

Investigation of Enhancing Surface Hardness in Ti-6Al-4V Alloy by TIG Welding

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Abstract. The Ti-6Al-4V alloy is the most important and widely used titanium alloy which enjoys the welding, forging and machining capabilities. For this reason, it has extensive usage in automobile and military applications. Moreover, this alloy has the capability of being heat treated in order to reach a maximum strength up to 165 Ksi. But, one of its disadvantages is the low hardenability. In this regard, this paper investigates the increase of surface hardness by TIG welding. For this purpose, all the samples were investigated using optical microscope after casting. Also the phase detection was done by XRD method. The results show that with a 75A continuous current, the fully Martensitic microstructure is obtained with a Vickers hardness as high as 600.

Keywords: Titanium, TIG welding, mechanical properties, Hardness.

1. Introduction

Titanium is the 9th most abundant element in the earth's crust and the 4th most abundant structural metal after metals like Al, Mg and Fe which has been widely used in different industries such as oil, gas and petrochemical industries since 1950s because of its lightness, high strength-to-specific weight ratio, high resistance against corrosion, good creep resistance and good fatigue resistance [1]. Pure titanium has an allotropic structure such that in the temperatures below 883°C it has the structure α with hexagonal closed pack (HCP) lattice and in the temperatures above this limit it has the structure β with Body-Centered Cubic (BCC) lattice. The translocation temperature α/β is intensively affected by alloy elements and/or impurities in such a way that some of the alloy elements act as β -stabilizer and some of the others act as α -stabilizer in titanium. Hence, based on these microstructures, the titanium alloys are classified into four groups: α alloys, α -like alloys, β metastable alloys and $\alpha+\beta$ alloys [2,3].

Amongst the $\alpha+\beta$ alloys is the Ti-6Al-4V alloy which is the most important and widely used titanium alloy which had contributed 55% of total titanium consumption in the world in 1987. This alloy is also amongst the primary titanium alloys which its date goes back to 1950s. Extensive application of this alloy stems from high welding, forging, machining and heat treatment capability to reach maximum strength up to 165 Ksi. Moreover, from metallurgical standpoint, it is stable up to temperatures as high as 482°C. The extensive application of this alloy in aerospace is related to manufacturing turbine engine and airplane body components. Also, it can be used as a widely used material in the surgical implants and race machines. Figure 1 shows the application of this alloy in different aerospace industries [3,4].

Low hardness, high adhesive wear, low resistance against abrasive wear, weak wear behavior and variable and relatively high friction coefficient are amongst the disadvantages of titanium and its alloys. The reasons for tribological properties of titanium stem from its crystalline structure and electron arrangement. Hence, in order to use the Ti-6Al-4V alloy in engineering applications, it's necessary to improve the surface properties by surface engineering processes.

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To improve surface properties and perform surface hardening, different methods have been suggested and used such as Laser Beam Welding, Electron Beam Welding, and Plasma Arc Welding. Although welding is recognized as a process for connecting parts, but it is regarded as one of the most important and widely used coating processes through mass-coating on the surface of industrial parts. One of the modern surface welding methods is known as Gas Tungsten Arc Welding or TIG. In this method, a non-consumable tungsten electrode is used which the inert gas with a conical shape flows around it and protects the arc and weld pool against the atmosphere. This method was firstly used in 1940 for welding Al and Mg alloys, stainless steels, and low-alloy carbon steels with a thickness smaller than 6 mm. In 1941, the U.S. defense industries adopted the TIG welding method in seeking for the better ways for connecting light metals in military applications and specially airplane manufacturing [5,6].

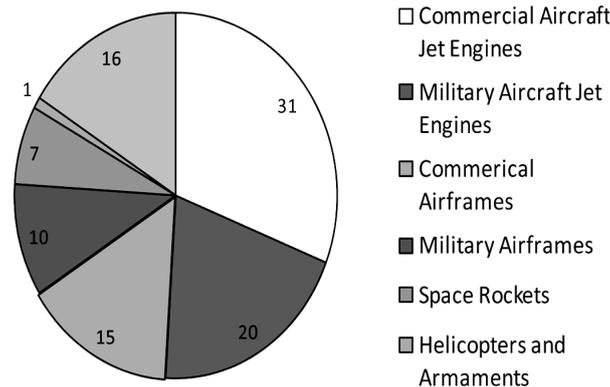


Fig. 1: The use of Ti in the aerospace industry by 2006 [2,3]

In this paper, the impact of using TIG welding in surface hardening of the important and widely used Ti-6Al-4V alloy has been investigated.

2. Materials and Method

The raw investment casted sample with a cylindrical shape and with dimensions $h=5\text{mm}$, $d=12\text{mm}$ and chemical composition shown in the table 1 was provided for testing.

Table 1: Chemical composition of casted part

Element	Al	V	C	Fe	O	N	H	Ti
Wt. %	6	4	0.13	0.1	0.1	0.04	0.002	Bal.

In order to evaluate the microstructure, the metallography process and the preparing of the sample was carried on according to routine activities (cutting, sanding, polishing, and engraving). Since the samples are existent in small dimensions, they were cold-mounted in room temperature. The Epoxy Resin was selected as the desired material for cold-mounting, because it enjoys lower contraction [7]. Also for engraving, the Kroll's solution with chemical composition as (3 ml HF + 6 ml HNO₃ + 991 ml H₂O) was used. For investigating the microstructure, an OLYMPUS CK40M optical microscope (OM) were used. For calculating the phase percent's, the Celemex Image Analyzer was been used. For this purpose, 10 images were randomly selected from each flow and the average percent of each phase was reported. Also the hardness testing was carried on using Vickers test.

The surface TIG welding process was performed by moving the torch with constant speed $3\text{mm}\cdot\text{s}^{-1}$ and continuous currents as high as 50, 60 and 75 amperes and a pulsed current as high as 75 amperes and using a tungsten electrode with constant apex angle equal to 60 degrees and a 45-degree angle relative to sample surface. For protection purposes, the pure argon gas with purity as high as 99.99% and a velocity of 10 L/min covering the sample surface was used.

3. Results and Discussions

Figure 2 shows the sample microstructure before TIG welding. The microstructure can be separated into three regions shown by arrows. This microstructure is the most ideal microstructure resulted from casting process, because the microstructure contains the phase β which is transferred from high temperatures. Due to existence of vanadium element which acts as β -stabilizer, this phase is stable in ambient temperatures. The phase β is recognized in the microstructure through dark positions. On the other hand, the phase α is shown in the form of layered and needle-shaped phase with bright color. This phase has been created in a penetrating transformation process due to transformation of phase β from high temperature during cooling and transiting the transformation temperature (883°C). There are some regions around the phase α as composition of dark and bright lines which have separated these layers. These regions can be interpreted as two-phase $\alpha+\beta$ regions [7].



Fig. 2: Microstructure of casted sample.

Figure 3 shows the sample microstructure after TIG surface treatment.

With a 50A continuous current (figure 3a), the sample microstructure includes coaxial phase α and phase β which the phase β is observed non-continuously in α grain boundaries. The grain size of phase α is in average equal to $8\mu\text{m}$ which verifies the impalpable variation in average diameter of α grains relative to raw sample. At a distance 2 mm from the surface, the base metal structure is the same as raw sample structure [8,9,10].

With a 60A continuous current (figure 3b), the sample microstructure includes phase α , primary phase α and converted phase β that the phase α is in the form of coaxial and the Martensitic phase, α' , contributes 20% of the structure. At a distance 1mm from the surface, the structure is similar to microstructure of the sample after surface treatment with 50A continuous current (α is coaxial and β is in non-continuous form in α grain boundaries) and at a distance 2 mm from the surface, the base metal structure is the same as the raw sample microstructure (α is in coaxial form and β is in continuous form in α grain boundaries) [8,9,10].

The microstructure of the sample with 75A continuous current (figure 3c) will be completely in the form of Martensitic α' . The Martensitic microstructure α' has been constituted from separate plates which have been intensively twinned and have HCP structure. In this structure, the grain refinement is caused by transformation of $\beta(\text{bcc})$ to $\alpha'(\text{hcp})$ and increase of dislocation density due to rapid refrigeration resulted from base metal. At a distance 1mm from the sample surface, the structure includes coaxial α elongated α in about 10% and transformed β phases. The Martensitic phase α' contributes about 40% of the structure. At a distance 2mm from the sample surface, the microstructure includes coaxial phase α , phase α which is elongated about 5% and the phase β in the form of a non-continuous phase in α grain boundaries. At a distance 3mm from the surface, the base metal structure is the same as the raw sample microstructure.

With 75A pulsed current (figure 3d), the microstructure includes Martensitic phases of α' and primary α and the transformed phase β . Formation of phase α' will be caused by base metal refrigeration after stopping the TIG process and contributes 25% of the matrix. With average refrigeration speed, the elongated phase α is obtained in 50 degrees centigrade above the β transformation, namely in temperatures around 1160°C . About 10% coaxial phase α is also observed. At a distance 2mm from the sample surface, the structure contains Martensitic phase α' at an amount about 5%, the phase α in elongated form, about 10% coaxial primary α phase and the phase β in the form of non-continuous in the α grain boundaries. At a distance 2.5mm from the surface, the base metal structure is the same as the raw sample.

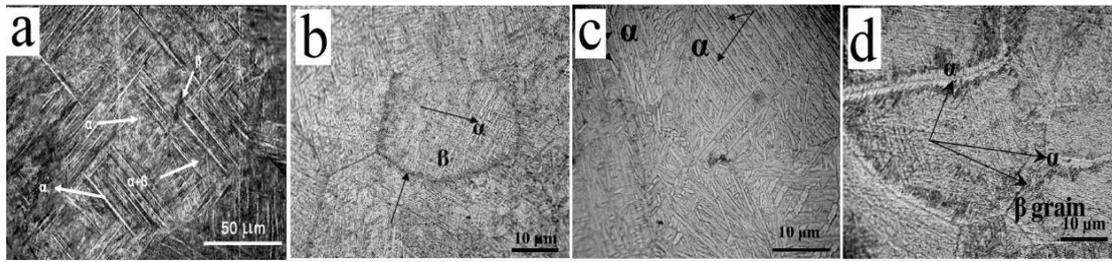


Fig. 3: Microstructure of the hardened samples per current: a)50, b)60, c)75 ,d)75 pulse.

3.1. Results Obtained from Hardness Testing

In table3, the results of hardness testing for hardened samples and in figure 3 these results in terms of distance are presented.

As one can see in figure 3, in the formed surface layer, with a 50A continuous current, the hardness variations are reduced from the sample surface towards center with a mild gradient; but considerable increase in surface hardness has not been obtained compared to base metal. This trend has a steep gradient with a 60A current and the sample has a mean hardness. With a 75A continuous current, the trend of hardness variation has a steep gradient and the maximum surface hardness has been obtained in this state. With a 75A pulsed current, the hardness variations have a mild and slow gradient and the sample has a relatively high hardness.

Table 3: Results obtained from hardness measuring for tested samples

Distance from the surface (mm)	Current(A)			
	50	60	75	75 pulse
0	380	503	600	520
1	355	401	505	450
2	337	339	406	376
3	336	335	339.4	335.9
4	335	334	334.1	334.5

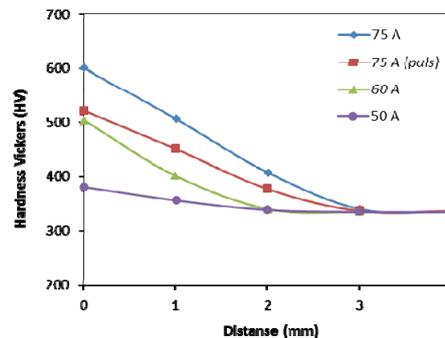


Fig. 4: Diagram for variations of hardness versus distance for welded samples

4. Result

In this research, the increase of hardness in Ti-6Al-4V alloy by welding has been investigated and the following results were concluded:

- After welding, with a 75A continuous current, the fully martensitic structure was obtained and consequently a Vickers hardness of 600 was obtained.
- With an increase in the current, both penetration depth and hardness are increased.
- The Martensitic phase α plays the most important role in increasing the alloy hardness by TIG welding.

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