Influence of TIG Welding Thermal Cycle on Temperature Distribution and Phase Transformation in Low-cost Titanium Alloy

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Abstract. Low-cost β-phase titanium alloys are starting to get a lot of attention and application in aircraft and mechanical engineering. They are effectively hardened by heat treatment and have a strength 10-20% higher than α-alloys. However, during TIG welding of low-cost titanium alloys, difficulties arise due to a change in the structure and the formation of metastable phases in the welded joint. The main criterion for choosing the modes of TIG welding is the optimal interval of the cooling rate in the weld, therefore it is advisable to compare different modes of TIG welding, including the use of pre-heating, by their thermal effect on the weld metal and the heat-affected zone.

1. Introduction

Titanium is one of the most important of modern structural materials and in current industrial production the semi-finished products of titanium alloys take an important place. Titanium alloys having high indices of mechanical properties, high corrosion and high-temperature resistance are perspective structural materials, which have found application in aircraft, space [1, 2], marine engineering, power machine building, oil-and-gas and chemical branches [3]. Nevertheless, titanium is also characterized by very high production costs which are approximately 6 times and 30 times higher, respectively, in comparison to those to obtain the same quantity of aluminum or steel relegating titanium to high demanding sectors [4, 5]. These costs are due to the necessity to use special industrial processes to prevent the contamination of titanium from interstitials (especially oxygen and nitrogen) which are detrimental for its ductility. The automotive industry is showing interest in the employment of titanium for the light weighting of structural components that will eventually result in less oil consumption and lower emission of green-house gases [6]. The use of original techniques and cheap alloying elements are the two main factors, which can lead to cost reduction for titanium parts. During TIG welding thermal cycle of low-cost titanium alloys, the metastable β-phase is fixed in the welded joint, which could lead to chemical heterogeneity and low mechanical properties [7, 8].

The cooling rate also has an effect on the degree of intragranular liquidation of the alloying elements, which is especially pronounced with slow cooling [9]. At low cooling rate there is an increase in liquidation in accordance with the diffusion mechanism of crystallization. As the cooling rate increases, liquidation decreases and may not be realized if the diffusion mechanism of crystallization changes to non-diffusion.

2. Aim of the work

The aim of this work is to carry out analytical study of the thermal conditions in the welding zone using finite element modeling of the TIG welding thermal process for low-cost titanium alloy Ti-2.8Al-
5.1Mo-4.9Fe, the configuration of thermal fields in the welding zone, the distribution of cooling rates and the number of metastable phases in the welded joint.

3. Materials and procedure of investigation

For experiment, 200x100x6mm plates of low-cost titanium alloy Ti-2.8Al-5.1Mo-4.9Fe was used.

Study of the influence of the TIG welding thermal cycle influence on the structural-phase state of welded joints of low-cost titanium alloy was performed by mathematical modeling of the TIG welding process by finite element method using ANSYS software. The study took the influence of such parameters of the TIG process into account the influence of such parameters of the TIG process as welding current, arc voltage and speed of anode spot on the size and shape of the base metal penetration, heat affected zone, probable phase composition of weld metal and HAZ [10].

The finite element model of the TIG welding thermal process is based on the heat balance equation with a scanning heat source, the basis of which is the equation of thermal conductivity and boundary conditions describing the heat transfer of the welded joint with the environment

\[ \rho c \frac{\partial T}{\partial t} = \frac{\partial}{\partial x} \left( \lambda_x \frac{\partial T}{\partial x} \right) + \frac{\partial}{\partial y} \left( \lambda_y \frac{\partial T}{\partial y} \right) + \frac{\partial}{\partial z} \left( \lambda_z \frac{\partial T}{\partial z} \right), \]  

(1)

where \( T \) – temperature, \( ^\circ\text{C} \); \( t \) – current time, s; \( \rho \) – material density, kg/m\(^3\); \( c \) – specific heat, kJ/(kg·K); \( \lambda \) – thermal conductivity, W/(m·K).

The following boundary conditions describe the heat exchange of the product with the environment:
1. \( T_{y=0} = T_e \) - the set temperature of the product at the initial time, equal to the ambient temperature (20 °C).
2. The heat flux on the surface in the area of the heat source is equal to (2) (fig. 1).

\[ -\lambda \frac{\partial T}{\partial x} = q_T + q_p + q_d \]  

(2)

where \( q_T \) - convective heat transfer J/sec, \( q_p \) –side surface radiation, J / sec, \( q_d \) – surface heat flow distribution J/sec.

![Figure 1](image)

Figure 1. Finite element model of TIG welding thermal process: a – boundary conditions applied in model, b – size of mesh elements in the model, mm

Study of the influence of the TIG welding thermal cycle influence on the structural-phase state of welded joints of low-cost titanium alloy has been performed by mathematical modeling of the TIG welding process by finite element method using ANSYS software. The study took the influence of such parameters of the TIG process into account the influence of such parameters of the TIG process as welding current, arc voltage and speed of anode spot on the size and shape of the base metal penetration, heat affected zone, probable phase composition of weld metal and HAZ.
The obtained temperature field was used to determine the maximum temperatures and cooling rates in the section of the welded joint. The used finite-element three-dimensional model of thermal welding processes is proposed in [12]. Taking the above initial and boundary conditions into account the above initial and boundary conditions, the calculated thermal fields were obtained in the workpiece being deposited. Based on the results of calculations, isotherms of maximum temperatures were built, which were used to determine the geometry and dimensions of the fusion zone, HAZ, and the zone of polymorphic transformation.

To assess the probable phase composition of the cooling weld and HAZ metal, the calculated CCT diagram of the low-cost titanium alloy Ti-2.8Al-5.1Mo-4.9Fe was used. In order to obtain the values of the physical characteristics for the new titanium alloy, it is possible to use computer models to calculate the thermophysical and physical properties of multicomponent alloys during solidification and cooling. One of the main methods for obtaining such data is thermodynamic modeling by the CALPHAD method based on the theory of multicomponent alloys [13]. Using the CALPHAD method for nonequilibrium processes, the Scheil-Gulliver model (SG model) was used, which gives great results for multicomponent alloys and allows to obtain dependencies of many parameters on their composition and temperature [14].

The properties of individual phases in multicomponent systems, such as molar volume, thermal conductivity, density, are expressed by functions similar to those used to simulate thermodynamic processes in excess multicomponent alloys [15]. After the properties of the individual phases have been determined, the property of the final alloy is calculated using well-proven mixture models. Such models, which were originally developed for two-phase systems, have been extended to multicomponent structures. Extensive databases of the corresponding parameters currently exist for most steels, aluminum and titanium alloys [16]. Using this approach allowed to obtain the physical and thermal-physical properties and kinetics of phase transformations of studied low-cost titanium alloy using numerical simulation.

To study heat input and pre-heating influence on phase transformations in weld metal and HAZ, TIG welding was carried out on 6 different modes [table 1].

Table 1. Modes of low-cost titanium alloy Ti-2.8Al-5.1Mo-4.9Fe TIG welding

| Mode # | Welding Current, A | Arc voltage, V | Welding speed, m/h | Heat input, kJ/cm² | Pre-heating temperature, °C |
|--------|--------------------|---------------|-------------------|-------------------|-----------------|
| 1      | 240                | 12            | 10                | 17280             | -               |
| 2      | 240                | 12            | 10                | 17280             | 400             |
| 3      | 320                | 12            | 16                | 14440             | -               |
| 4      | 320                | 12            | 16                | 14440             | 400             |
| 5      | 350                | 12            | 10                | 25200             | -               |
| 6      | 310                | 12            | 10                | 22320             | 400             |

4. Results

4.1. Obtaining weld metal and HAZ form and size

Based on obtained isotherms of maximum temperatures, depth and width of the weld metal and the zones of thermal influence were determined (Fig. 2).

Selected modes were chosen in a way, which allowed to obtain complete and incomplete penetration of the weld metal. This was done in order to determine the effect of preheating on the shape and size of the weld metal and heat affected zone (table 2). Thus, when using preheating in the mode with higher heat input (mode #2), the penetration depth increased by 17%, compared with the mode without preheating (mode #1). For the mode with less heat input, the use of preheating increased the penetration depth by 16% (modes #3 and #4). At the same time, the width of the HAZ when using preheating also increased.
Figure 2. Depth and width of the weld metal and HAZ of welded joints of low-cost titanium alloy obtained in different welding modes: a – mode #1, b – mode #2, c – mode #3, d – mode #4, e – mode #5, f – mode #6.

Table 2. Values of penetration depth, welding bath width and thermal impact zone width

| Mode # | Penetration depth, mm | Weld metal width, mm | HAZ width, mm |
|--------|-----------------------|----------------------|---------------|
| 1      | 4.22                  | 6.35                 | 10.81         |
| 2      | 5.11                  | 6.81                 | 11.18         |
| 3      | 4.02                  | 5.96                 | 9.89          |
| 4      | 4.8                   | 6.6                  | 11.08         |
| 5      | 6                     | 8.6                  | 12.78         |
| 6      | 6                     | 8.67                 | 15.38         |

4.2. Calculation of cooling rates

The diagram (Fig. 3) shows the temperature of the transformation beginning $b \rightarrow \alpha + b$ ($800...900°C$), for cooling rates $10-0.001 °C/s$ and the temperature of the transformation end of the $b \rightarrow \alpha + b$ transformation ($580...675 °C$) in same cooling rates.

As was investigated in previous papers [17, 18], lower heat input allows to obtain much better phase composition of weld metal and HAZ in comparison to higher heat input. So in this paper, we will study phase composition of welded joints, obtained on modes #5 and #6 – with full penetration and preheating.

For these modes, the cooling rates were calculated in the temperature range from 1200 °C to 150°C. Analysis of the calculated data showed that during cooling from a temperature of 1667 °C to 800 °C, the highest cooling rates are noted in the weld metal. When cooling from a temperature of 1200 °C, the cooling rate in the middle of the weld reaches 306 °C/s (Fig. 4), and in the fusion zone, the cooling rate reaches 130 °C/s. In this temperature range, pre-heating does not lead to noticeable changes in cooling rates, but have higher area size with higher cooling rates (130 °C/s) at the bottom of the weld, meaning higher $\beta$-phase percentage in fusion zone.
Figure 3. CCT diagram of low-cost titanium alloy Ti-2.8Al-5.1Mo-4.9Fe

![CCT Diagram](image)

Figure 4. Cooling rates in temperature range from 1200°C to 1000°C

In the temperature range 900...800 °C (Fig. 5), the cooling rate of the weld metal in the center is 4.8 mm wide and at a depth of 1.85 mm is 130...70 °C/s, except small part in the middle of the weld metal, where cooling rates exceeds 130 °C/s - up to 170 °C/s. In the rest of the weld metal and the heat affected zone, the cooling rates level down to 31...23 °C/s. For a sample with pre-heating, the maximum cooling rates are almost on the same level - 175 °C/s, and the area were the cooling rates of 130...70 °C/s is only a bit bigger than for a sample without pre-heating. But in case of pre-heating, going through heat affected zone, we can see, that cooling rates are much lower with bigger cooling rates gradient, then in sample without pre-heating.

![Cooling Rates](image)

Figure 5. Cooling rates in temperature range from 900°C to 800°C
In the temperature range of 800...700 °C (Fig. 6), corresponding to the temperature of the polymorphic transformation of low-cost titanium alloy Ti-2.8Al-5.1Mo-4.9Fe, the cooling rate decreases and in the fusion zone they are in the range from 59...23 °C/s, with small part on top of each sample having maximum cooling rates at 130...70 °C/s. In the HAZ, maximum cooling rate of 11 °C/s is recorded.

![Cooling rates in temperature range from 800°C to 700°C](image)

**Figure 6.** Cooling rates in temperature range from 800°C to 700°C

Obtained results show, that higher cooling rates are obtained in weld metal in the sample with pre-heating, but in a mean time, heat affected zone have lower cooling rates in temperature ranges, that correspond to polymorphic transformation temperature. As known from different studies, due to rapid cooling rates in heat affected zone, wide range of structures could be produced there, and many of these structures are expected to be non-equilibrium. Reduced cooling rates in HAZ could improve homogeneity of microstructure in HAZ and, therefore, improve mechanical properties of the weld.

### 4.3. Phase composition prediction

To predict the phase composition of the weld and HAZ metal, the amount of β-phase in the weld and the heat-affected zone of the welded joint was experimentally determined. The amount of the β-phase was determined by computer processing of the obtained microsections of the welded joint. The structure was studied in the middle of a 6 mm thick sample (Fig. 7).

![Scheme for determining the dimensions of the sections of maximum temperatures in the welded joint](image)

**Figure 7.** Scheme for determining the dimensions of the sections of maximum temperatures in the welded joint (L is distance to the test point).

L is the distance from the middle of the weld to the test point on the welded joint transverse microsection. The amount of β-phase in the base metal of the low-cost titanium alloy is 64% (Fig. 8, d). The weld metal consists of β-phase grains that are equiaxed and elongated in the direction of heat removal, the hair-like boundaries of which appear against the background of the dendritic structure (Fig. 8, a). The amount of β-phase in the center of this section is 87%. The fusion zone (Fig. 8, b) is located at a distance of 2.3 mm from the weld axis, on the right in the photo - weld grains against the background of the dendritic structure, on the left - equiaxed β grains of the HAZ section near the fusion zone. The amount of β-phase in this area is 75%. The HAZ section, where the complete polymorphic transformation occurred during welding, consists of equiaxed β-grains (Fig. 8, c), the amount of β-phase is at the level of 71%. The section of the HAZ where incomplete polymorphic transformation is observed has a width of 2.5 mm. In β-grains, there are particles of other phases that are found in the base metal, in particular α-phases. The β-phase amount is 49%. At the boundary of the transition from
the site of incomplete polymorphic transformation to the base metal, the amount of β-phase is 48% (table 3).

Table 3. Values of penetration depth, welding bath width and thermal impact zone width

| Welded joint area | L, mm | Amount of β-phase, % |
|------------------|-------|----------------------|
| Weld metal center| 0     | 87                   |
| Fusion zone      | 2.3   | 75                   |
| HAZ/complete polymorphic transformation | 4.3 | 71 |
| HAZ/incomplete polymorphic transformation | 6.7 | 49 |
| Area of incomplete recrystallization      | 7.4   | 48                   |
| Base metal       | 9.5   | 64                   |

In both cases, metastable β-phase is fixed in center of weld metal, with area size is 26 mm² for welding mode without pre-heating and 22 mm² for welding mode with pre-heating (fig. 9). Area size of HAZ, where transformation β→(α+β) occurs, is 97 mm² and 111 mm² for modes with and without pre-
heating respectively. This is due to the large gradient of cooling rates in different temperature ranges. Base metal consists from \( \beta \)-phase in both cases.

Figure 9. Scheme of phase composition of welded joints: a – welded joint obtained on mode #5, b – welded joint obtained on mode #6

5. Conclusions
A finite element model of the TIG welding thermal processes has been developed for low-cost titanium alloy Ti-2.8Al-5.1Mo-4.9Fe, with and without pre-heating of welded joint to a temperature of 400 °C.

CCT diagram of low-cost titanium alloy were build, indicating the lines of the beginning and the end of anisothermal transformations.

This finite element model of the TIG welding thermal processes allowed to determine size and shape of weld metal and heat affected zone, in which polymorphic transformations take place with formation of metastable \( \beta \)-phase. It also allowed to obtain the dependence of the phase composition in weld metal and HAZ based on the cooling rates of the low-cost titanium alloy Ti-2.8Al-5.1Mo-4.9Fe welded joint.

These dependencies showed, that using pre-heating with temperature 400 °C could help to obtain welded joints with less percentage of metastable \( \beta \)-phase in the weld metal, and higher area percentage of two-phased (\( \alpha+\beta \))-phase. Reduced cooling rates in HAZ could improve homogeneity of microstructure in HAZ and, therefore, improve mechanical properties of the weld.

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