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ELECTRODYNAMIC TREATMENT OF WELDED JOINTS OF ALUMINIUM AMg6 ALLOY IN THE PROCESS OF HEATING THE WELD METAL

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ABSTRACT

The effect of thermal action in the process of electrodynamic treatment (EDT) of welded joints of AMg6 alloy on their stress-strain states was investigated. Based on the Prandtl–Reuss ratio for the movement of elastic-plastic environment at elevated temperatures, a mathematical model of evaluation of stress state of metal materials as a result of their interaction with the electrode-indenter at EDT was developed. On the basis of the developed model, a calculated evaluation of the effect of elevated temperatures on residual stresses of a preliminary strained plate of AMg6 alloy as a result of EDT was carried out. The verification of the results of the calculation with the use of welded plates of AMg6 alloy of 2 mm thickness was carried out. Thermal action was carried out with the help of the accompanying EDT preheating of the weld metal. To evaluate the effect of the thermal potential of EDT on residual stresses, TIG welding of butt joint specimens was performed. EDT of specimens at the temperature T_{EDT} = 20 and 100 °C was performed. Applying the method of electron speckle-interferometry, the values of the longitudinal component (along the longitudinal axis of the weld) of residual welding stresses in the central cross-section of the specimens before and after EDT were measured. The thermal impact on EDT was provided with the use of a heat gun, and the heating temperature was controlled by an infrared thermometer. It was revealed that heating of the weld in the process of its EDT along the longitudinal axis of a butt joint provides greater values of residual compressive stresses in the weld centre as compared to the treatment at T = 20 °C.

KEYWORDS: electrodynamic treatment, welded joints, accompanying heating, residual welding stresses, aluminium alloys

INTRODUCTION

The use of energy of pulsed electromagnetic fields (PEMF) for regulating residual stresses in the technologies for treatment of structural materials is relevant for the modern industry. One of such methods, characterized by energy efficiency and ease of realization, is electrodynamic treatment (EDT) of welded joints [1].

The modern trend in engineering practice is the study of measures aimed at improving the efficiency of EDT. One of them is the combination of the EDT process with preheating of the treatment zone. Scientific principles of using thermal potential at EDT are based on the results of the work [2], where it is shown that heating of preliminary tensioned thin rods of low-carbon steel facilitates an increase in the efficiency of their treatment by PEMF to reduce the level of residual stresses. Considering that EDT efficiency is determined by an electric pulsed component of electrodynamic action [3], the thermal action can intensify mechanisms of relaxation of residual welding stresses. This should have a positive effect on regulation of stress-strain states of metals, alloys and welded joints during their EDT.

The aim of the work is to study the effect of preheating the weld metal in the process of EDT on residual stresses of welded joints of aluminium AMg6 alloy.

According to the results of studies with the use of EDT of preliminary loaded plane specimens of aluminium AMg6 alloy applying longitudinal tension σ_x, it was found that the maximum indices of treatment efficiency were achieved at a value of σ_x, which is close to the yield strength $\sigma_{0.2}$ of the metal [4]. As an efficiency criterion, a discrete decrease in the tensile stresses σ_x of the specimen as a result of EDT was taken. Under the conditions, where the stresses σ_x did not reach or exceeded the level $\sigma_{0.2}$, a decrease in EDT efficiency as compared to the treatment of the specimen at $\sigma_x = \sigma_{0.2}$ was determined. The presence of residual tensile stresses in the active zone of the welded joint of AMg6 alloy, which is close to $\sigma_{0.2}$, creates the preconditions for effective use of EDT to relax the latter [1]. Investigations of stress states of welded joints of AMg6 alloy after EDT at different T_{EDT} allowed evaluating thermal potential as an increase in treatment efficiency factor.

MODELING OF STRESS STATES IN THE PLATES OF AMg6 ALLOY FROM THE IMPACT ACTION OF THE ELECTRODE-INDENTER AT EDT IN THE CONDITIONS OF THEIR HEATING

Taken into account the abovementioned, it should be noted that EDT with a compatible heating of the treatment zone can be effective as compared to EDT with-

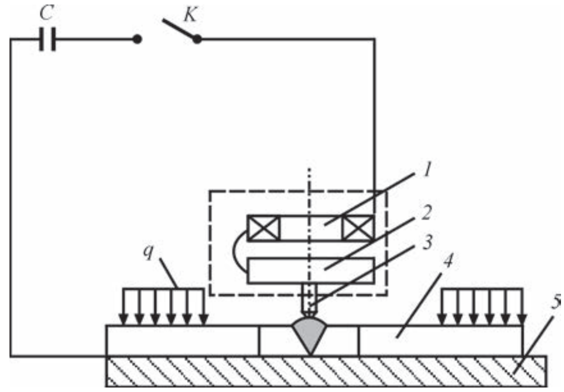

Figure 1. Scheme of EDT of plates: *1* — inductor; *2* — disc; *3* — movable electrode-indenter; *4* — specimen being treated; *5* — working table; *q* — load fixing the specimen [5]

out heating to reduce residual welding stresses. The search for the optimal EDT mode is associated with an experimental evaluation of a large number of process parameters. An alternative solution is the mathematical modeling of the EDT process, which allows evaluating the change in the stress-strain state of welded joints after the treatment in the conditions of elevated temperatures that have not been conducted so far.

On the basis of the work [5], mathematical modeling of the effect of temperature T_{EDT} was carried out on the stress states of welded plates of aluminium AMg6 alloy as a result of the impact action of the electrode-indenter. The creation of dynamic pressure on the surfaces of EDT-treated plates was carried out according to the scheme (Figure 1). The EDT-treated specimen *4* in the form of a welded plate is located on the working table *5*. After starting the contactor *K* of the discharge cycle of the capacitance *C* on the inductor *1*, the latter generates a magnetic field of appropriate power, under the action of which the disc *2* of nonferromagnetic material together with the electrode-indenter *3* obtain different values of the initial speed V_0 in the direction of the working table *5*. The values V_0 were found on the basis of previous studies. The impact interaction of the EDT electrode-indenter with the surface of the plates leads to the formation of different levels of residual stresses and strains in them depending on the value V_0.

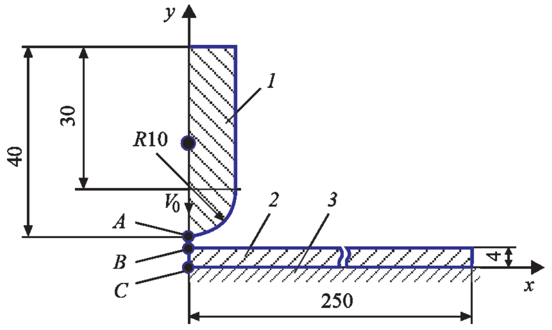

Figure 2. Design scheme of the process of dynamic loading of EDT-treated plates: *1* — electrode-indenter; *2* — specimen being treated; *3* — absolutely rigid base; *A* is the point on the outer surface of the electrode-indenter; *B* is the point on the outer surface of the plate; *C* is the point on the back surface of the plate [5]

Creation of a mathematical model of the dynamic component of EDT in the conditions of elevated temperatures was carried out using a simplified two-dimensional (2D) plane production. The design scheme of the problem of the process of impact interaction of the electrode-indenter with the plates [5, 6] is presented in Figure 2. The presence of the abovementioned geometric symmetry of the bodies being in impact interaction allows considering only half of their cross-section with the simultaneous imposition of appropriate boundary conditions on it. These conditions include the imposition of a ban on the movement of nodes of a finite element mesh (FEM) of the bodies, located on the axis of the symmetry, in the horizontal direction "*X*". The presence of the plates of the working table 5 in the scheme of electrodynamic treatment (Figure 1) is advisable to be replaced with resting on an absolutely rigid base *3* (Figure 2), which in the mathematical definition will be equivalent to the imposition of a ban on moving in the vertical direction "*Y*" of the FEM nodes, belonging to the lower surface of the plate contacting the working table.

For numerical modeling, a continuum model of the environment was used. This made it possible to record the laws of conservation of mass, quantity of movement and energy in the form of differential equations in partial derivatives [5]. In the mathematical definition, the behaviour of materials of the plate (aluminium AMg6 alloy) and electrode-indenter (copper M1) under the action of external pulse load was described using the ideal elastic-plastic rheological model of the material, which in the library of materials of the program ANSYS/LS-DYNA is called "PLASTIC-KINEMATIC". The effect of elevated (above the room) temperatures T_{EDT} was set by the values of the modulus of elasticity *E* and the yield strength $\sigma_{0.2}$ at $T_{\mathrm{EDT}} = 20$ and 100 °C.

Residual welding stresses were modeled by setting the longitudinal (along the axis *X* in Figure 2) component of tensile stresses σ_x, the values of which were taken equal to $\sigma_{0.2}$ of AMg6 alloy at appropriate temperatures. The normal contact interaction of the hemispherical cylindrical electrode-indenter of 15 mm diameter (diameter of the sphere is 30 mm) weighing 102.5 g of copper M1 alloy with a plate of AMg6 alloy of 250×250×2 mm was modelled. The mechanical characteristics of the plate and indenter, being in a contact interaction, are given in Table 1. The electrode-indenter receives the value $V_0 = 5$ m/s, which was determined on the basis of the previous studies [5]. The final calculated distribution of residual stresses σ_x component in the plates was determined along the impact line (direction V_0 in Figure 2).

Figure 3 shows the results of modeling the residual distributions of a longitudinal (along the weld) component of stresses σ_x along the impact line in the plates $\delta = 2$ mm. It can be seen that the compressive stresses σ_x along the impact line on the contact and reverse surfaces of the plates reach 0.3 σ_y of AMg6 alloy at $T = 20$ °C (α) and are close to σ_y at $T = 100$ °C (*b*).

EQUIPMENT AND PROCEDURE OF EXPERIMENTAL INVESTIGATIONS

In order to verify the results of mathematical modeling, EDT of the specimens of butt welded joints the size of 250×250×2 mm with a central weld was carried out. Before welding, the specimens were rigidly fixed on the assembly table by clamping straps along the longitudinal welded edges at a distance of 20 mm from them according to the scheme in Figure 1. Welded joints were produced by automatic TIG welding at the values of voltage, current and speed of the process, respectively, $U_a = 20.1$ V, $I_a = 115$ A and $v_w = 5$ mm/s. As an additive, the wire of grade ER5356 ESAB with a diameter of 1.6 mm, fed into the arc zone at a rate $v_{wf} = 33$ mm/s was used.

After welding and complete cooling of the specimens by the method of electron speckle-interferometry [7] before and after EDT, the values σ_x of residual welding stresses in the weld centre, along the fusion line and at a distance of 10 mm from the weld centre were determined.

EDT of specimens in manual mode at the charge voltage and capacitance of the capacitor, respectively $U_w = 500$ V and $C = 5140$ μF, was carried out along the longitudinal axis of the weld (Figure 4).

At the first stage of the studies, the evaluation of the initial residual stress state of the welded plate No. 1 was performed, which was subsequently subjected to EDT at $T_{EDT} = 20$ °C. At the second stage after evaluation of the initial residual stress state of the plate No. 2, it was subjected to EDT at $T_{EDT} = 100$ °C.

The thermal effect on the specimens was performed by the technological heat gun BOSCH 660 LCD and the temperature T_{EDT} was controlled by the infrared thermometer GT-810. The EDT scheme in the conditions of accompanying heating is shown in Figure 4, *a*, the process of EDT and the treatment zone of welded joints at $T_{EDT} = 100$ °C are respectively in Figure 4, *b*, *c*.

Table 1. Mechanical characteristics of plate of AMg6 alloy and indenter of M1 alloy

Number	Material	T, °C	Density ρ, kg/m³	Modulus of elasticity E, GPa	Poisson's ratio μ	Yield strength $\sigma_{0.2}$, MPa
1	AMg6	20	2640	71	0,34	150
2	AMg6	100	2640	65	0,34	130
3	M1	20	8940	128	0,35	300

DISCUSSION OF THE EXPERIMENTAL RESULTS

The distribution of σ_x in the central cross-section of the specimens of butt joints without EDT and after its application at $T_{EDT} = 20$ and 100 °C is shown in Figure 5. It can be seen that EDT has a positive effect on the distribution of stresses σ_x in the experimental specimens, changing them from tensile to compressive stresses in the weld centre and along the fusion line. Therefore, the peak values of tensile stresses σ_x in the initial state (before EDT) in the weld centre, along the fusion line and at a distance of 10 mm from the weld centre reached 60, 90 and 50 MPa (Figure 5, *a*).

After EDT at $T_{EDT} = 20$ °C (Figure 5, *b*), the stresses σ_x were transformed into compressive stresses, and their peak values in the weld centre, along the fusion line and at a distance of 10 mm from the weld centre reached –35, –25 and –5 MPa, respectively.

After EDT at $T_{EDT} = 100$ °C (Figure 5, *c*), the compressive stresses σ_x in the weld centre and along the fusion line did not exceed –80 and –1 MPa. At a distance of 10 mm from the weld centre, the tensile stresses σ_x reached 40 MPa, i.e., they did not change significantly as compared to the initial state, which can be seen when comparing columns *3*, respectively in Figure 5, *a*, *c*.

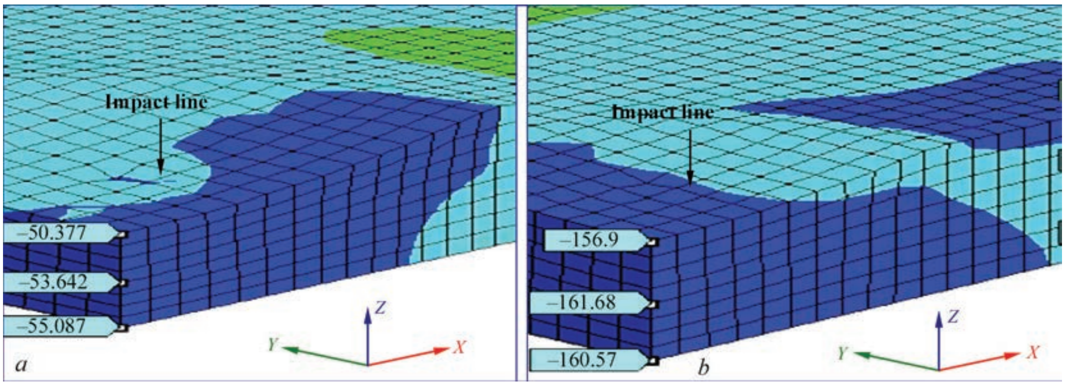

Figure 3. Final calculated distribution of residual stresses σ_x, MPa along the impact line in the plate from AMg6 alloy $\delta = 2$ mm after EDT at different values of T_{EDT}: *a* — 20; *b* — 100 °C

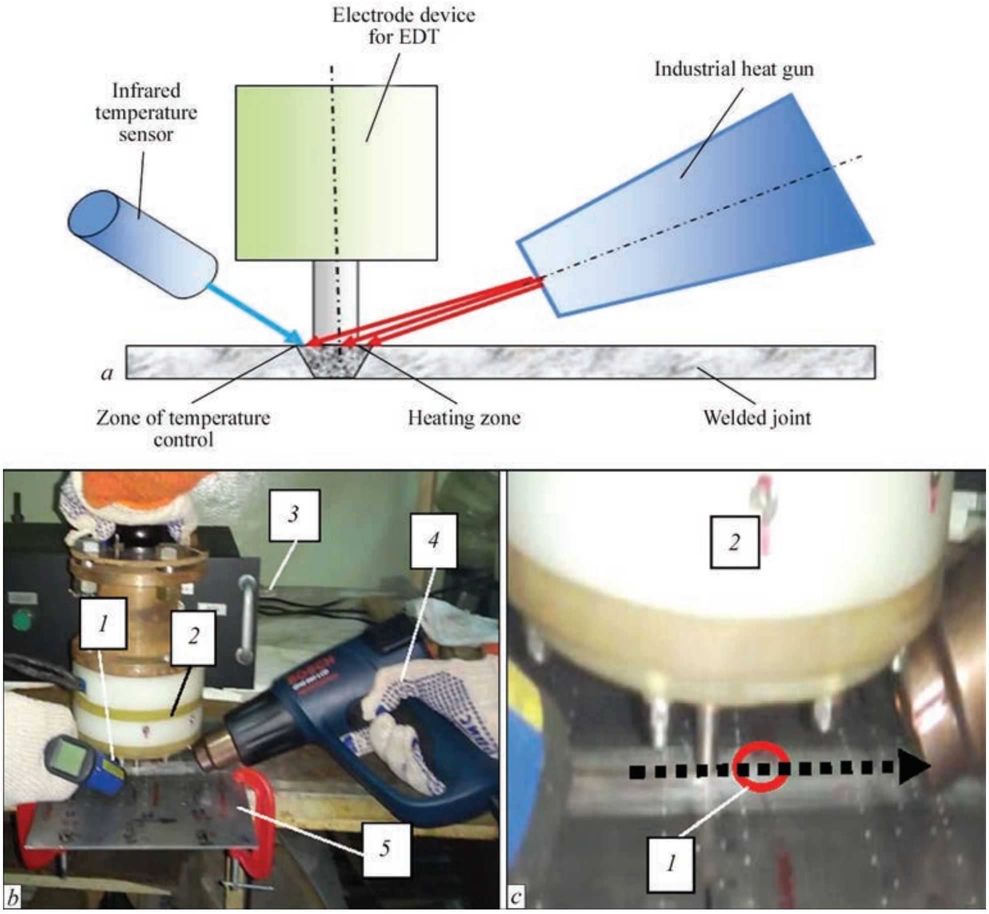

Figure 4. Procedure of verification of the effect of accompanying heating on the efficiency of EDT of welded joints: *a* — scheme of investigations; *b* — EDT process of welded joints in the conditions of elevated temperature (*1* — temperature sensor; *2* — electrode device for EDT; *3* — EDT power supply; *4* — industrial heat gun; *5* — welded joint specimen); *c* — location of the electrode device *2* relative to the treatment zone *1*, where the arrow indicates the direction of treatment along the weld line

Based on the abovementioned, it can be noted that preheating of the weld metal in the process of EDT contributes to an increase in the gradient of σ_x distribution in the cross-section of the specimen and a growth in values of the compressive stresses σ_x in the weld centre (column 1 in Figure 5, *a–c*).

Heating of the weld to the temperature T_{EDT} = = 100 °C provides thermoelastic deformation $\varepsilon_т$ of the elongation of AMg6 alloy in the weld zone, at which the metal reaches the yield strength $\sigma_{0.2}$, the value of which is lower than $\sigma_{0.2}$ at T_{EDT} = 20 °C. A decrease in $\sigma_{0.2}$ at T_{EDT} = 100 °C, causes a decrease in residual stresses due to an increase in plastic tensile deformation of the weld metal, which is the result of electroplastic deformation of the latter according to the mechanism shown in [1, 3, 4]. Also an increase in ductility of AMg6 alloy occurs during heating, which is characterized by an increase in the value of relative elongation δ respectively from 22 % at T_{EDT} = = 20 °C to 34 % at T_{EDT} = 100 °C [8]. This facilitates an increase in the density of electric contact of the pair “indenter-metal” at their interaction at T = 100 °C as compared to EDT at T_{EDT} = 20 °C. This results in a more intensive (as compared to EDT at T_{EDT} = 20 °C) plastic deformation of the metal in the contact zone due to the electroplastic effect [9]. This contributes to the formation of local plastic tensile deformations, resulting in an increase in the compressive stresses in the treatment zone.

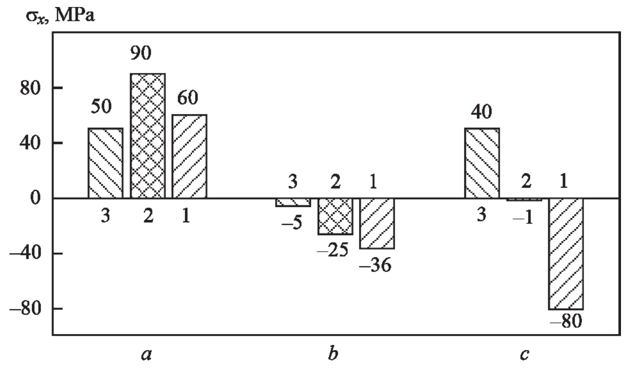

Figure 5. Distribution of σ_x in the central cross-section of the specimens of butt joints: *a* — without using EDT; *b* — after EDT at T_{EDT} = 20 °C; *c* — after EDT at T_{EDT} = 100 °C (*1* — weld centre; *2* — fusion line; *3* — at a distance of 10 mm from the weld centre)

The higher gradient of σ_x distribution under the heating conditions is confirmed by the comparison of Δσ values at T_{EDT} = 150 and 20 °C. The value of Δσ was determined as the absolute difference of stresses between the values of σ_x in the weld centre and

Table 2. Values of $\Delta\sigma$ in the weld centre and along the fusion line of specimens of welded joints from AMg6 alloy

Number	T_{EDT}, °C	$\Delta\sigma$, MPa	
		Weld centre	Fusion line
1	20	95	115
2	100	140	91

along the fusion line of the specimens in the initial state (without EDT) and after the treatment at different T_{EDT}. The obtained values of $\Delta\sigma$ in different areas of the weld at a variation of T_{EDT} are given in Table 2.

From the data in Table 2, it can be seen that EDT at T_{EDT} = 100 °C is more effective (as compared to EDT at T_{EDT} = 20 °C) to increase the level of compressive stresses in the weld centre. But for the fusion line, the opposite is true. Thus, EDT at elevated temperatures promotes an increase in the gradient of distribution of electrodynamic effect on the residual stress states of welded joints. Let us note that under cyclic loading, where the effect of residual stresses is more significant than under static one, the fracture of welded joints mostly takes place along the fusion line. Therefore, as the optimal scheme of EDT, the treatment along the fusion line at T_{EDT} = 150 °C should be considered, but this requires further investigations.

Taken into account the abovementioned, it should be noted that the thermal potential is one of the important factors in optimizing the stress states of welded joints of AMg6 alloy at EDT, but the optimization of the scheme and parameters of electrodynamic actions requires further investigations.

CONCLUSIONS

1. The rationality of using accompanying heating of a welded joint of AMg6 alloy during its electrodynamic treatment is substantiated. It is shown that thermal action in general has a positive effect on the efficiency of EDT of welded joints as compared to their treatment at a room temperature.

2. An experimental procedure was developed, on the basis of which investigations were conducted to evaluate the effect of EDT-compatible preheating of the treatment zone on the stress state of welded plates at EDT.

3. It was found that EDT of the welded joint centre in the conditions of its accompanying heating is more effective for regulating residual stresses in the weld centre and less effective along the fusion line as compared to EDT without preheating.

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CONFLICT OF INTEREST

The Authors declare no conflict of interest

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