

HIGH VOLTAGE ELECTRIC PULSE WELDING OF TITANIUM WITH STAINLESS STEEL

ВЫСОКОВОЛЬТНАЯ ЭЛЕКТРОИМПУЛЬСНАЯ СВАРКА ТИТАНА С НЕРЖАВЕЮЩЕЙ СТАЛЬЮ

Prof. dr. Grigoryev E.

Faculty of Experimental and Theoretical Physics – National research nuclear university «MEPhI», Russia

Abstract: Investigations into the welding of titanium and stainless steel have shown that application of a short electric current pulse and pressure produces stronger welded joints composed of both similar and different metals of considerably different thickness. A combination of a short electric pulse with simultaneous high speed application of mechanical pressure in the weld zone causes high-speed deformation of the contact zone. The process of joint formation itself does not cause any appreciable diffusion during welding. The greatest energy emission and the maximal heating occur on the contacting surfaces being welded with the passage of an electric current pulse through the welding zone. Depending on the initial state of the surfaces and parameters of the pulse effect this can result in melting without formation of joint, formation of a strong welded joint with characteristics no less than those of welded metals, and in destruction of the contact zone. Simultaneously with intensive heating, and due to applied pressure, high-speed deformation of materials takes place and a strong welded joint is formed. The zone of interaction of titanium with 18-10 stainless steel was studied using the method of micro-X-ray spectrum analysis with a "CAMEBAX MBX-1S" analyzer. The qualitative and quantitative analyses show that intermetallics have not been found in intermediate layer. Optimal parameters for the welding of titanium and stainless steel have been determined on the basis of the tests conducted.

KEYWORDS: TITANIUM, STAINLESS STEEL, HIGH VOLTAGE ELECTRIC PULSE CURRENT WELDING

1. Introduction

Titanium and its alloys are characterized by high strength at relatively low specific gravity as well as by high corrosion resistance in the air, in sea water and in many corrosive environments. In consideration of its properties titanium is used in chemical industry, aircraft industry and nuclear power engineering [1]. It is not possible to make a joint of high mechanical properties by direct titanium with steel using conventional welding methods. Joining of titanium with steel is effected with the use of special welding methods. The aim of this paper is to present joining method titanium with stainless steel by high – voltage electric – current pulse and to point out advantages of this method.

The effect of high – voltage electric current pulses on the surfaces of contacting metallic conductors leads to considerable changes in the surface structure. Depending on the initial state of the surfaces and parameters of the pulse effect this can result in melting without formation of a joint, formation of a strong welded joint with characteristics no worse than those of welded metals, and in destruction of the contact zone [2]. A combination of a short electric pulse with simultaneous application of mechanical pressure in the weld zone brings about high-speed deformation of the contact zone. The process of joint formation itself does not cause any appreciable diffusion during welding.

The greatest energy emission and maximum heating occur on the contacting surfaces being welded with the passage of an electric current pulse through the welding zone. Simultaneously with intensive heating, and due to applied pressure, high-speed deformation of materials takes place and a strong welded joint is formed. Calculations have shown that localization of energy emission during the passage of an electric current pulse has the following scale of l_T :

$$l_T \leq \frac{1}{j_c} \sqrt{\frac{\kappa T_c}{\rho}} \quad (1)$$

where: ρ is electrical resistivity of material, T_c – characteristic temperature in the contact zone, k – thermal conductivity of material, j_c – current density.

As follows from (1), the main heating of material up to $T \sim T_c$ is localized in the vicinity of contact in the zone $\sim 2l_T$ wide. All high-speed deformation welding processes are located in this zone.

The above physical phenomena and quantitative estimates make it possible to formulate a simplified scheme of high-speed flow of material in the zone of weld formation. Joint formation is due to deformation and initial profile crumbling of the contacting surfaces. With the intensive heating of the contact zone material

becomes more plastic, its viscosity being reduced. This contributes to intensive plastic deformation of material in the weld zone. Assuming a characteristic scale of material flow in the contact zone $l \sim 10^{-3}$ m, weld formation time of no less than current pulse duration $\tau_0 \sim 10^{-4}$ s, and estimating the magnetic viscosity of materials being welded as $\nu_m = \rho / \mu \mu_0 = 0,05$ m²/s, one can calculate the Reynolds magnetic number:

$$\text{Re}_m = \frac{l^2}{\tau_0 \nu_m} \approx 10^{-2} \ll 1 \quad (2)$$

When $\text{Re}_m \ll 1$ the set of equations for magneto hydrodynamics allows for simplifications, since media transformations can be neglected in calculating axial current magnetic field.

Generally, Reynolds number is $\text{Re} = Vl/\nu \approx 20$, where: V – velocity, ν – kinematics viscosity of material. When $\text{Re} \approx 20$, and $\text{Re}_m \ll 1$, the set of equations is simplified and velocity has only a radial component – along the contact surface (the problem has cylindrical symmetry). Analysis shows that at the initial stage of the process of weld joint formation, the electric current magnetic field prevents weld formation at the moment of the current pulse passage. When current density exceeds the critical value of j_* no welded joint is formed:

$$j_* \cong \sqrt{8\pi P / \mu \mu_0 S}, \quad (3)$$

where: P is average pressure in the contact zone, S – contact surface area.

At the final stages of welded joint formation (when cavities are being closed by flowing material), magnetic field facilitates weld formation – the speed of material flow increases with the passage of a current pulse.

Characteristic time of welded joint formation can be obtained on the basis of a set of equations:

$$\tau_* = 3\eta \left(\frac{R_0}{h_0} \right)^2 \left(\frac{8P}{\pi x_*} - \mu \mu_0 I^2 \right)^{-1} \frac{1 - x_*^4}{x_*^4} \quad (4)$$

where: η is viscosity of material, I – welding current, R_0 – initial radius of contact spot, h_0 – value of surface roughness, R_* – final radius of contact spot, $x_* = R_*/R_0$.

To get a strong welded joint of different materials with variable thickness a short current pulse ($\tau \sim 10^{-3} \div 10^{-4}$ s) was used at a high-voltage discharge of a battery of capacitors.

2. Experimental procedures and results

The purpose of the work was to determine the possibility for the pulse effect of electric current and pressure to produce welded joints of various component parts of different thickness from 18-10 stainless steel and titanium. Characteristics of the chemical composition of 18-10 stainless steel and titanium are resulted in Table 1 and Table 2 respectively.

Table 1: The chemical composition of 18-10 stainless steel

Chemical element	Si	Cu	Mn	Ni	Ti	P	Cr	S
mass %	0.8	0.30	2.0	9.0-11.0	0.6-0.8	0.035	17.0-19.0	0.020

Table 2: The chemical composition of titanium

Chemical element	Fe	C	Si	N	Ti	O	H
mass %	≤0.18	≤0.07	≤0.1	≤0.04	98.61-99.7	≤0.12	≤0.01

The schematic of the Electrical Discharge Welding (EDW) system is shown in Figure 1.

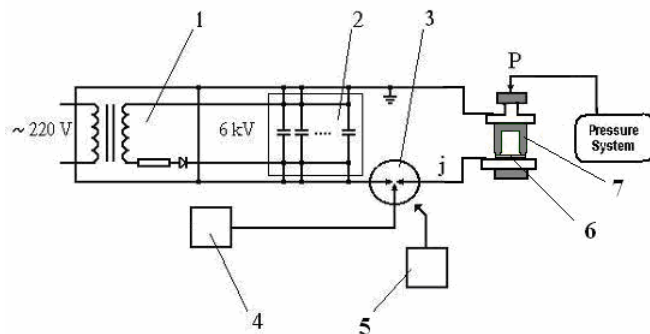


Figure 1. Schematic of EDW system.

1 – charging unit, 2 – capacitor bank, 3 – trigatron switch, 4 – electrical discharge ignition system, 5 – pulse electrical discharge registration system, 6 – titanium foil, 7 – 18-10 stainless steel ring.

Electrical Discharge Welding (EDW) apparatus for high – voltage electric – current pulse welding consists basically of charging unit (1); a bank of capacitors (2), trigatron switch (3), electrical discharge ignition system (4) and pulse electrical discharge registration system (5). The capacitor bank consists of thirty 200 μ F capacitors that can store up to 6 kV. EDW uses the pulse current generated by the capacitor bank to heat jointed specimens (6) and (7) subjected to constant pressure during the welding process. The discharge current is measured by a toroidal Rogowsky coil (5). An oscillograph showing a typical output from the Rogowsky coil is shown in Figure 2.

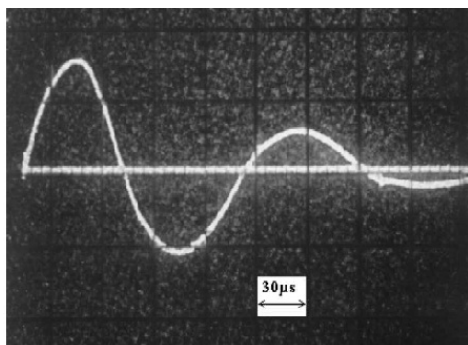


Figure 2. Typical pulse current trace from registration system (Rogowsky coil)

In our experiments the welded joints of foil (thickness $t = 100 \mu\text{m}$) and massive ring ($D = 16 \text{ mm}$, $d = 10 \text{ mm}$, where: D , d – external and internal diameters of ring) were investigated. The component parts mentioned above have been made of both materials.

It was established experimentally that the optimum value of the amplitude of the current density to weld of 18-10 stainless steel is $(3,3 \pm 0,1) \cdot 10^9 \text{ A/m}^2$, and for titanium is $(2,9 \pm 0,1) \cdot 10^9 \text{ A/m}^2$. Figures 3 and 4 show dependence of the tensile strength (σ_B) of the connection parts made by EDW of 18-10 stainless steel (Figure 3) and titanium (Figure 4) on the pressure P in the joints during EDW.

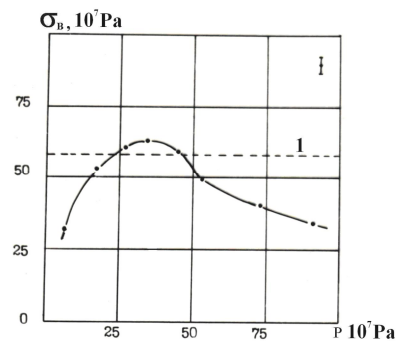


Figure 3. The pressure dependence of the tensile strength of stainless steel joints (1 – the ultimate strength with TIG welding).

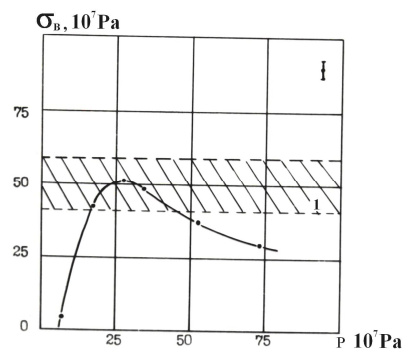


Figure 4. The pressure dependence of the tensile strength of titanium joints (The shaded region 1 corresponds to a tensile strength of Ti).

To test workability of the welded joints, they were subjected to the following external effects: temperature, vibration, shock loads and external pressure. Strength (a test in internal pressure) and airtightness were chosen as the principle criteria in quality estimation of the welded joints. Airtightness was checked with helium leak detector, the value of helium flow through the welded joint should not exceed $1.3 \cdot 10^{-2} \text{ Pa/s}$. The experimental results of the test compounds for leaks are presented in Table 3.

Table 3: Results of tests for airtightness of welded joints

№	Materials		Internal pressure, 10^5 Pa	Tightness yes / no
	Foil	Massive ring		
1	titanium	18-10 stainless steel	25	yes
2	titanium	titanium	25	yes
3	18-10 stainless steel	18-10 stainless steel	25	yes
4	18-10 stainless steel	titanium	25	yes

It should be noted that joints of titanium and 18-10 stainless steel are of the greatest scientific and practical interest, rather than Ti-Ti or stainless steel-stainless steel joints. However, wide utilization of joints of this kind is constrained by the unsatisfactory ability of

these materials to weld together. Phase diagram of the Fe-Ti system shows low solubility of Fe in Ti (0,05 – 0,1%). Practically all traditional processes welding of titanium with steel lead to the formation of a hard and brittle intermetallic layers (TiFe, TiFe₂, TiNi, etc.) in the zone of interaction. This leads to cracking of welded joint under thermal stresses.

The zone of interaction of titanium with 18-10 stainless steel during the pulse effect of electric current and pressure was studied using the method of micro-X-ray spectrum analysis with a "CAMEBAX MBX-1S" analyzer using a standard technique.

Investigations have shown:

The width of the intermedial layer, namely penetration depth Ti→Fe, Fe→Ti, Cr→Ti, Ni→Ti does not exceed 1 – 2 μm (Figure 5), i. e. it is nearly equal to the minimal diameter of a "CAMEBAX MBX-1S" analyzer microprobe.

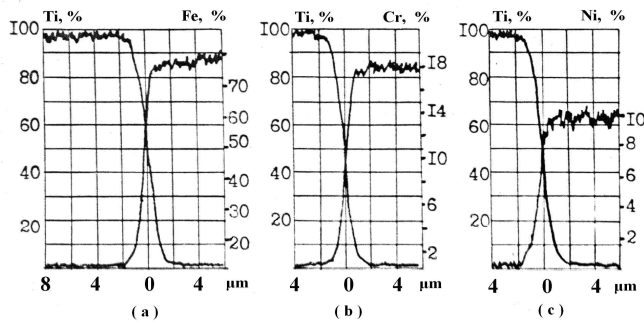


Figure 5. The character of distribution: (a) Ti-Fe; (b) Ti-Cr; (c) Ti-Ni in the contact zone of joint of titanium and 18-10 stainless steel.

The width of the intermedial layer (with the accuracy of 1 – 2 μm) does not depend on voltage (U) of the battery of capacitors and pressing force (F).

Qualitative (according to "QUALI" program) and quantitative ("CORREX" program) analyses did not detect intermetallics of the TiFe, TiFe₂, TiNi; mutual diffusion of elements through the joint zone of titanium and stainless steel have not been detected either. Therefore we can conclude that diffusion processes do not hold when short electric current pulse and pressure are applied for welding.

3. Conclusion

Optimal parameters for the welding of titanium and 18-10 stainless steel were determined on the basis of the tests conducted.

Investigations into the welding of titanium and 18-10 stainless steel showed that application of a short electric current pulse ($\tau \sim 10^{-3} - 10^{-4}$ s) and pressure produces improved strength welded joints composed of both similar (18-10 stainless steel - 18-10 stainless steel and titanium - titanium) and different (titanium - 18-10 stainless steel) metals with considerably variable thicknesses.

4. References

- [1] K. Szymlek, Review of Titanium and Steel Welding, Methods Advances in Materials Sciences, Vol 8, N 1, 2008, p 186-194.
- [2] E. G. Grigoryev, V. N. Bazanov: Electric Current Pulse Welding of Titanium with 18-10 Stainless Steel, Electric Current Pulse Welding of Titanium with 18-10 Stainless Steel, Advanced Materials Research, Vols. 83-86, 2010, p 1251-1253.