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INFLUENCE OF ELECTRODE SHAPE ON STRESS-STRAIN STATE OF AMg6 ALLOY DURING ITS ELECTRODYNAMIC TREATMENT

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ABSTRACT

The advantages of using electrodynamic treatment (EDT) of metal in the welding process as compared to EDT at room temperature were substantiated. The advantages and disadvantages of using electrode for EDT in the form of a cylindrical rod and a roller in the welding process were considered. Using the method of mathematical modeling in planar and axisymmetric statements, the effect of a shape of the electrode-indenter on stress-strain state of the welded plate from aluminium AMg6 alloy after applying the dynamic EDT component was evaluated. The features and differences of creation and use of developed mathematical models were described. The distribution of values of the stress-strain state throughout the thickness of the plate was determined, in particular, the values of the zone of plastic deformations and stresses during interaction of the plate with the electrode-indenter moving at a speed of 5 m/s. It was found that the use of a cylindrical indenter with a hemispherical working end (of axisymmetric shape) as compared to the roller (of planar elongated shape) is more effective from the standpoint of optimizing the residual stressed state in the plate. The use of a cylindrical indenter leads to the formation of compressive stresses in the plate with the values up to –120 MPa. This should have a positive effect on the distribution of residual welding stresses under the action of the dynamic EDT component.

KEYWORDS: electrodynamic treatment, aluminium alloy, impact interaction, mathematical modeling, residual stresses, plastic deformations, electrode-indenter, movement, elastoplastic environment

INTRODUCTION

The problem of regulating residual welding stresses and deformations in structures of aluminium alloys is relevant, which is caused by their use in various industries and transport, where stress-strain states significantly affect the service characteristics of products.

A prospective method of regulating stress-strain states of structures is electrodynamic treatment (EDT) of welded joints, which is based on initiating electrodynamic forces in the metal of products occurring while passing electric current pulse (ECP) in the latter [1, 2]. The use of EDT allows changing the stress-strain state (SSS) of welded joints by means of point impacts of the electrode-indenter in the welded joint zone with a simultaneous ECP passing. During EDT, the welded joint metal is subjected to electrodynamic action that initiates electroplastic effect in the treatment zone and, as a result, relaxation of residual welding stresses [3].

Realization of EDT of longitudinal welded joints, including also in the welding process, requires expanding capabilities of the method by optimizing the conditions of contact interaction of the electrode for EDT with the metal surface to be treated. The realization of the EDT method in the welding process provides shortening in the time of manufacturing a welded structure as a result of transition from successive to simultaneous welding and treatment. It also creates opportunities to automate this technology.

The hardware for the method is limited by organization of a synchronous movement of the welding torch and the electrode device for EDT – the “Torch + EDT Electrode” system. I.e., the “Torch + EDT Electrode” system is constantly moving along the weld. This requires structural and technological solutions, which are aimed at a qualitative providing of a discrete dynamic interaction of the contact surface of the EDT electrode, which moves constantly along the weld. At the same time, the interaction occurs at the moment of passing ECP throughout the electrode to the welded joint metal.

Two variants of interaction were considered. During realization of the first variant, a dynamic contact of the hemispherical end of a cylindrical electrode with a plane surface of the welded joint, subjected to

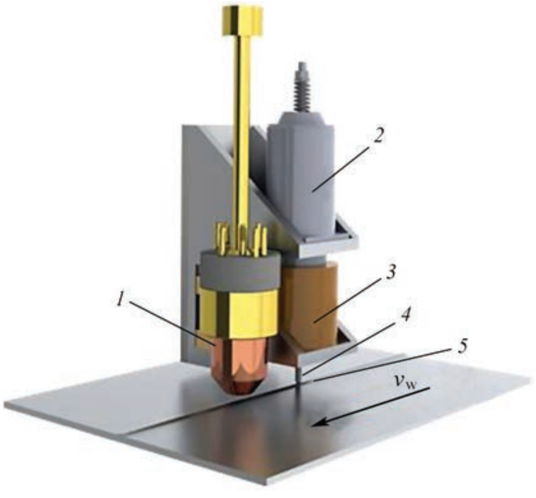

Figure 1. Variant of circuit diagram of contact of EDT electrode in the form of a cylinder with weld metal: *1* — torch for welding; *2* — inductor of linear vertical movement; *3* — electrode system; *4* — EDT electrode; *5* — weld; v_w — welding direction

EDT, was realized [1–3]. At the second variant, a dynamic contact of the surface of a cylindrical roller, rolled on the surface of the weld, subjected to EDT, was realized.

Figure 1 presents the circuit of a cylindrical electrode *4* with the weld metal *5*. The contact interaction of the hemispheric end of the electrode with a plane surface of the metal being treated was carried out using the inductor of a linear vertical movement *2*. The inductor was located along the total vertical axis with the electrode system *3* for fixing the electrode *4*. The disadvantages of the circuit in Figure 1 include the need in a discrete positioning of the electrode relative to the longitudinal central weld axis and counteracting jamming of the electrode in the process of continuous longitudinal movement of the "Torch + EDT Electrode" system in the welding process.

Figure 2 presents the circuit diagram of the contact of the electrode *4* in the form of a roller with the metal of the welded joint *5*, which is mounted on the assembly plate *6*. The roller has a shape of a cylinder that rolls on the surface of the welded joint. The contact interaction of the roller surface was carried out along the generating line of the cylinder using a linear displacement inductor *1*. The inductor was colocated with the system of fixing *3* the roller, fixed in the casing *2*. This design is simpler in realization than that presented in Figure 1, where there is a series of discrete dynamic contacts of the electrode with the surface of the weld in the process of producing a weld. In the design of the electrode in the form of a roller, the discreteness is eliminated due to a continuous rolling of the latter along the weld, which is accompanied by periodic ECP passing into the weld (through the roller).

When comparing the diagrams in Figures 1 and 2, it should be noted that the latter is simpler in realization because of elimination of the discreteness of a contact interaction due to rolling of the electrode on the weld surface. Until now, no studies of the influence of the electrode shape on SSS of the metal in the contact area after EDT have been conducted. Therefore, the evaluation of residual SSS of the metal, which is a consequence of its dynamic contact interaction with the electrode in the form of a cylinder or a roller, is relevant.

Some issues of experimental determination of stresses after welding were considered in [1], but such methods allow finding values of welding stresses only on the surface of the body and as a result of its partial destruction. In order to more fully evaluate SSS of such structures, modern means of mathematical modeling are used. The paper [2] describes the results of computer modeling of the process of impact interaction of the electrode-indenter with the welded plate (only dynamic EDT component was considered), which was carried out on the basis of the Prandtl–Reuss ratios [3], describing the movement of the medium

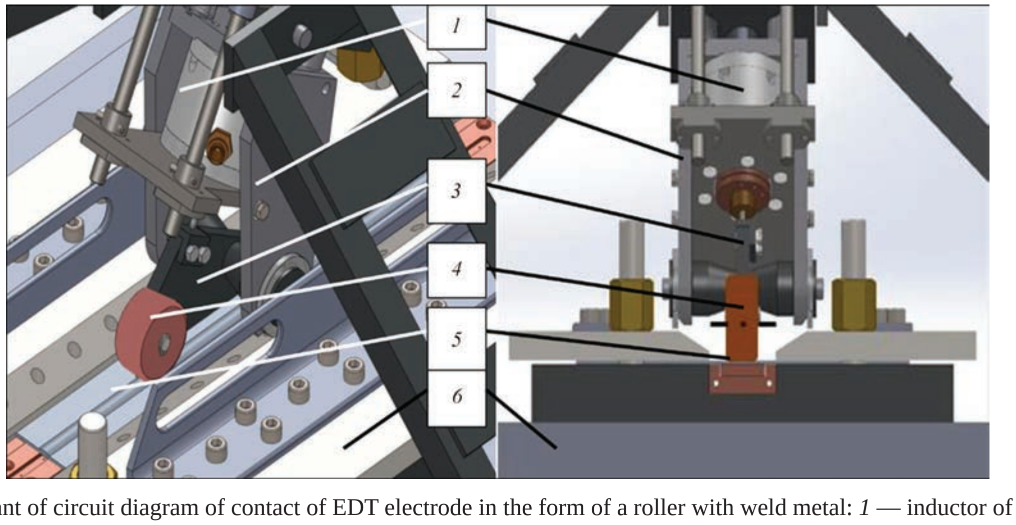

Figure 2. Variant of circuit diagram of contact of EDT electrode in the form of a roller with weld metal: *1* — inductor of linear movement; *2* — casing of roller fixation; *3* — roller fixation system; *4* — EDT electrode; *5* — welded joint; *6* — assembly plate

in the planar two-dimensional Lagrangian statement using the ANSYS/LS-DYNA software. It should be noted that the use of such a statement corresponds to the modeling of the EDT process of a plate with a planar electrode-indenter of an infinite length.

At the same time, EDT is carried out by electrode-indenters of an axisymmetric shape, for example, in a shape of a cylinder. Then, modeling of the EDT process with such an indenter should be carried out using another — axisymmetric statement.

Thus, the aim of the work is a mathematical evaluation of the influence of the electrode-indenter shape on the stress-strain state of the plate after applying the dynamic electrodynamic treatment component.

CALCULATION (MATHEMATICAL) MODEL OF THE PROBLEM

The calculation scheme of the process of treatment of the welded plate by the dynamic EDT component is presented in Figure 3.

In Figure 3, it is seen that in the process of impact interaction, two bodies take part. The first is a plate (*2*) with a thickness of 4 mm and a width of 50 mm, which is made of AMg6 alloy and is located on a completely rigid surface (desktop *3*). The second body is a copper electrode-indenter (*1*), which moves in the direction of the plate at a speed v_0 = 5 m/s.

A shape of the cross-section of the indenter conventionally consists of two elementary figures: a rectangle with a width of 20 mm and a height of 30 mm and a semicircle with a radius of 10 mm.

Since the cross-sections of the plate and indenter have geometric symmetry, then in Figure 3, only their right halves, relative to the *Y* axis (indenter line), are presented.

Thus, mathematical calculations using the planar statement will correspond to modeling the EDT process of a plate using a roller. A roller was modeled in the form of a plane electrode with a cross-section located across the conditional weld (Figure 4, *a*). This generally corresponds to the circuit diagram shown in Figure 2.

At the same time, calculations using the axisymmetric two-dimensional statement will correspond to modeling the EDT process of a plate by a cylindrical electrode with a hemispherical end. The electrode is located along the impact line (along the *Y* axis in Figure 3), as is shown in Figure 4, *b*. This generally corresponds to the circuit diagram shown in Figure 1.

The main difference between the two mathematical models mentioned above is that in the planar statement the contact of the electrode-indenter with the plate is realized along the line, and in the axisymmetric one — at the point.

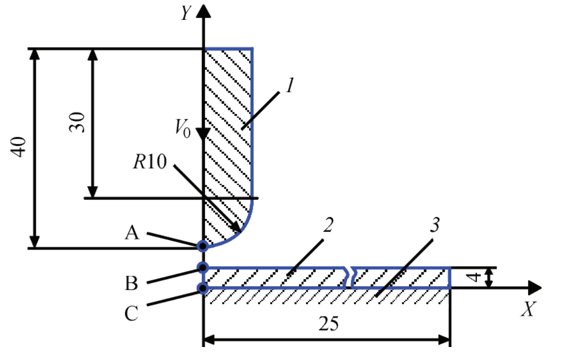

Figure 3. Calculation scheme of the process of treatment of the plate with the dynamic EDT component: *1* — electrode-indenter; *2* — treated plate; *3* — absolutely rigid table. Points along the impact line: A — on the surface of the indenter; B — on the facial surface of the plate; C — on the back surface of the plate

The finite-element model of the problem in both statements had the same quantity of finite elements and nodes, namely: a quantity of finite elements (SOLID 162 type) is 128203 units; a quantity of nodes is 131042 units. The behavior of materials of the plate and the electrode-indenter was described using a rheological elastoplastic model of materials, in which the value of the dynamic yield strength is assumed to be equal to the yield strength σ_y. The values of parameters of these models were as follows:

- AMg6 alloy (plate): density ρ = 2640 kg/m^3; Young's modulus of elasticity E = 71 GPa; Poisson's ratio μ = 0.34; yield strength σ_y = 150 MPa;
- copper of M1 grade (electrode-indenter): density ρ = 8940 kg/m^3; Young's modulus of elasticity E = = 128 GPa; Poisson's ratio μ = 0.35; yield strength σ_y = 300 MPa.

Thus, in order to evaluate the influence of a shape of the electrode-indenter (in planar or axisymmetric statements) on the effectiveness of the dynamic EDT component, a mathematical modeling of the process of its interaction with the plate metal at a contact speed V_c = 5 m/s was carried out. The value of V_c was set by the charging voltage of the capacitors U_{ch} = 500 V

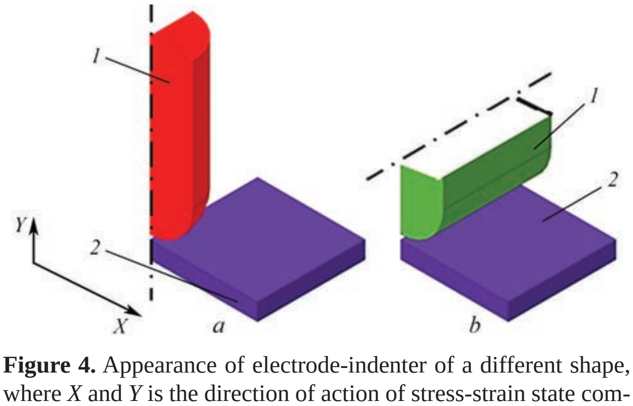

Figure 4. Appearance of electrode-indenter of a different shape, where *X* and *Y* is the direction of action of stress-strain state components (where *1* — electrode; *2* — plate): *a* — cylinder with a hemispherical working end; *b* — roller

Table 1. Calculation parameters of interaction between the electrode and the plate at the place of contact

Type of symmetry	Duration of contact, μs	Depth of penetration of the indenter into the plate, mm	Depth of contact zone in the plate, mm	Width of contact zone in the plate, mm
Planar	86	0.176	0.168	1.89
Axial	128	0.285	0.266	2.56

with a capacity of C = 6600 μF. This provided the energy of a single electrodynamic action E_{EDT} = 825 J.

The modeling was carried out using the ANSYS/LS-DYNA software based on the Prandtl–Reuss ratios, which describe the movement of an elastoplastic medium.

MODELING RESULTS AND THEIR COMPARISON

The conducted numerical calculations showed the main differences in the process of interaction of the electrode-indenter of a different shape with the plate, which are summarized in Table 1.

From the data in Table 1, it is seen that the duration of a contact between the bodies in the axisymmetric statement is by 42 μs (50 %) longer than the duration in the planar one. This is explained by the peculiarities of the energy exchange processes between the electrode-indenter and the plate. Accordingly, as the interaction time increases, deformations in the contact zone also grow, which affects its dimensions in the plate. The depth of the indenter penetration was determined as the maximum movement of the point A (see Figure 3) into the middle of the plate from its surface, and accordingly, the depth of the contact zone was determined as the movement of the point B (see Figure 3) from the initial position to the position corresponding to the end of the contact.

An increase in the depth of the contact zone by 55 % and its width by 35 % in the axisymmetric statement as compared to the planar one leads to a corresponding increase in the zone of plastic deformation and the amount of effective plastic deformations ε^p_{eff} across the thickness of the plate (Figure 5).

The distribution of ε^p_{eff} in the planar statement propagates over a half of the thickness of the plate (2 mm) and has a shape of a segment of a circle with a radius of 2 mm (Figure 5, *a*). In the axisymmetric statement, the zone of plastic deformation reaches the back surface of the plate and has a shape close to a trapezoid, the upper base of which is 8 mm long, and the lower one is 4 mm (Figure 5, *b*). Analyzing the data of Figure 5, it should be noted that the point contact interaction of the hemispherical end (axisymmetric statement) contributes to a greater intensity of plastic deformation as compared to a linear one (planar statement). When comparing the data of Figure 5, *a*, *b*, it can be seen that propagation of the zone of plastic deformation along the cross-section of the plate with the axisymmetric statement is greater than in the planar one.

Also from Figure 5, it is seen that in the planar statement, the maximum values ε^p_{eff} are formed on the contact surface of the plate with the electrode-indenter in the cross-section area near the plane of symmetry. In the case of the axisymmetric problem, the opposite occurs. As is seen from Figure 5, *b*, the peak values ε^p_{eff} are shifted by 1.8–2.0 mm from the impact line (axis of symmetry).

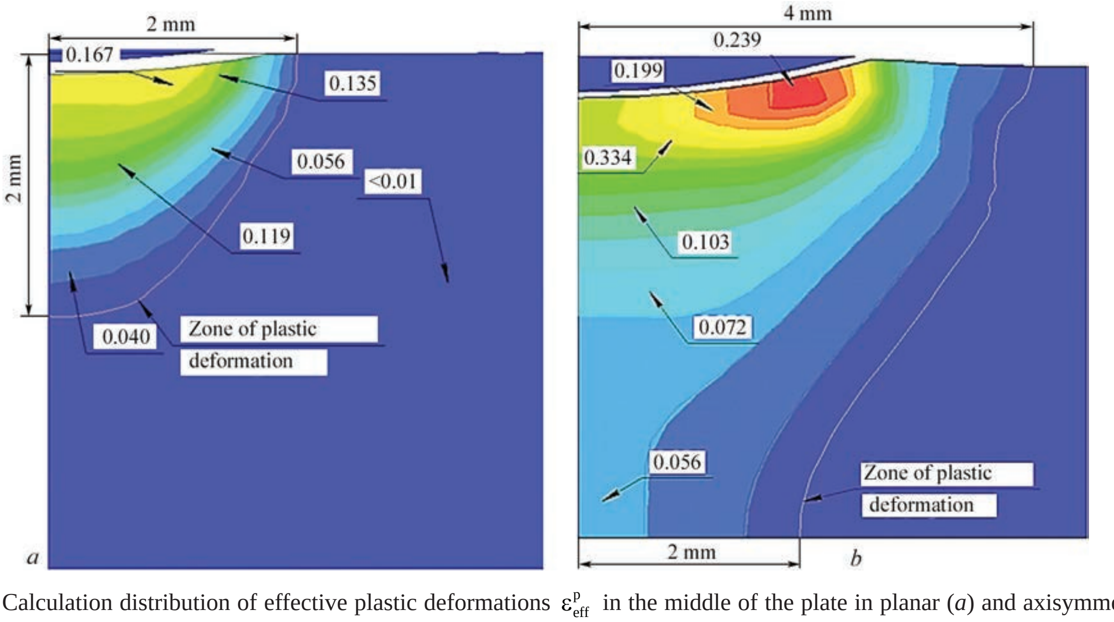

Figure 5. Calculation distribution of effective plastic deformations ε^p_{eff} in the middle of the plate in planar (*a*) and axisymmetric (*b*) statements

For comparison, the values of maximum ε^p_{eff} and the values ε^p_{eff} at the points B and C (Figure 3), located along the impact line, are given in Table 2. It is seen of the data from Table 2 that the use of an axisymmetric electrode-indenter as compared to the planar one leads to an increase in the maximum ε^p_{eff} by more than 1.4 times. When comparing the values ε^p_{eff} at the points B and C (see Table 2), it is seen that the change in a shape of the electrode-indenter almost does not affect ε^p_{eff} at the point B (the difference in values does not exceed 10 %), but ε^p_{eff} at the point C differs by an order. At the same time, the values ε^p_{eff} at the point C for both types of symmetry (variants of the indenter shape) are almost 4 times smaller than at the point B, which is explained by a gradual dissipation of the kinetic energy of the indenter throughout the thickness of the plate.

Based on the differences of the deformation pattern presented in Figure 5, it is relevant to evaluate the influence of each component of residual deformations on the final value ε^p_{eff} (Figure 6). The data of Figure 6, *a* indicate an almost uniform distribution of ε^p_x over the thickness of the plate in the planar statement, where the values of this component change within the range from –0.01 to 0.01. In the case of the axisymmetric problem, at the point of contact, a zone of tensile deformations with the peak values of about ε^p_x = 0.08 is created. In this case, under the pressure of the electrode-indenter, the material from the central tension zone is flowing in the radial direction from the impact line. This leads to the formation of compres-

Table 2. Values of effective plastic deformations ε^p_{eff} at different types of symmetry

Type of symmetry	Maximum values ε^p_{eff}	Values ε^p_{eff} on surfaces of the plate	
		Facial (point B, Figure 3)	Back (point C, Figure 3)
Planar	0.171	0.165	0.004
Axial	0.239	0.151	0.038

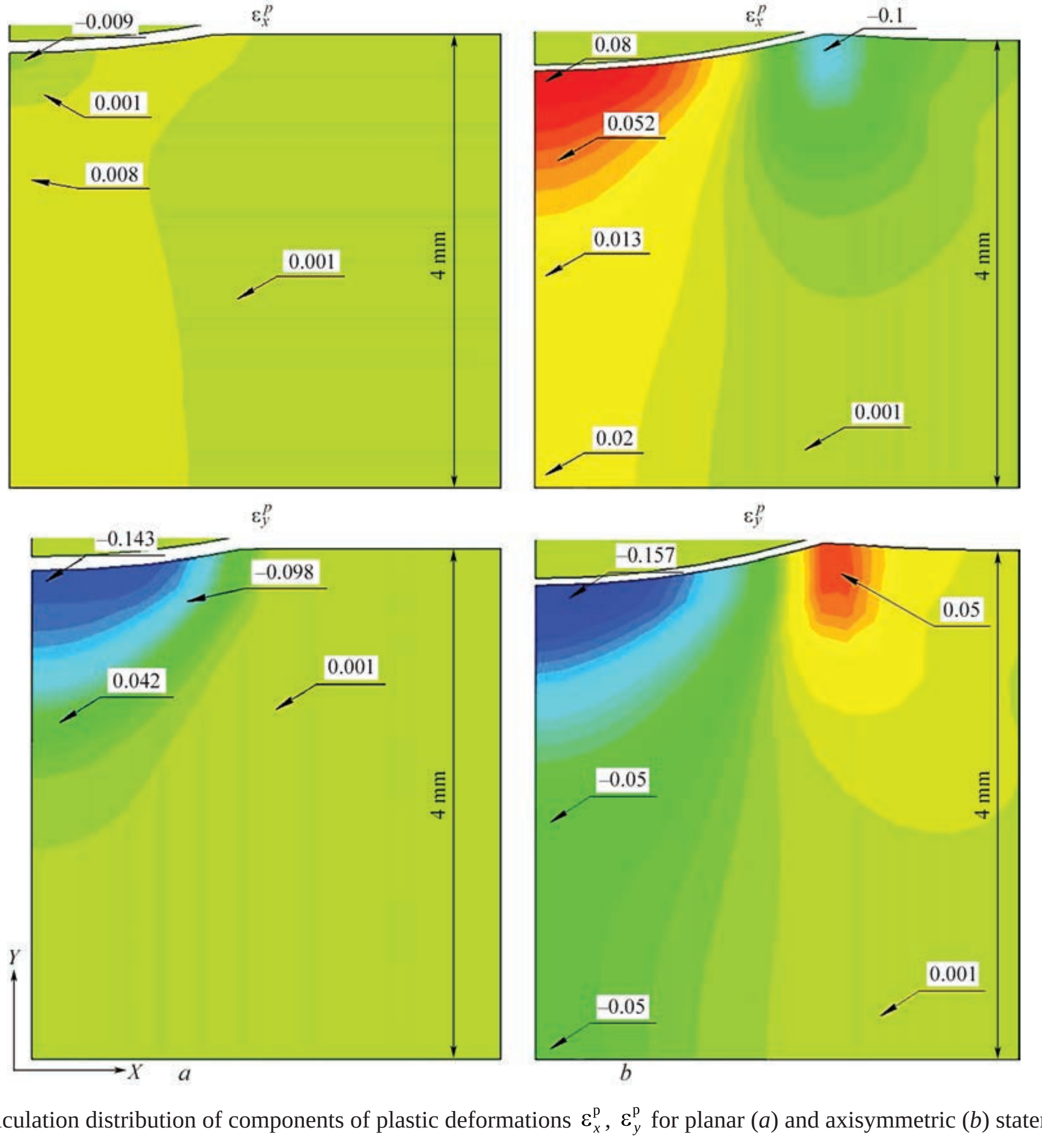

Figure 6. Calculation distribution of components of plastic deformations ε^p_x, ε^p_y for planar (*a*) and axisymmetric (*b*) statements

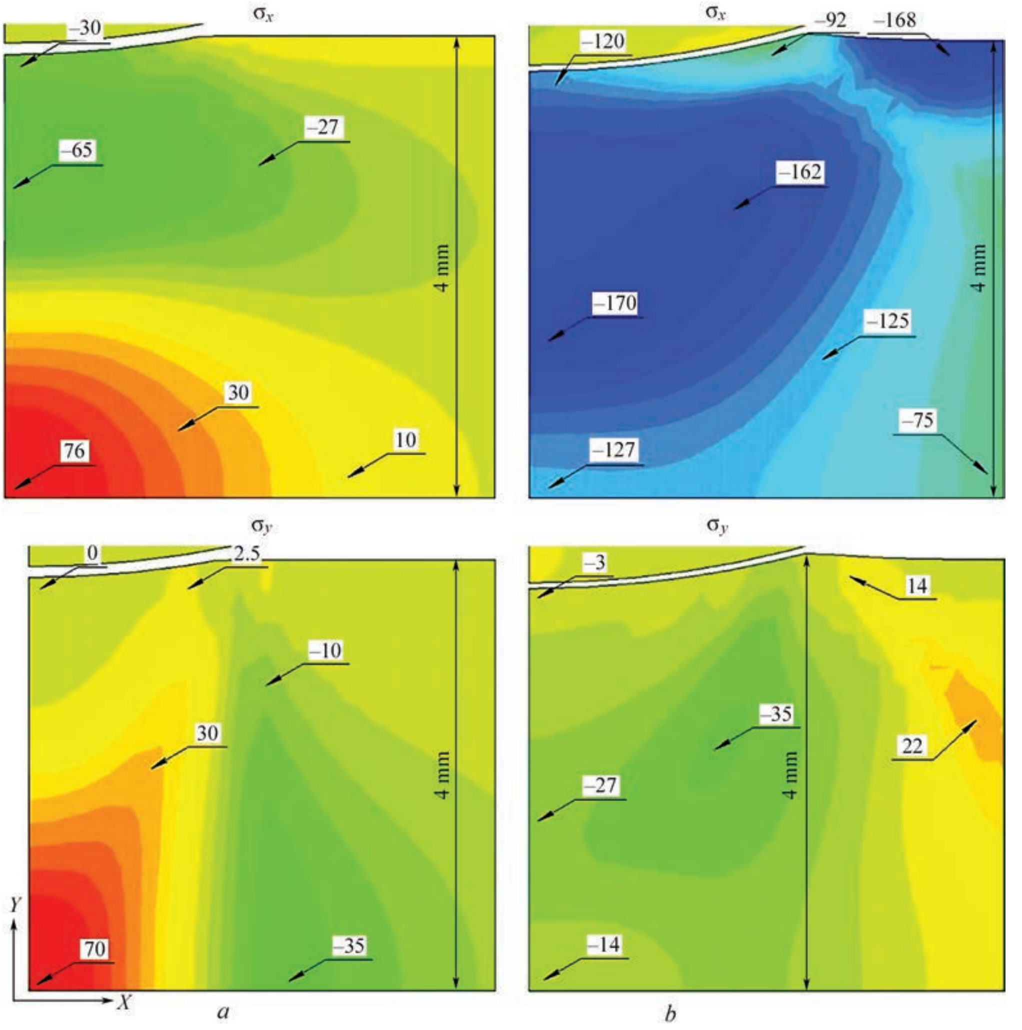

Figure 7. Distribution of values of components of residual stresses σ_x, σ_y (MPa) for planar (*a*) and axisymmetric (*b*) statements

sion deformations ε^p_{eff} = –0.1 on the facial surface of the plate of a sufficiently localized zone, which generally does not affect the overall strain state of the tested cross-section of the plate. When comparing the deformation patterns of Figure 6, it can be seen that the axisymmetric statement (Figure 4, *b*) provides a more optimal distribution of plastic deformations (as compared to the planar one — Figure 4, *a*), where tensile ε^p_{eff} have larger values. The consequence of this is the formation of residual compression stresses larger in values.

If we consider the distribution of values of another component of deformations ε^p_y then regardless of a shape of the indenter at the point B (Figure 3), the formation of almost identical zones of compression deformations is observed. In this place, the maximum values for the problem in the planar statement ε^p_y = = –0.14 (Figure 6, *a*), and in the axisymmetric one ε^p_y = –0.16 (Figure 6, *b*).

As is known, a strain state is a consequence of action of the corresponding stresses in the structure. In order to analyze the distribution of values of the stressed state components over the thickness of the plate, appropriate calculation patterns of the distribution of σ_x and σ_y were plotted (Figure 7).

From Figure 7, it is seen that depending on a shape of the electrode-indenter (conditions of symmetry of the mathematical model), the residual stressed state formed in the plate has significant differences. For the problem in the planar statement, the distribution of residual stresses σ_x (directed perpendicular to the impact line — Figure 3) is formed in the form of two characteristic zones (Figure 7, *a*). The first is the compression zone near the facial surface of the plate with the values σ_x = –22 MPa. The second one is the tensile zone near the back surface of the plate with the stress values up to σ_x = 76 MPa. In the axisymmetric statement (Figure 7, *b*) only one zone is formed over the whole thickness of the plate — the zone of compression stresses with the maximum value up to σ_x = –120 MPa.

According to the results of analysing the pattern of distributing values of the component of the stressed state σ_y (directed along the impact line — Figure 3), which is formed in the case of using a plane indenter, it is possible to see an almost rectangular zone of ten-

Table 3. Calculation values of residual stressed state components σ_x and σ_y across the thickness of the plate (from the point B to the point C)

Type of symmetry	Stressed state component	Coordinate of the point across the thickness of the plate (along the impact line), mm				
		0 (point B)	1	2	3	4 (point C)
Planar	σ_x, MPa	–25	–56	–23	46	76
	σ_y, MPa	0.1	0.01	17	53	80
Axial	σ_x, MPa	–131	–155	–161	–164	–128
	σ_y, MPa	–0.08	–9	–15	–20	–5

sile stresses (Figure 7, *a*). The maximum values are reached by tensile stresses on the back surface of the plate (point C in Figure 3) σ_y = 76 MPa. Also, on the back surface at a distance of 2.5 mm from the impact line, the zone of compression stresses σ_y = –36 MPa is formed. The minimum values of tensile stresses are reached on the facial surface (point B) σ_y = 0.01 MPa.

In the axisymmetric statement (Figure 7, *b*), a pattern of stresses is somewhat different. Throughout the thickness of the plate, an almost uniform distribution of values of the component σ_y of compression stresses is formed. The difference between the maximum and minimum value of this component of stresses along the impact line does not exceed 20 MPa.

The calculation values of residual stressed state components σ_x and σ_y across the thickness of the plate (from the point B to the point C) are given in Table 3. The comparison of values of the stressed state components along the impact line (Table 3) shows that unlike a plane electrode-indenter, the use of an axisymmetric indenter leads to the formation of almost uniform distribution of both stress components σ_x and σ_y.

In addition, the use of a plane electrode-indenter (roller) leads to the formation of both compression stresses as well as undesired tensile stresses with values that can reach a half of the value of the yield strength of the material. However, the use of the electrode-indenter of an axisymmetric shape leads to the formation of both components of stresses as compression stresses, the values of which can reach –120 MPa. This can have a positive effect on residual stressed states of welded structures even applying only the dynamic EDT component [4].

But, as is shown above, the practical use of the electrode in the form of a roller has advantages over the cylinder from the standpoint of simplicity and ease of use. Considering the abovementioned, in the future, the studies of stressed states of welded structures after EDT with the use of a roller at higher power characteristics of electrodynamic actions, in particular, at an increase of ECP frequency should be provided.

CONCLUSIONS

1. The use of a cylindrical electrode-indenter with a hemispherical working end for EDT as compared to a plane elongated electrode in the form of a roller, at the same speed of their movement being 5 m/s, results in:

● distribution of the zone of effective plastic deformations ε^p_{eff} to the whole thickness of the plate, which has a shape close to a trapezoid (in the case of a plane indenter, the zone ε^p_{eff} extends to only half of a thickness of the plate and has a shape of a circle segment), and the values of maximum deformations are 1.4 times higher than similar values formed from the action of a plane indenter.

● formation of almost uniform distribution of both components of a stressed state — both σ_x and σ_y across the thickness of the plate, which, unlike the other (planar) statement of the problem are compression stresses, the values of which can reach –120 MPa.

2. The use of an axisymmetric electrode-indenter provides a more effective regulation of the dynamic EDT component and stressed state of the plate throughout the whole its thickness provided that other things are equal, which helps to reduce the level of residual welding tensile stresses.

3. It was proved that the practical use of the electrode in the form of a roller has advantages over the cylinder from the standpoint of simplicity and ease of use. Taken into account the abovementioned, the study of stressed states of welded joints after EDT with the use of a roller at higher power characteristics of electrodynamic actions is promising for optimizing the service characteristics of welded structures.

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CONFLICT OF INTEREST

The Authors declare no conflict of interest

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Hypertherm Associates to formally close down its legal entity in russia

Dordrecht, The Netherlands — Nov. 1, 2022 — Hypertherm Associates, a U.S. based manufacturer of industrial cutting products and software, today announced plans to formally close its legal entity in russia. This announcement follows a decision in March of this year to suspend business because of russia's military invasion of Ukraine.

The continued humanitarian crisis and unpredictable business environment have caused Hypertherm Associates to conclude that a resumption of its russia business is not going to be possible for some time.

The company has worked to reassign affected Associates to new roles within its European and Middle East operations and is grateful to the many russian partners who helped Hypertherm Associates grow its business over the past two decades.

Hypertherm Associates is a U.S. based manufacturer of industrial cutting products and software. Its products, including Hypertherm plasma and OMAX waterjet systems, are used by companies around the world to build ships, airplanes, and railcars; construct steel buildings, fabricate heavy equipment, erect wind turbines, and more. In addition to cutting systems, the company creates CNCs and software trusted for performance and reliability that result in increased productivity and profitability for hundreds of thousands of businesses. Founded in 1968, Hypertherm Associates is a 100 percent Associate-owned company, employing approximately 2,000 Associates, with operations and partner representation worldwide.
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