MATHEMATICAL MODELLING OF STRUCTURAL TRANSFORMATIONS IN HAZ OF TITANIUM ALLOY VT23 DURING TIG WELDING*

S.V. AKHONIN, V.Yu. BELOUS, A.F. MUZHICHENKO and **R.V. SELIN**
E.O. Paton Electric Welding Institute, NASU
11 Bozhenko Str., 03680, Kiev, Ukraine. E-mail: office@paton.kiev.ua

Issues of weldability of multi-component titanium alloys are covered in many studies. As experimental investigations are time- and labour-consuming, it seems reasonable to use mathematical methods for evaluation of the effect of parameters of the welding thermal cycle on structural transformations occurring in the HAZ. In the present study the effect of the thermal cycle of argon-arc welding on shape and size of the weld, length of HAZ and kinetics of structural transformations in the HAZ metal is investigated by the mathematical modelling methods by an example of TIG welding of high-strength titanium alloy VT23. Calculations using the 3D mathematical model of the thermal processes occurring in titanium during welding, based on the differential thermal conductivity equation, were carried out by employing the finite element method application package. The calculations made it possible to determine size and shape of the weld and HAZ, in which the polymorphic transformations take place to form the α-, α″- and β-phases. The calculations showed that the α″-phase may form in the weld metal at the highest cooling rates. The low-ductility ω-phase does not form at the investigated process parameters and welding speeds of 10 m/h because of comparatively low cooling rates within the 500–600 °C temperature range. The results obtained can be applied in development of the technology for welding of advanced titanium alloys. 4 Ref., 6 Figures.

Keywords: *TIG welding, mathematical modelling, titanium alloy, cooling rate, polymorphic transformations*

Tungsten electrode arc welding in the atmosphere of inert gases (TIG), such as argon and helium, is still the most common, relatively simple and versatile method for fabrication of structures from titanium alloy. It makes it possible to perform welding in various spatial positions and sufficiently quickly readjust the equipment when type of the joint and thickness of the metal welded are changed. One of the ways of widening the technological capabilities of narrow-gap TIG welding of heavy sections and cladding operations is to use the external controlling magnetic field for deflection of the welding arc [1]. Experimental investigations of the thermal processes occurring in the welded joint during welding of titanium by the magnetically controlled arc are labour-consuming and costly because of a large quantity of parameters of the welding process, especially in a case of welding of high-strength titanium alloys. Therefore, the authors performed analytical investigation of thermal conditions in welding of plates of titanium alloy VT23 by mathematical modelling of the process.

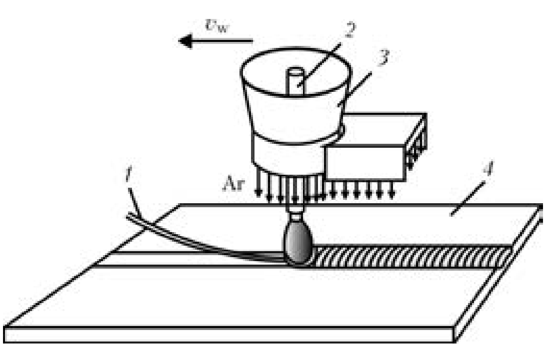

Figure 1. Flow diagram of the process of TIG welding of titanium: *1* — filler wire; *2* — tungsten electrode; *3* — protecting nozzle; *4* — workpiece

Modelling allowed investigating the effect of such process parameters as welding speed and heat input on shape of the base metal penetration zone and HAZ, on values of the maximal cooling rates in different regions of the HAZ metal, and temperature gradients in cooling [2].

Flow diagram of the process of cladding of titanium parts is shown in Figure 1.

Calculations of the thermal conditions accompanying the process of melting of the metal surface were made by using the mathematical model based on the differential thermal conductivity equation in the 3D Cartesian coordinate system.

The finite element 3D model of the thermal processes of square-groove cladding of titanium

*The article is based on the presentation made at the 6th International Conference «Mathematical Modelling and Information Technologies in Welding and Related Processes» (29 May–1 June, 2012, Katsiveli, Ukraine).

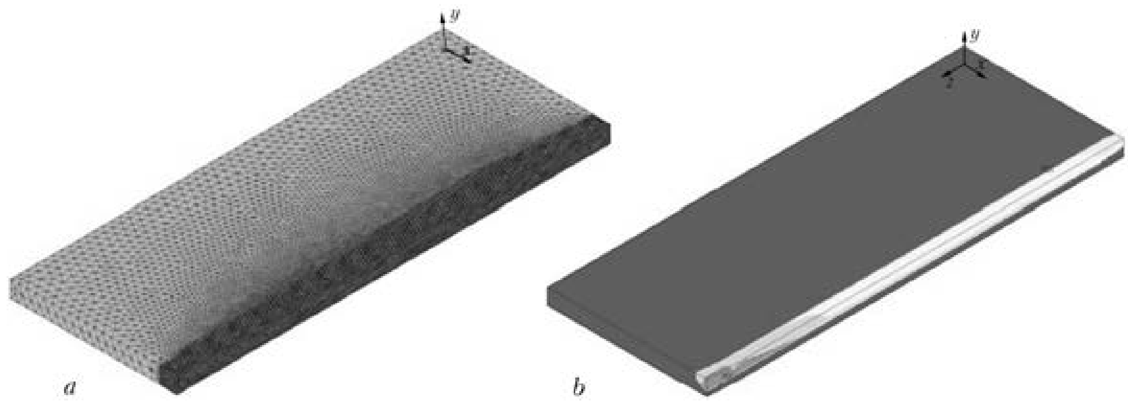

Figure 2. Finite element model used in calculations (*a*), and result of calculations of thermal fields (*b*)

plates with a moving heat source is shown in Figure 2, *a*. Here the results are given for half of the welded joint.

The following parameters were selected as the initial data for the calculations: v_w = 10 m/h, I_w = 220 A, U_a = 12 V.

The calculated thermal fields (Figure 2, *b*) in a clad part were obtained with allowance for the above initial and boundary conditions by using the ANSYS software module. The calculation results were used to plot the isothermal lines of maximal temperatures, from which geometry and size of the penetration zone, HAZ and polymorphic transformation zone (Figure 3, *a*), as well as distribution of maximal cooling rates and temperature gradients in cross section of the welded joint were determined. Comparison of the calculation results on shape of the penetration zone with the experimental data showed the satisfactory agreement between them (see Figure 3).

Welded joints on high-strength titanium alloy VT23 are sensitive to the cooling rate [3]. The results obtained allow evaluating the probable phase composition of the cooling weld and HAZ metals. The diagram (Figure 4) shows the temperature of beginning of the $\beta \rightarrow \alpha''$ martensitic transformation (560 °C), the lines of beginning and end of high-temperature diffusion decomposition of the β-phase, and the line of beginning of precipitation of the low-temperature α_l-phase. The line of the $\beta \rightarrow \omega$ transformation is marked in a cooling rate range of 59–11 °C/s.

Analysis of the obtained calculation data showed that in cooling from a temperature of 1667 to 890 °C the highest cooling rates are noted in the weld metal, where they may amount to 400 °C/s. In the fusion zone the cooling rates may reach 130 °C/s, and in the major part of the HAZ metal the cooling rate is not in excess of 30 °C/s.

Upon reaching a temperature of 900 °C, the cooling rate in the weld decreases to 130 °C/s, and that of the region corresponding to the

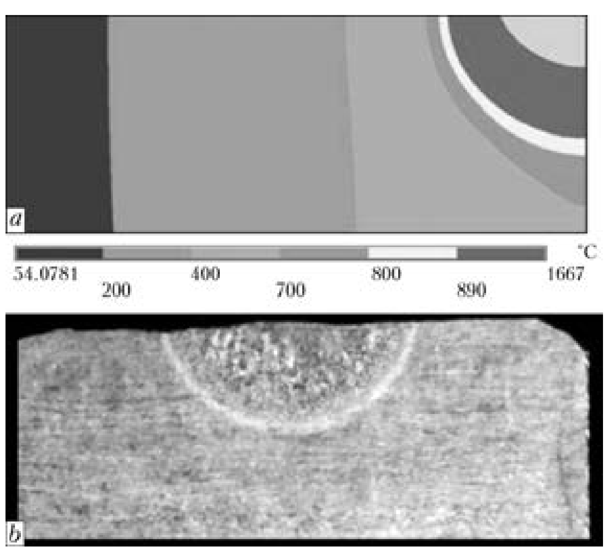

Figure 3. Isothermal lines of maximal temperatures obtained as a result of calculation (shown is half of the welded joint) (*a*), and transverse macrosection of cladding using tungsten electrode (*b*)

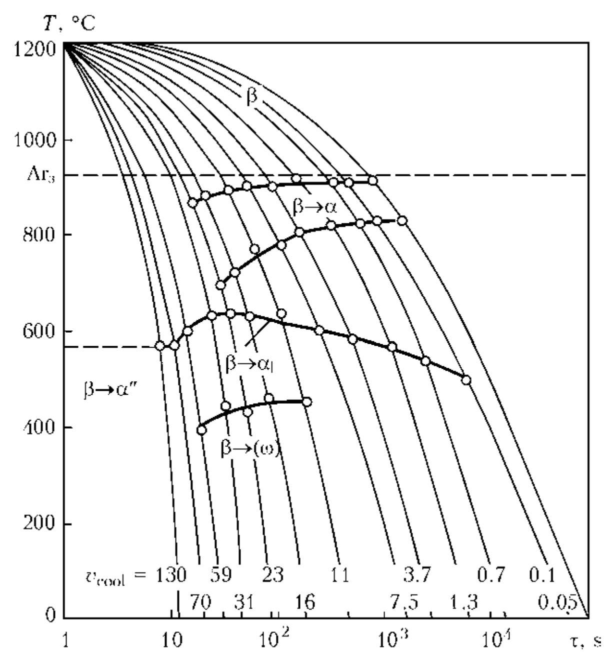

Figure 4. Diagram of anisotropic transformations of titanium alloy VT23 [3]

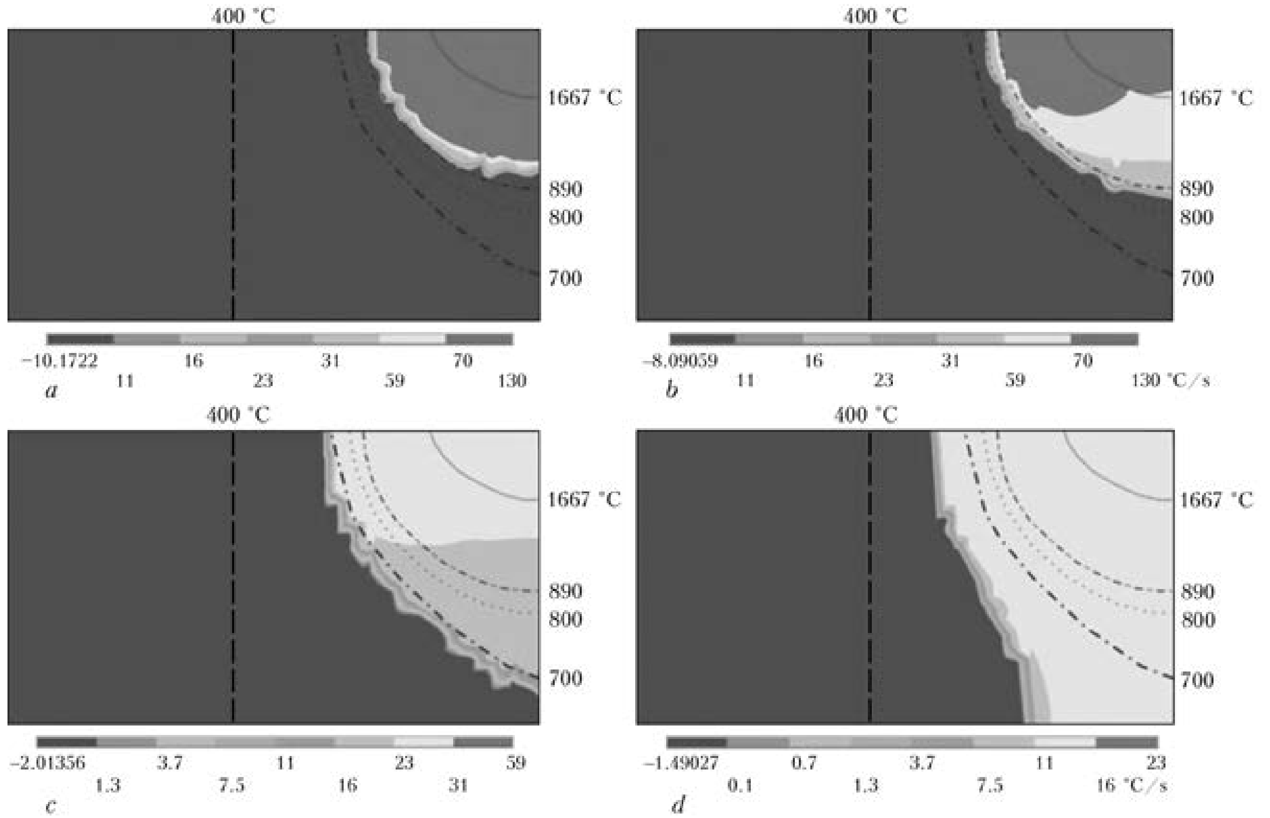

Figure 5. Distribution of maximal cooling rates across the welded joint on titanium alloy VT23 in temperature range of 1000–890 (*a*), 890–800 (*b*), 700–600 (*c*) and 600–500 (*d*) °C at v_w = 10 m/h, I_w = 220 A and U_a = 12 V (*dashed lines* — characteristic isothermal line of maximal temperatures)

coarse-grained zone increases to 70 °C/s. In cooling from 890 to 800 °C, the cooling rate in the weld is 70–130 °C/s. The α″-phase laminae form in this case. In cooling in this temperature range (890–800 °C) the upper part of the welded joint metal has the highest cooling rate. Therefore, the largest size of precipitates of the high-temperature α-phase might be expected in this zone (Figure 5, *a*, *b*). It should be noted that the maximal temperature gradient at a temperature of 890 °C is in the HAZ metal, rather than in the upper part of the cooling weld metal (Figure 6). In a temperature range of 700–600 °C the cooling rate in the upper part of the welded joint metal is still highest and amounts to 23–31 °C/s (Figure 5, *c*), while in cooling from 600 to 500 °C the cooling rate in general becomes levelled across the HAZ metal and equals 11–16 °C/s. In this case, decomposition of the β-phase enriched with β-stabilisers occurs to precipitate the so-called low-temperature α_l-phase [4], which differs from the high-temperature one in that it contains more alloying elements and is much finer. Low ductility of the α_l-phase is responsible for a substantial decrease in ductility of the welded joints on alloy VT23 made at the above process parameters.

Cooling in a temperature range of 500–400 °C/s takes place against a background of levelling of the cooling rates in the weld and HAZ metals. In this case the cooling rates are 3.7–7.5 °C/s, being almost uniform over the entire HAZ metal. No decomposition of the β-phase to form the ω-phase occurs in this temperature

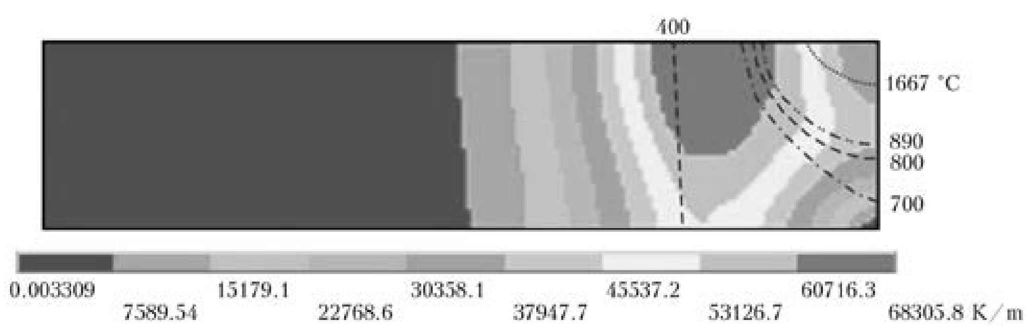

Figure 6. Distribution of temperature gradients across the welded joint on titanium alloy VT23 at 890 °C

range because of the comparatively low cooling rates.

No cooling rates below 0.05 °C/s were detected in the welded joint. Therefore, the weld and HAZ metals consist of a mixture of the α- and β-phases, there proportion being different for different regions of the welded joint.

Conclusions

1. The mathematical model was developed to describe the thermal processes occurring in titanium during TIG welding. The model made it possible to determine size and shape of the weld and HAZ, in which the polymorphic transformations take place to form the α-, α″- and β-phases.

2. The calculations showed that the α″-phase may form in the weld metal having the highest cooling rates.

3. The low-ductility ω-phase does not form in the weld or HAZ metal of the welded joints on titanium alloy VT23 made at the above process parameters because of comparatively low cooling rates in a temperature range of 500–600 °C.

4. Decrease in ductility of the welded joints on titanium alloy VT23 is related to the α_1-phase, which forms in the β-solid solution regions enriched with alloying elements in cooling at a rate of 70–0.1 °C/s.

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Received 24.01.2013

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A new ingenious control system ensuring a high welding quality at lower electrode metal spatter is applied in the developed asynchronous welding generator. It is possible to manufacture asynchronous welding generator not only for manual arc welding, but also for other welding processes, for instance CO_2 welding, as well as for air-plasma cutting, without any significant additional expenses.

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