MECHANICAL PROPERTIES OF ARC WELDED IN VACUUM Ti-6Al-4V ALLOY

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Titanium alloys are known for their good mechanical properties, low density, excellent corrosion resistance and low thermal conductivity. These properties define titanium and its alloys as highly suitable for medicine, automotive and aerospace industries. Unfortunately, the thermal cycle during welding of alpha-beta alloys (Ti-6Al-4V) can significantly change their strength, toughness and plasticity. The scope of present work is to investigate the possibility for producing Ti-6Al-4V welds by arc discharge in vacuum and to establish the influence of the welding parameters on dimensions and mechanical properties of the welds. The experiments presented here were carried out in an installation for hollow cathode arc treatment in vacuum. Cylindrical and elliptical tantalum cathodes were used. The welding was carried out without filler material and groove. Tensile test and hardness test of specific welds zones were used for mechanical properties determination. The results, presented in this work, describe the dimensions of the fusion zone and heat affected zone of welds, produced by hollow cathode arc welding using different welding parameters. The mechanical properties of the welds were determined.

Keywords: Titanium Alloy, Welded Joints, Mechanical Properties.

INTRODUCTION

Titanium based alloys are known as a material suitable for aerospace and automobile industries and are widely used in medicine. This is due to their better performance as a construction material over other materials because of their good mechanical properties, low density, excellent corrosion resistance in most aggressive media, low thermal conductivity etc.

After heat treatment α+β alloys possess increased toughness and high strength. These alloys represent about 70% of the USA market of titanium alloys and Ti-6Al-4V (Gr-5, Gr-5ELI) composes 56% from the whole USA market of titanium and titanium alloys (Lütjering and Williams, 2007).

The presence of β-phase at room temperature has as a result grain size refinement and increase in strength, ductility, toughness and weldability; the existence of β-phase along with α introduces the possibility for heat treatment (Zubarev and Kolomenskij, 2010; Zubarev and Kolomenskij, 2011; Leyens and Peters, 2003).

Ti-6Al-4V can be subjected to different heat treatment depending on the desired combination of mechanical properties; most used heat treatment of this alloy includes: annealing and quenching with subsequent ageing. The lowest strength and the highest ductility are observed after annealing; and the highest strength together with reasonably good ductility the alloy demonstrates after quenching and ageing.

The heat affected zone is what defines the weldability of titanium alloys (Nerovnyj and Jampolskij, 2002; Muraviev and Kleshnina, 2010). The most important structural changes and connected to them changes in properties occur, except at the fusion zone, at the areas next to the weld metal, where the metal is being heated up to temperatures of $(0,9\div1,0)T_m$ (T_m – melting point). The next areas are subjected to phase transformations resulting in metastable phases formation.

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The main difficulties connected to welding of titanium and its alloys are provoked by their high chemical activity, formation of pores and cold cracks, propensity for grain size enlargement near the weld. Welding of α+β alloys (including Ti-6Al-4V) can significantly change their strength, toughness and ductility. The low toughness is result of the phase transformations occurring at the weld metal and at the heat affected zone.

Titanium alloys are most often welded by TIG welding or welding in vacuum (Lisiecki, 2012; Niagaj, 2012; Ranatowski, 2008; Yassin *et al.*, 2012).

The aim of the present work is to investigate the possibility for welding titanium alloy Ti-6Al-4V by vacuum arc welding with hollow cathode and to determine the influence of welding parameters on geometric dimensions and mechanical properties of the produced welds.

METHOD AND MATERIALS

The presented here experiments were carried out in a device for vacuum arc welding with hollow cathode. Figure 1 represents the used device.

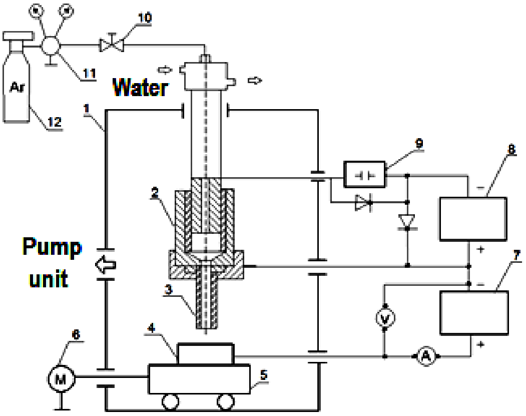

Figure 1. Scheme of the device for vacuum arc treatment: 1 – vacuum chamber; 2 – burner; 3 – hollow cathode; 4 – welded parts; 5- manipulator; 6 – electric motor; 7 – main power supply; 8 - auxiliary power supply; 9 - capacitor battery; 10 – gas supply; 11 - pressure reducing valve; 12 – container for plasma forming gas.

The device consisted of a 0.5 m^3 vacuum chamber, pump set, appliances for gas supply, flow-meters and welding power source. The welding burner (2) and the ancillary welding equipment (5), providing the reciprocating move, were mounted in the chamber (1). The required chamber pressure was achieved and maintained by the vacuum set, comprising three vacuum pumps - rotary vacuum pump, roots vacuum pump and diffusion vacuum pump. All experiments were carried out at pressure of 3 Pa. The plasma forming gas was Ar, purity 99.999%.

The working mode parameters are shown in Table 1. They were picked out according to recommendation for titanium alloys welding, taking into account the need for full penetration. The used cathodes were cylindrical and elliptical (Fig. 1, position 3). The cathodes were of tantalum foil; cathodes length was 30 mm and wall thickness –

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0.2 mm. Dimensions and shapes of cathodes are shown in Table 1. The welding process was carried out without filler material and without groove.

Table 1. Welding modes

No	Current I, A	Welding speed V, mm/s	Cathode dimensions mm	Gas quantity Q, l/h
1	100	4,2	∅4	2,3-2,4
2	115	4,2	∅4	2,3-2,4
3	130	5,5	∅4	2,3-2,4
4	115	5,5	elliptical 5,6 x 2	2,3-2,4
5	130	6,5	elliptical 5,6 x 2	2,3-2,4

The welded parts were made from titanium alloy Ti-6Al-4V (Gr-5) with dimensions 100x50x2 mm (LxWxH). The chemical composition of the welded parts was determined by XRF and is given in Table 2.

Table 2. Ti-6Al-4V Chemical composition

V, %	Al, %	Ti, %
4,27	6,1	89,57

Figure 2 shows the produced weldments. The mechanical properties of the weldments were determined using tensile testing and hardness testing at some characteristic areas of weldments. Weldments were cut into specimens for tensile testing, as shown in Figure 2b.

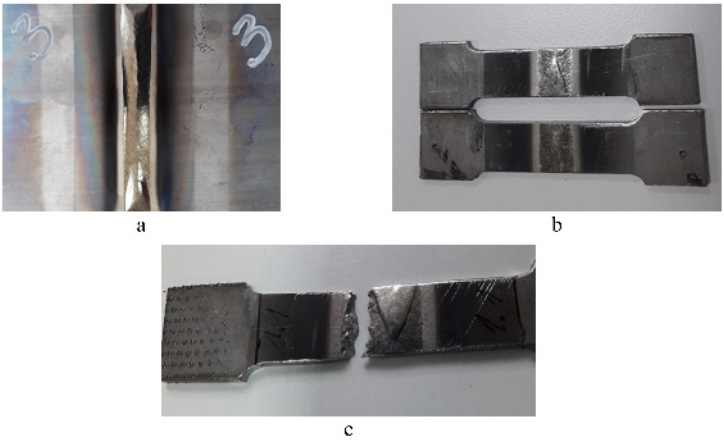

Figure 2. General appearance of produced welds (a); specimens for tensile testing (b); fractured after tensile testing specimen (c)

RESULTS

Table 3 summarises the dimensions of the fusion zones and heat affected zones of the produced weldments. The analysis of these dimensions indicated that during welding with cylindrical hollow cathode (modes 1, 2, 3) the size of the fusion zone and heat affected zone increased with increasing current value (modes 1 and 2). Simultaneous increase in current value and welding rate (mode 3) led to formation of fusion zone and heat affected zone with same dimensions as the obtained at lower current (mode 3 vs. mode 1).

The change in the cathode cross section shape from cylindrical to elliptical, with the ellipse wide side along the welding axis, led to decrease in the dimensions of both the fusion zone and the heat affected zone (Table 3, modes 4 and 5).

Table 3. Dimensions of the obtained zones

Welding mode No	Fusion zone width, mm (see Fig. 3)	Dimension of heat affected zone, mm (see Fig. 3)
1	9	2,3
2	10,5	2,5
3	9	2,5
4	7	1,65
5	8	2,05

Table 4 and Figure 3 represent the measured values of mechanical properties of the as-delivered Ti-6Al-4V and of the produced by us weldments. The results in Table 4 indicated that welding worsened the behaviour of Ti-6Al-4V in tensile test, and that was demonstrated by lower yield strength, ultimate tensile strength and elongation. That was caused by structural changes that took place at the areas heated to temperatures above β-transus temperature (above 995 ±15 °C for Ti-6Al-4V). It should be noted that for all weldments the fracture occurred at the boundary between fusion zone and heat affected zone (Fig. 2 c). Similar behaviour was observed by other authors too (Denney and Metzbower, 1989; Kramár, Michalec and Kovačócy, 2012).

Hardness measurements were carried out at different, randomly chosen volumes of the characteristic zones of weldments; it was found out that all measured values were close (almost equal). That fact led to the conclusion that the hardness was uniformly distributed within each individual zone. Differences in hardness values were observed only in transition from one zone to another.

Base material demonstrated higher hardness as it is seen in Table 4. That fact is meaningful, considering the as-delivery state of the base metal: quenching and ageing, at which Ti-6Al-4V is characterized with hardness values of 360 up to 400 HV. The hardness values decreased at the transition from the base metal to the heat affected zone; the hardness showed its lowest values at heat affected zones. Measured hardness values at weld metal were higher than those at heat affected zone but still lower than those of base material (Table 4). Considering that: 1) the measured hardness values are typical for both annealed and quenched structures and 2) the cooling rates in our experiments were not determined, a definite statement about the state (annealed or quenched) of fusion zone and heat affected zone cannot be made.

In order to establish the structure of weld metal and heat affected zone, the produced weldments were aged at different temperatures. The ageing was carried out in a vacuum furnace for heat treatment, at pressure of 100 Pa and temperatures range from 350 to 550°C with step of 50°C, soaking time of 2 h.

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Table 4. Mechanical properties of the base metal and weldments

Welding mode No	Yield strength $R_{p0,2}$, MPa	Tensile strength R_m, MPa	Elongation A, %	Hardness Fusion zone HV5 (HRc)	Hardness Heat affected zone HV5 (HRc)
As delivered	1002	1089	10	390 (39,8)	
1	940	1010	5	363 (37,0)	359 (36,4)
2	780	975	5	369 (37,8)	356 (36,1)
3	840	930	4,5	364 (37,1)	353 (35,9)
4	843	957	5	366 (37,6)	355 (36,0)
5	850	955	6	365 (37,2)	350 (35,5)

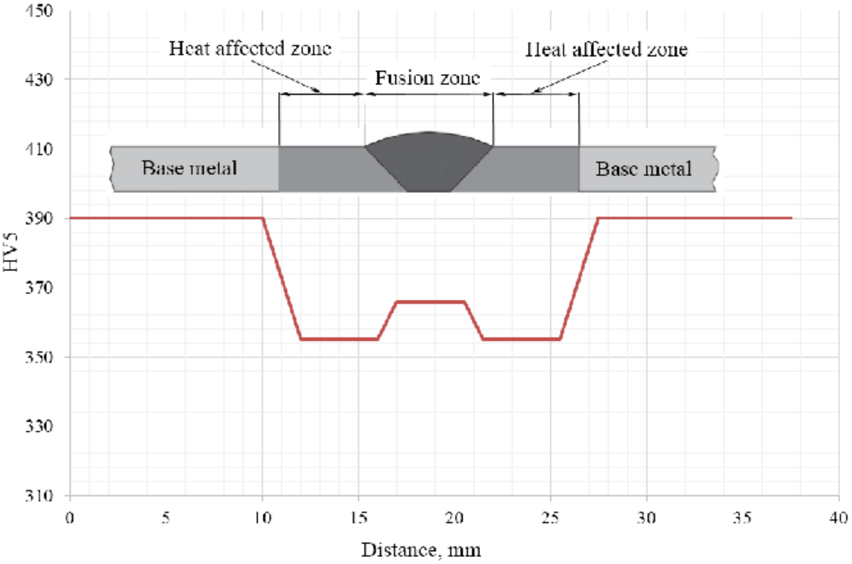

Figure 3. Hardness distribution at the different zones of weldments

Hardness testing after ageing showed increase in hardness values all over the specimens; that increase was up to 20-25 HV5. The measured hardness values after ageing at 500°C were highest in our experiments. The observed increase in hardness values could be attributed to incomplete ageing in as-delivery state of Ti-6Al-4V (inadequate ageing time or temperature). Heating at 500°C for 2 h caused ageing processes to become more completed, thus the hardness values increased. As for the hardness increase at heat affected zone and weld metal, it can be assumed that in some restricted volumes cooling rate after welding was sufficiently high for quenching; as a result quenching occurred at these restricted volumes. Ageing took place only at these volumes and led to hardness increase.

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CONCLUSIONS

1- Altering the main welding parameters makes it possible to produce heat affected zones and fusion zones of different dimensions.
2- Using an elliptical cathode instead of a cylindrical one allows to reduce the geometric dimensions of fusion zone and heating affected zone
3- Produced weldments have lower mechanical properties viz. strength and ductility. Enhancement of these properties could be expected after welding modes that provide greater cooling rates.
4- Ageing after vacuum arc welding with hollow cathode leads to hardness increase.

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