B	C	B. m.*
Yield Strength/MPa	272	277	298	274
UTS / MPa	413	417	415,4	406
Elongation / %	23,7	24,4	22,3	24,0
Bendig Angle / β°	> 140	> 140	> 140	-
Fracture location	HAZ**	HAZ**	HAZ**	-
*Base metal, **heat affected zone				

In the fusion zone, where the material has melted, the peak temperature goes beyond the solidus of the material. After the fusion line, the material has been heated to a temperature above some solid-state formation temperature. In this region, the material transformed to β phase during the heating part of the weld thermal cycle. During cooling, it will again undergo transformation, with the product formed depending upon the local cooling rate. Finally there is a critical temperature, which is specific for a certain alloy depending upon its phase transformation kinetics, below which no microstructural changes occur during the heating cycle. Beyond this point it has unaffected the base material.

CONCLUSIONS

On the basis of practical studies accomplished and the results obtained from the effect of TIG welding on microstructure, tensile, bending and hardness of the C. P. Ti, the following conclusions may be drawn:

- for C. P. Ti, weld with acceptable visual quality were produced by TIG welding with the three different arc welding current. The best strength and ductility of the welds achieved (specimen B) was 417 MPa, 24,4 %, which was only 3 % higher than that of parent metal,
- in all cases microstructure consisting of colonies of parallel α plates and coarse grains are appeared in fusion, fine grains in HAZ and equal mid range grains in the base metal. The α plates were finer in the lower heat input welds and the coarsier in the highest heat input welds,
- the highest hardness values of the joint is obtained with the lowest arc current, due to the low heat input and cooling rate,
- an excellent mechanical properties are obtained with mid range of arc current which also caused more uniform, and fine grains inside fusion zone and HAZ compared with the others.

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