FORMATION OF NARROW-GAP WELDED JOINTS ON TITANIUM USING THE CONTROLLING MAGNETIC FIELD

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The mechanism of formation of welded joints in a narrow groove under the external effect of the controlling magnetic field is suggested. Dependence of the argon plasma flow rate and gas-dynamic pressure of the arc on the weld pool surface upon the welding process parameters and tungsten electrode geometry was established by the experimental-calculation method.

Keywords: *TIG welding, titanium, magnetic control of the arc, narrow gap, formation of joints*

TIG welding of titanium in argon atmosphere is a widely applied method for joining parts with a thickness of up to 100 mm. As a rule, the more than 16 mm thick joints are produced by multilayer filler-wire welding with groove preparation. The multilayer U-groove welding method is of low productivity and cost effectiveness, the heat-affected zone in this case being quite big.

The narrow-gap TIG argon-arc welding method has received wide acceptance lately for fabrication of thick structures. Compared to U-groove welding, this method allows decreasing the volume of the deposited metal, reducing the consumption of labour for preparation of edges of the parts welded, and substantially increasing the productivity of welding.

However, for successful implementation of the narrow-gap welding process it is necessary to overcome certain difficulties, the main one being ensuring a reliable fusion of vertical side walls of the groove. With traditional TIG welding the major portion of the heat energy of the arc is consumed for penetration of the narrow groove bottom or repeated penetration of the previous-pass weld metal. Therefore, to ensure the reliable fusion of the vertical walls of the narrow groove it is necessary to provide redistribution of heat input into the welded joint, which can be achieved by mechanically moving the tungsten electrode [1] or affecting the arc by the external magnetic field [2].

The E.O. Paton Electric Welding Institute developed the technology for narrow-gap TIG welding by using the controlling magnetic field, which makes it possible to redistribute the heat energy of the arc within the preset limits between the bottom wall of the groove, vertical side walls and molten weld pool. According to this technology, welding is performed with a tungsten electrode lowered into the groove and with a protective nozzle located over the weld edges, this reducing the groove width to 10–11 mm. Magnetic core of the electromagnet is combined with a filler wire feed guide, and is placed in the groove ahead of the tungsten electrode. The electromagnet induces the magnetic field, the force lines of which within the arc zone are directed mostly along the welding line. The value of magnetic induction within the arc zone amounts to 12 mT. This field is transverse with respect to the arc, and its direction changes into the opposite at a certain frequency.

The purpose of this study was to investigate the mechanisms of formation of joints by narrow-gap TIG welding using the controlling magnetic field. The authors suggest the following mechanism of formation of the narrow-gap TIG welded joints using the external controlling magnetic field. Interaction of the external controlling reversible magnetic field generated by the electromagnet with the arc current induces Lorentz force F_a, which deflects the arc and leads to displacement of the anode spot in a direction of action of this force:

$$\vec{F}_a = \vec{j}\vec{B}, \qquad (1)$$

where $\vec{j}$ is the density of the arc current, A/m^2; and $\vec{B}$ is the magnetic induction, T.

Redistribution of the welding arc energy input into the metal welded and fusion of vertical walls of the groove in the base metal during narrow-gap welding are provided by the alternating deflection of the arc to the side walls of the groove under the effect of Lorenz force F_a (Figure 1). The key parameters of the controlling magnetic field for narrow-gap welding are values of the component of magnetic induction along the welding direction, B_x, transverse component of magnetic induction, B_y, and frequency of reversing of the magnetic field, w.

At the initial time moment, when the arc is at the centre of the magnetic core, magnetic induction in a direction of axis y is equal to zero, i.e. $B_y = 0$. Hence, the arc is affected only by component F_x of the Lorentz force in a plane normal to the weld axis. Deflection of the arc to the extreme position generates additional component F_y of the Lorentz force, the direction of which depends on the direction of component B_y (Figure 2). Under the effect of F_y, the anode spot is

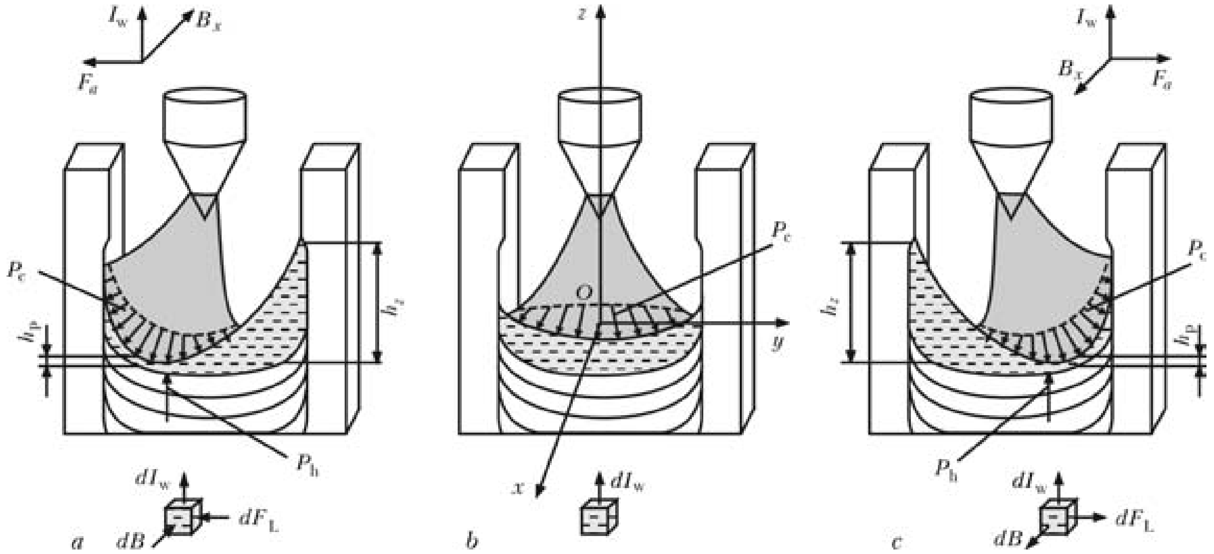

Figure 1. Schematic of fusion of side walls of the groove and location of the welding arc in extreme (*a*, *c*) and intermediate (*b*) positions

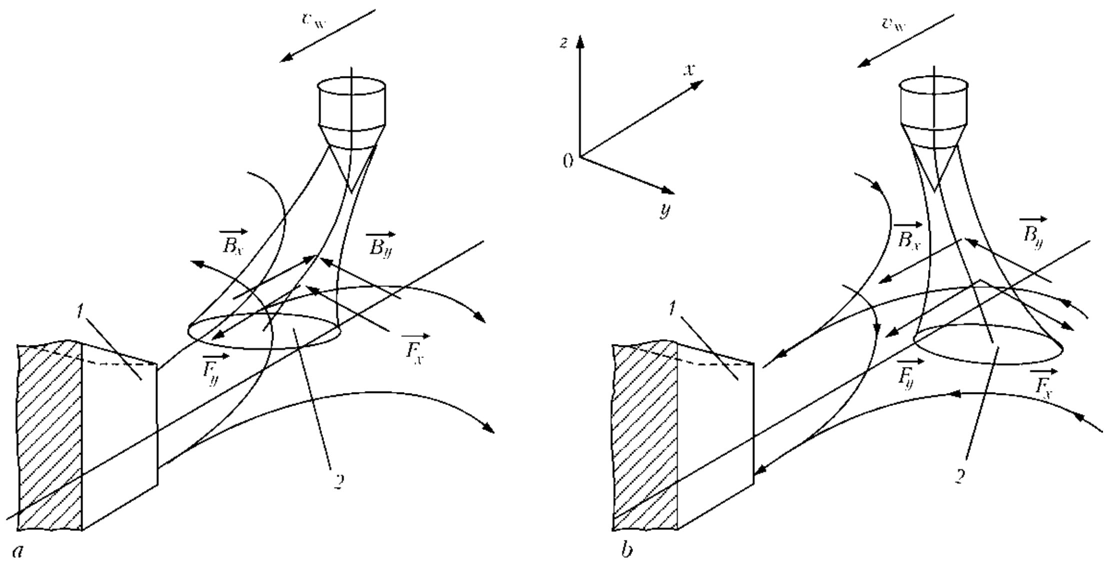

Figure 2. Direction of magnetic induction and forces affecting the arc in narrow-gap welding at the extreme left (*a*) and right (*b*) positions of the arc: *1* — magnetic core; *2* — anode spot; $\vec{B}_x$ and $\vec{B}_y$ — components of magnetic induction in planes *zOx* and *zOy*, respectively; $\vec{F}_x$ and $\vec{F}_y$ — components of the Lorentz force generated by interaction of components $\vec{B}_x$ and $\vec{B}_y$; v_w — welding speed

moved along the welding direction to the head part of the weld pool.

The force of pressure of the arc column plasma, P_c (see Figure 1) causes the weld pool surface to sag, thus pushing off the molten metal from the wall fused and head part of the weld pool to its tailing part and the opposite wall of the groove. As a result, thickness of the molten metal layer under the arc decreases, and thickness of the molten metal layer, h_z, in the tailing part of the weld pool increases. Lorentz force F_L generated due to interaction of the current in the weld pool and external controlling magnetic field, and the force of hydrostatic pressure of the molten pool metal, P_h, prevent the liquid interlayer thickness from decreasing. With alternating deflection of the arc to the side walls of the groove the molten metal flows over from the walls fused by the arc (Figure 3, *a*), this resulting in excitation of transverse oscillations of the molten pool metal. Disappearance of the molten metal interlayer under the arc may cause lacks of fusion in the form of cavities that are not filled with molten metal and undercuts (Figure 3, *b*). Investigations on estimation of variations in values of the above forces during narrow-gap welding were carried out to analyse their effect on the behaviour of the molten metal.

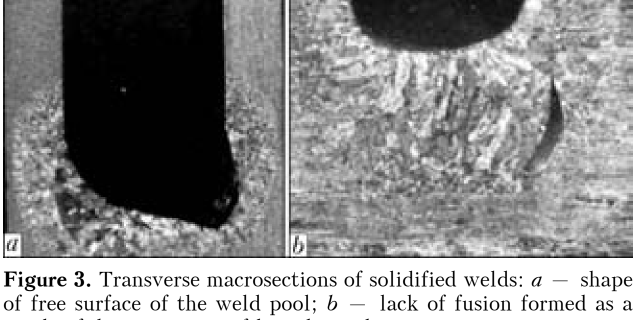

Figure 3. Transverse macrosections of solidified welds: *a* — shape of free surface of the weld pool; *b* — lack of fusion formed as a result of disappearance of liquid interlayer

Figure 4. Photos (light filter IKS-5) of the 5 mm diameter flat-tip electrode with a tip width of 1 (*a*), 2 (*b*) and 5 (*c*) mm, and the arc gap in narrow-gap welding at I_w = 400 A

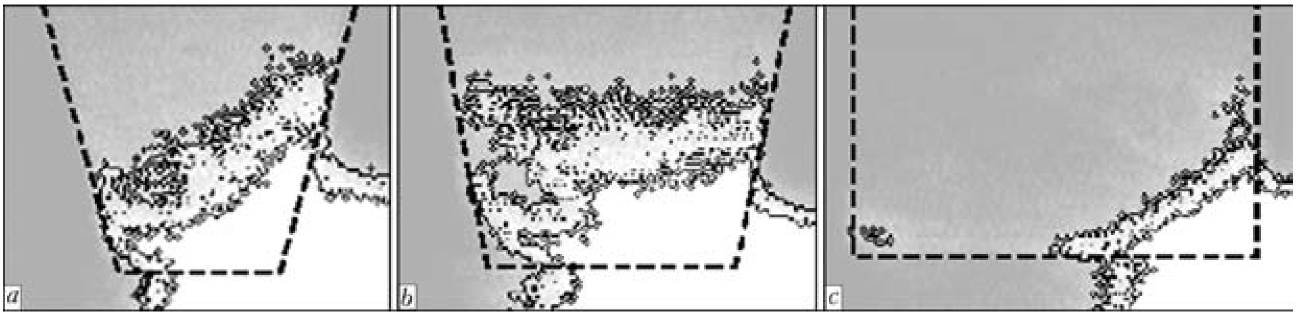

Figure 5. Images of the arc column near cathode in narrow-gap welding at I_w = 400 A after computer processing: *a*–*c* — see Figure 4

Lorenz force F_L induced in the weld pool by the magnetic field can be estimated from the following formula:

$$F_L = (I_w B_x) h_p, \quad (2)$$

where h_p is the depth of the molten metal interlayer under the arc in the weld pool (see Figure 1).

As proved by experimental studies, the depth of the weld pool within the arc affected zone during narrow-gap welding decreases from 2 to 1 mm with increase in values of the transverse component of magnetic induction B_x from 2.5 to 12.0 mT and longitudinal component $B_z \le 4.0$ mT [3]. In this case the value of Lorenz force F_L is not in excess of $5 \cdot 10^{-3}$ N.

The force of pressure of the arc column plasma, P_c, can be estimated by determining geometric parameters of the arc. Assuming that the arc in narrow-gap welding of titanium has the shape of a cone with a height equal to arc length l_a and radii of the arc column near cathode R_{cath} and near anode R_{an}, respectively, of the upper and lower bases of the cone, it is possible to estimate the rate of the gas-dynamic plasma flow and total force of pressure of the arc column on the weld pool surface.

Distribution of plasma flow rate v_z was determined by the procedure suggested in study [4]. The total force of pressure of the arc column plasma on the weld pool surface was determined from the formula for a conical model of the welding arc [5]:

$$F_c = \mu_0 I_w^2/(4\pi) \ln (R_{an}/R_{cath}), \quad (3)$$

where μ_0 is the magnetic permeability.

Geometric parameters of the welding arc near cathode were estimated by filming the real arc process (Figure 4) followed by computer processing of the resulting images (Figure 5). Diameter of the arc near anode was determined by the divided anode procedure [6].

Tungsten electrodes with a rod diameter of 5 mm, having a cone-shaped (Figure 6, *a*) or flat (Figure 6, *b*) tip, can be used for narrow-gap welding of titanium with the magnetically controlled arc. An electrode with the flat tip is located during welding with its wide side across the weld axis. The flat-tip tungsten electrodes are advantageous in that they allow regulating displacement of the cathode spot in alternating deflection of the arc under the effect of the external magnetic field and, hence, within the certain limits, as well as heating of the tungsten electrode edge. Also, they allow changing geometric parameters of the arc

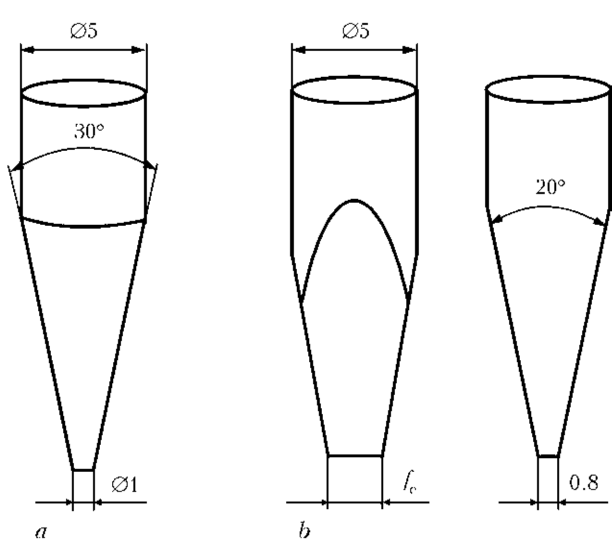

Figure 6. Types and sizes of tungsten electrodes used for narrow-gap welding of titanium, having cone-shaped (*a*) and flat (*b*) tips

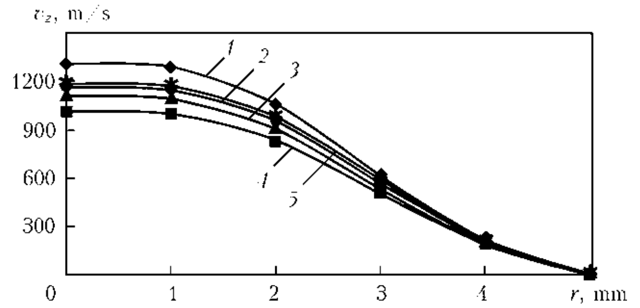

Figure 7. Distribution of plasma flow rate v_z near anode at width of the tip of the flat-tip electrode f_e equal to 1.0 (*1*), 2.5 (*2*), 2.0 (*3*), 2.5 (*4*) and 5.0 (*5*) mm: r — distance from the anode centre

discharge by selecting only one parameter — electrode tip width f_e.

Results of calculation of distribution of the plasma flow rate are shown in Figure 7, and those of the total force affecting the weld pool surface are shown in Figure 8. Analysis of the results indicated that the use of the cone-shaped tungsten electrode in narrow-gap welding at I_w = 400 A provides the maximal plasma flow rate and maximal pressure of the arc column on the weld pool surface, $P_c \approx 2.5 \cdot 10^{-2}$ N. When using an electrode with flat tip f_e = 1.0 mm wide, pressure of the arc column plasma is $P_c \approx 2.4 \cdot 10^{-2}$ N. The use of an electrode with flat tip f_e = 2.5 mm wide provides the largest diameter of the arc column near cathode and minimal plasma flow rate with the minimal pressure of the arc. Increasing the tip width to more than 3.0 mm leads to decrease in diameter of the arc column near cathode, as well as increase in both plasma flow rate and arc pressure on the weld pool surface. Decrease in diameter of the arc column, in the opinion of the authors, is related to lower heating of tungsten electrodes with a tip more than 3.0 mm wide.

The analysis conducted allows a conclusion that in narrow-gap welding the force of pressure of the arc plasma is much in excess of Lorentz force F_L. That is why the pressure of the arc plasma is balanced in the main by the force of hydrostatic pressure of the molten pool metal. Therefore, the main cause of formation of lacks of fusion and undercuts in narrow-gap welding is increase in pressure of the arc column plasma. It is well-known that the pressure of the arc on the molten metal can be decreased by decreasing the welding current. However, this will lead to decrease in productivity of the welding process. The arc pressure on the molten metal can also be decreased by changing geometric parameters of the arc. In particular, the use of the flat-tip tungsten electrodes in narrow-gap welding allows reducing the rate of the gas-dynamic plasma flow and arc pressure on the weld pool surface.

Comparison of the results of calculation of the arc plasma pressure with the results of investigation of transverse macrosections of the welds shows that no undercuts and lacks of fusion will form in the welds providing that the arc plasma pressure does not exceed $2 \cdot 10^{-2}$ N. Therefore, to reduce the probability of formation of defects in the form of lacks of fusion and

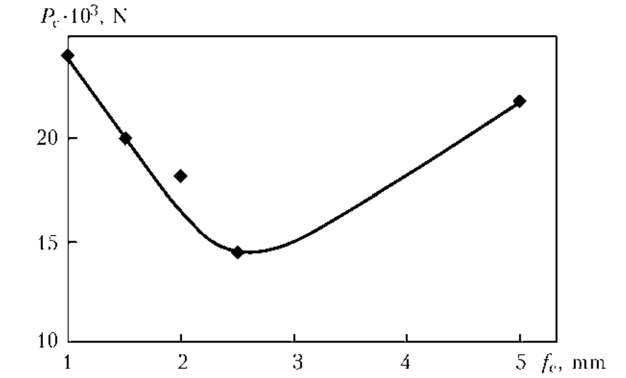

Figure 8. Dependence of total pressure of the arc column plasma P_c on width of the tip of the flat-tip electrode f_e in narrow-gap welding at I_w = 400 A and l_a = 5 mm

undercuts in the welds, in narrow-gap welding with the controlling magnetic field it is necessary to use tungsten electrodes with a special shape of the tip that provides decreased values of the arc pressure on the weld pool surface.

CONCLUSIONS

1. The mechanism of formation of a welded joint in the narrow groove under the effect of the external controlling magnetic field was suggested. According to this mechanism the vertical walls of the groove are fused due to the heat of the anode spot that is moved in turns to the opposite side walls with reversing of the magnetic field, thus pushing off the molten metal to the vertical walls and tailing part of the weld pool due to the effect of the force of gas-dynamic pressure of the arc plasma.

2. Dependence of the argon plasma flow rate and gas-dynamic arc pressure on the weld pool surface in narrow-gap welding with the magnetically controlled arc on the welding process parameters and width of the tip of the flat-tip tungsten electrodes was proved by the experimental-calculation method.

3. It was shown that the use of tungsten electrodes with the tip of an increased width allows decreasing the total value of the force of pressure of the arc column plasma on the weld pool surface, thus preventing formation of the lack of fusion type defects in the welds.

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