FINITE ELEMENT ANALYSIS OF TEMPERATURE AND PHASE COMPOSITION OF TITANIUM ALLOY BY TIG WELDING

Titanium and its alloys have been widely used in varied industries such as aerospace, automobile, marine, chemical, medical due to their high strength, corrosion resistance and toughness. One of the factors constraining the widespread use of titanium alloys is the high cost of titanium parts, which is associated with the technology of their manufacture and the relatively high cost of the raw materials used. Reducing the cost of products involves the development of alloys using cheap raw materials and such technological processes that provide higher efficiency in the use of consumed energy and materials. The most promising in terms of reducing the price is the creation of economically alloyed alloys with improved processability, since for titanium the cost of manufacture accounts for most of the total cost of parts. In recent years, lowcost alloyed titanium alloys are becoming more common, in which expensive alloying elements are replaced by inexpensive and accessible elements, such as iron, carbon, oxygen and nitrogen, but their weldability is still under heavy investigation.

In this study a mathematical model of argon-arc welding with tungsten electrode of an economically alloyed titanium alloy Timetal LCB has been developed. To calculate the effect of welding mode parameters on the formation of a weld, a three-dimensional mathematical model of thermal processes in titanium was built for welding with a scanning heat source, which is based on the differential heat equation. Comparison of the calculation results with experimental data confirmed the adequacy of the developed mathematical model. Based on this model, the thermal fields in the welded joint are determined.

Nowadays the finite element method (FEM) is a suitable method for simulation of the welding process phenomena. It is possible the prediction of weld geometry through the optimization of the welding parameters. FEM simulation can calculate the weld pool shape, thermal distortion, residual stress and metallurgical change for various combinations of welding parameters. In FEM simulation, one of the topics is the choice of the heat source parameters, which is paramount for a satisfactory representation of welding process.

Keywords: model; thermal process; titanium alloy; methods of mathematical simulation; welding parameters.
забезпечують більш високу ефективність використання споживаної енергії та матеріалів. Найбільш перспективним з точки зору зниження ціни є створення економічно легованих сплавів з покращеною технологічністю, оскільки вартість виготовлення титану становить більшу частину загальної вартості деталей. Останніми роками все частіше використовуються низько затратні титанові сплави, в яких дорогі легуючі елементи замінюються недорогими та доступними елементами, такими як залізо, вуглець, кисень та азот, але їх зварюваність ще залишається під значним дослідженням.

У даній роботі розроблена математична модель аргонодугового зварювання вольфрамовим електродом економічно легованого титанового сплаву Timetal LCB. Для розрахунку впливу параметрів режиму зварювання на формування шва була побудована тривимірна математична модель теплових процесів у титані для зварювання скануючим джерелом тепла, основана на диференціальному рівнянні теплопровідності. Порівняння результатів розрахунку з експериментальними даними підтвердило адекватність розробленої математичної моделі. На основі цієї моделі визначаються теплові поля в зварному шві.

На сьогодні метод скінчених елементів (МСЕ) є підходящим методом для моделювання явищ зварювального процесу. Можливо прогнозування геометрії зварного шва за рахунок оптимізації параметрів зварювання, моделювання МСЕ дозволяє обчислити форму зварного шва, напружения, деформації та металургічні зміни для різних комбінацій параметрів зварювання. У моделюванні МСЕ одна з основних тем – це вибір параметрів джерела тепла, що є першорядним для задовільного подання зварювального процесу.

Ключові слова: модель; теплий процес; титановий сплав; методи математичного моделювання; параметри зварювання.

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АНАЛІЗ ТЕМПЕРАТУРНИХ ПОЛЕЙ І ФАЗОВОГО СОСТАВА ТИТАНОВИХ СПЛАВІВ, ПОЛУЧЕННИХ ТИГ СВАРКОЮ, МЕТОДОМ КОНЧЕНЬХ ЕЛЕМЕНТОВ

Титан і його сплави широко використовуються в різних отраслях промисловості, таких як аерокосмічна, автомобільна, морська, хімічна, медична, благодаря високій прочності, корозійної стійкості та вязкості. Одним з факторів, сдерживаючих широке використання титанових сплавів, є висока кошторисності титанових деталей, що свято з технологією їх виготовлення, а також високая кошторисності використовується виробництвом. Сниження себестоимості продукції є ключовим фактором в розвитку титанових сплавів, а використання таких технологій їх виготовлення, як правило, веде до репрезентативного подання виробництва.

На основі цієї поручі одну з основних тем – це вибір параметрів джерела тепла, що є першорядним для задовільного подання зварювального процесу. На сьогодні метод скінчених елементів (МСЕ) є підходящим методом для моделювання явищ зварювального процесу. Можливо прогнозування геометрії зварного шва за рахунок оптимізації параметрів зварювання, моделювання МСЕ дозволяє обчислити форму зварного шва, напружения, деформації та металургічні зміни для різних комбінацій параметрів зварювання. У моделюванні МСЕ одна з основних тем – це вибір параметрів джерела тепла, що є першорядним для задовільного подання зварювального процесу.

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In this work, a mathematical model of argon-arc welding with a tungsten electrode of economically alloyed titanium alloy Timetal LCB was developed. For the calculation of the influence of parameters of welding regime on the formation of the weld, a three-dimensional mathematical model of thermal processes in titanium for welding scanning heat source was constructed, based on the differential equation of heat conduction. The comparison of the results of calculation with experimental data confirmed the adequacy of the developed mathematical model. Based on this model, thermal fields in the weld are determined.

Today, the finite element method (FEM) is a suitable method for simulation of the welding process phenomena. It is possible the prediction of weld geometry through the optimization of the welding parameters, FEM simulation can calculate the weld pool shape, thermal distortion, residual stress and metallurgical change for various combinations of welding parameters. In FEM simulation, one of the topics is the choice of the heat source parameters, which is paramount for a satisfactory representation of the welding process.

For this research, an economically alloyed Timetal LCB alloy doped with cheap eutectoid-forming elements (i.e. iron in an amount of 4.5%) was chosen (Table 1).

Table 1

| Ti  | Mo  | Fe  | Al  | O  |
|-----|-----|-----|-----|----|
| Base| 6,8 | 4,5 | 1,5 | 0,15 |

Problem statement

Titanium and its alloys have been widely used in varied industries such as aerospace, automobile, marine, chemical, medical due to their high strength, corrosion resistance and toughness. One of the factors constraining the widespread use of titanium alloys is the high cost of titanium parts, which is associated with the technology of their manufacture and the relatively high cost of the raw materials used.

Reducing the cost of products involves the development of alloys using cheap raw materials and such technological processes that provide higher efficiency in the use of consumed energy and materials. The most promising in terms of reducing the price is the creation of economically alloyed alloys with improved processability, since for titanium the cost of manufacture accounts for most of the total cost of parts.

Analysis of recent reports and publications

In recent years, lowcost alloyed titanium alloys are becoming more common, in which expensive alloying elements are replaced by inexpensive and accessible elements, such as iron, carbon, oxygen and nitrogen [1], but their weldability is still under heavy investigation.

The finite element method (FEM) is a suitable method for simulation of the welding process phenomena. It is possible the prediction of weld geometry through the optimization of the welding parameters, FEM simulation can calculate the weld pool shape, thermal distortion, residual stress and metallurgical change for various combinations of welding parameters. In FEM simulation, one of the topics is the choice of the heat source parameters, which is paramount for a satisfactory representation of the welding process.

For this research, an economically alloyed Timetal LCB alloy doped with cheap eutectoid-forming elements (i.e. iron in an amount of 4.5%) was chosen (Table 1).
This alloy belongs to the class of high-strength pseudo-beta titanium alloys and has the following mechanical characteristics (Table 2).

Table 2

| Ultimate tensile strength, MPa | Yield strength, MPa | El, % | RA, % | KCV, J/cm² |
|-------------------------------|---------------------|-------|-------|------------|
| 1187                          | 1166                | 13    | 40    | 3          |

When producing welded joints of pseudo-β-alloys by fusion welding, there are due to the high content of alloying elements in them, the crystalline structure of the β-phase of titanium and the tendency to develop chemical and physical heterogeneity in the weld metal and the HAZ. The specificity of phase and structural transformations in various parts of the welded joint caused by the thermal welding cycle, which results in a large number of metastable phases in the weld metal and HAZ, adversely affecting the mechanical properties of the welded joint, has a negative effect on the weldability of β-alloys. To reduce the formation of metastable phases, it is necessary to conduct welding with controlled cooling rates [2]. The use of preheating is one of the methods of influencing the cooling rate in a welded joint.

**Purpose of the Study**

Therefore, the purpose of this work is to study the effect of the thermal cycle of welding when using preheating on the shape and size of the weld metal and the HAZ, as well as on the cooling rate and phase composition of the cooling metal.

**Description of Main Material of Research**

The dependence of enthalpy on temperature for non-stationary thermal analysis with phase transition was determined for the pseudo-β titanium alloy Timetal LCB according to the Neumann-Kopp rule. In comparison with the technical titanium VT1-0, the heat capacity of the alloy Timetal LCB is 2 – 6% less, mainly due to the low heat capacity of Fe and Mo (Fig. 1).

![Figure 1. Comparison of the specific heat of VT1 technical titanium and Timetal LCB economically alloyed titanium alloy.](https://doi.org/10.32782/KNTU2618-0340/2020.3.2-2.13)
To calculate the effect of welding mode parameters on the formation of a weld, a three-dimensional mathematical model of thermal processes in titanium was built for welding with a scanning heat source, which is based on the differential heat equation:

\[
\rho c \frac{\partial T}{\partial t} = \frac{\partial}{\partial x} \left( \lambda \frac{\partial T}{\partial x} \right) + \frac{\partial}{\partial y} \left( \lambda \frac{\partial T}{\partial y} \right) + \frac{\partial}{\partial z} \left( \lambda \frac{\partial T}{\partial z} \right).
\]

The simulation was performed on a sample with dimensions 200x100x10mm, for which a finite element model was constructed. The following boundary conditions are formulated, describing the heat exchange of the product with the environment (Fig. 2).

Figure 2. Boundary conditions describing the heat exchange products with the environment.

This model was used to simulate welding processes in titanium alloys VT23 and VT19 [3]. Comparison of the calculation results with experimental data confirmed the adequacy of the developed mathematical model (Fig. 3). The difference in the width of the deposited bead in the calculated and experimental sample was 3.1%, the width of the return bead was 2.4%.

Calculations of thermal fields were carried out for 4 welding modes, with lower and higher heat input, as well as with and without using preheating (Table 3).

According to the calculation results, the isotherms of maximum temperatures were constructed, with the help of which the depth and width of the weld metal and the heat-affected zone were determined (Fig. 4).

Welding modes were chosen, in which the complete penetration of the weld metal was absent. This is done to determine the effect of preheating on the forum and the dimensions of the weld metal and HAZ. So, when using preheating in the mode with higher heat input (mode # 2), the penetration depth increased by 17% compared to the mode without preheating (mode # 1). For the regime 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 (Table 4).

The calculated cooling rates in the welded joint in different temperature ranges were constructed. In the temperature range of 1200 ... 1100 °C, high cooling rates above 200 °C / s are recorded. The diagram of the distribution of cooling rates (Fig. 5) shows that the cooling of the HAZ is more uniform using preheating.

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Figure 3. Adequacy of the developed mathematical model:

\( a \) – using the example of TIG welding of a two-phase high-strength titanium alloy VT23;
\( b \) – using the example of the TIG welding of a pseudo-\( \beta \)-titanium alloy VT19.

Table 3

Modes of argon-arc welding by tungsten electrode of lowcost titanium alloy Timetal LCB, for which modeling was performed

| №   | Welding current, \( A \) | Welding voltage, \( V \) | Welding speed, m/h | Heat input, kJ / \( cm^2 \) |
|-----|-------------------------|-------------------------|-------------------|-----------------------------|
| 1   | 240                     | 12                      | 10                | 17280                       |
| 2   | 240                     | 12                      | 10                | 17280                       |
| 3   | 320                     | 12                      | 16                | 14440                       |
| 4   | 320                     | 12                      | 16                | 14440                       |

Figure 4. The depth and width of the seam metal and heat-affected zone of welded joints of lowcost titanium alloy Timetal LCB obtained in different welding modes:

\( a \) – mode № 1, \( b \) – mode № 2, \( c \) – mode № 3, \( d \) – mode № 4.
### Table 4

Values of penetration depth of the weld metal and the width of the heat-affected zone

| №  | Penetration depth, mm | Width of HAZ, mm |
|----|-----------------------|------------------|
| 1  | 4,22                  | 10,81            |
| 2  | 5,11                  | 11,18            |
| 3  | 4,02                  | 9,89             |
| 4  | 4,80                  | 11,08            |

Figure 5. Cooling speeds in temperature range 1200-1000°C:

- \( a \) – mode №1,
- \( b \) – mode №2,
- \( c \) – mode №3,
- \( d \) – mode №4.

The same is observed in the temperature range of 1000 ... 900°C, where cooling rates above 130°C/s are also recorded in all modes. Starting from the temperature range of 600 ... 500°C/s, the cooling rates are aligned in all modes, both with and without preheating (Fig. 6).

Figure 6. Cooling speeds in temperature range 600-500°C:

- \( a \) – mode №1,
- \( b \) – mode №2,
- \( c \) – mode №3,
- \( d \) – mode №4.

Analyzing the obtained cooling rates, a comparative chart was drawn up (Fig. 7), from which it can be seen that the lowest values of the cooling rates are fixed at mode №4 using preheating during welding with a lower heat input.
Conclusions

Taking into account the preheating of the welded joint to a temperature of 400° C, a mathematical model of argon-arc welding with tungsten electrode of an economically alloyed titanium alloy Timetal LCB has been developed. Based on this model, the thermal fields in the welded joint are determined. It is shown that the use of preheating leads to an increase in the depth of penetration by 16 ... 17%, and the width of the HAZ to 10%. The fields of cooling rates of the welded joint were constructed, which made it possible to conclude that with the use of preheating, the cooling rate is less than without using it. Based on this, assumptions were made that when using preheating and welding in a mode with lower heat input, there will be less metastable phases in the weld metal and HAZ, and accordingly, this welded joint will have better mechanical characteristics.
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