ELECTRODYNAMIC STRAIGHTENING OF ELEMENTS OF SHEET WELDED STRUCTURES

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The need for regulation of residual distortion caused by welding in sheet metal structures is one of the urgent problems of modern welding fabrication. A promising approach featuring a low power consumption and not requiring metal-intensive equipment, is development of the method to lower welded joint distortion, based on application of electrodynamic treatment of welded joints by pulsed current. The objective of this work is investigation of effectiveness of electrodynamic straightening of elements of sheet welded structures. Influence of pulsed current electrodynamic treatment on lowering of residual form change in elements of sheet welded plates from AMg6 aluminium alloy and 30KhGSA and St3 structural steels was studied. Capacitive storage was used to generate pulsed current at electrodynamic treatment, and treatment was performed at contact interaction of working electrode, mounted in a flat inductor, with weld surface. A special fixture was used for electrodynamic treatment, allowing treatment of plates to be performed both in unrestrained state and with their pre-bending. Influence of successive application of current pulses at electrodynamic treatment and direction of plate treatment were studied. Results of the performed research showed that welded joint straightening by electrodynamic treatment allows an essential lowering of values of longitudinal and transverse deflection of welded plates from structural steels and aluminium alloy. It is established that the sequence of electrodynamic treatment performance in the direction «from middle to edges» is the most effective for reducing plate distortion, induced by welding. Application of «reverse» bending of plates initiating stresses on weld surface on the level of material yield point, in combination with electrodynamic treatment, allows practically eliminating residual distortion of longitudinal welded joints of AMg6 alloy and significantly lowering it in joints of structural steels. 12 Ref., 2 Tables, 3 Figures.

Keywords: *aluminium alloys, structural steels, longitudinal deflection, transverse deflection, electrodynamic treatment, preliminary outward bending, weld, automatic welding, coated electrode welding*

The need for regulation of residual distortion caused by welding in sheet metal structures is one of the urgent problems of modern welding production. At fabrication of new types of structures, materials and welding processes are used, for which the traditional methods of ensuring the specified fabrication accuracy are not always applicable. At the same time, under the conditions of rising prices for energy resources, the demand for straightening methods based on minimum power consumption [1], is quite high.

A promising approach differing by low power consumption and not requiring metal-intensive equipment, is development of straightening methods based on application of pulsed electromagnetic impacts on the welded joint.

Fundamental and applied investigations revealed the phenomenon of an abrupt increase of ductility and lowering of metal resistance to deformation under the impact of high-density current [2]. The phenomenon was called electroplasticity [3], and its practical application opened up new possibilities for technological treatment of structural elements from various metals and alloys, including refractory alloys.

Electrodynamic treatment (EDT) is one of the methods of current impact on metals and alloys. It is based on initiation of electrodynamic forces in the material, arising at transient processes accompanying current discharge running through the material [4]. At the impact of electrodynamic forces on the structure being treated, it may develop plastic deformations, lowering the level of its residual distortion. Here, the impact of current pulses on the welded joint leads to relaxation of its stress-strain state, determining the parameters of its residual form change [5–8].

The objective of this work was investigation of effectiveness of electrodynamic straightening of elements of sheet welded structures.

Treatment of welded joint samples by current pulses was performed in a unit, the main element of which was capacitive storage, and the work tool was a flat inductor connected to a disc from a nonferromagnetic material and cylindrical electrode, the spherical end face of which was the energy release zone at contact with welded joint treated surface at the moment of the discharge. The disc was designed for realization of the dynamic component of electrodynamic impact on

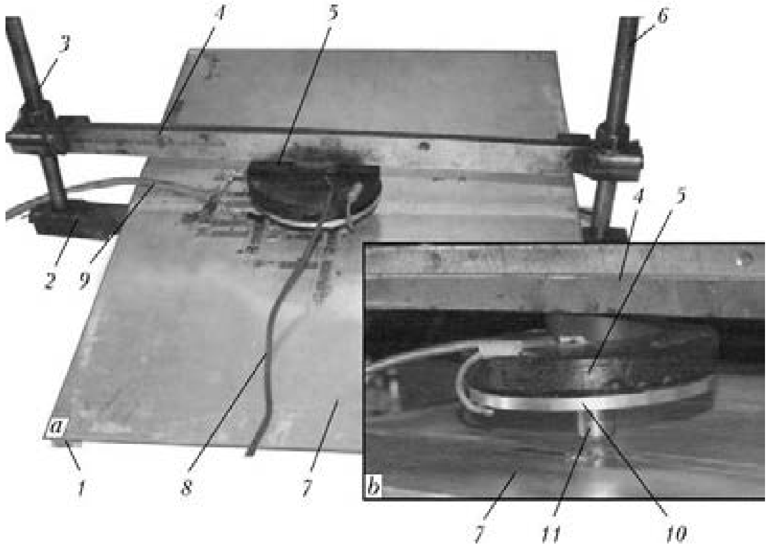

Figure 1. Appearance of fixture for EDT of AMg6 alloy welded joint (*a*) and inductor positioning on the weld (*b*) (for *1–11* see the text)

the metal. Principles of the unit operation [4] are based on transient electrodynamic processes running in the sample metal at storage discharge.

Considering the data of [4], where it is shown that the effectiveness of electrodynamic impact directly depends on current discharge stored energy, E, treatment mode, corresponding to E = = 800 J, was used to assess EDT influence on residual form change of welded plates.

Investigations of EDT influence on residual form change of welded structure elements was conducted on flat welded samples of 400 × 300 × × 3 mm size from 30KhGSA, St3 steels, as well as from aluminium alloy AMg6 (400 × 400 × × 4 mm). Butt welded joints of steels were made by coated electrode welding, and those of AMg6 alloy — by automatic welding in argon.

Treatment of welded joints was performed with application of a special fixture (Figure 1) designed for inductor positioning relative to the sample section to be treated, as well as fixed contact of electrode end face with metal surface. The fixture allows treatment of welded joints to be performed both in unrestrained state and after pre-bending.

Fixture (Figure 1, *a*) consists of supporting *2* and press-down *4* beams, designed for fastening welded joint sample *7* and flat inductor *5*, as well as for their switching into discharge circuit of capacitive storage using power cable *8*. Positioning of press-down beam *4* relative to sample *7* was performed with guide pins *6*, and vertical press-down force was created by loading nuts *3*. Strain-gauge ribbon cable *9* was used to monitor stresses at pre-bending, to achieve which toes *1* were mounted on plate corners. Relative position of inductor *5* with a disc from non-ferromagnetic material *10* and electrode *11* is shown in Figure 1, *b*.

The objective of the first stage of the work was investigation of influence of optimum sequence of electrodynamic impact application. For this purpose, assessment of influence of treatment zone location on the weld, as well as of the sequence of discharge running on residual distortion of plates was performed. Initial form imperfections caused by welding were preserved in the plates, and conditions of their assembly in the fixture ensured a guaranteed electric contact of the electrode with the surface of treated metal.

Sample assembly was performed at guaranteed contact of electrode end face with the weld surface, as shown in Figure 1, *b*. Selection of the weld as treatment zone is substantiated by the data of [9, 10], which show that effectiveness of electrodynamic impact is maximum at EDT of metal with elastic stress level close to $\sigma_{0.2}$. This is characteristic for weld central part, and, therefore, weld surface treatment should be performed for straightening of welded plates by EDT.

After plate assembly in the fixture, storage discharge was applied with subsequent assessment of the change of plate geometrical characteristics as a result of treatment. Initial values (after welding) of plate longitudinal deflection along unrestrained edges f_1 and f_3 and along the weld f_2, as well as values of transverse deflection at weld start Δ_s and finish Δ_f, were recorded as plate form change characteristics, as shown in Figure 2, *a*.

After EDT performance values of form change parameters f_{e1}–f_{e3}, $\Delta_{s.e}$ and $\Delta_{f.e}$ were also recorded. These parameters are shown in Table 1 together with the initial values.

Three treatment variants were studied, determining the sequence of current discharge application and their position. In the first variant EDT

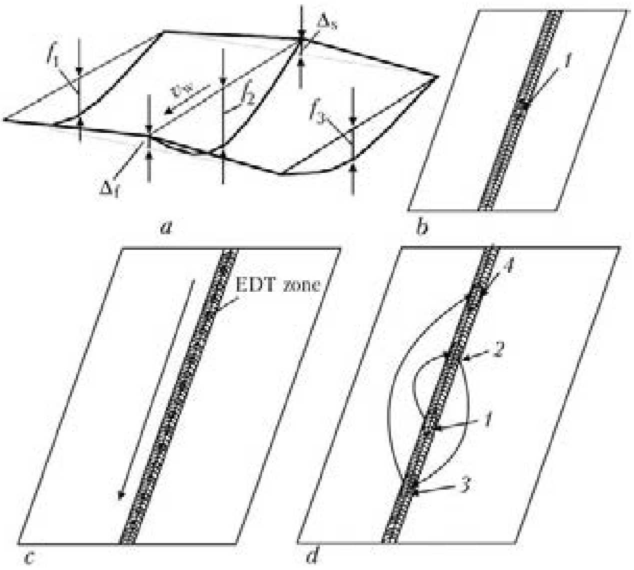

Figure 2. Geometrical characteristics of form change (*a*) and schematics of welded plate treatment: LOC (*b*), PASS (*c*), MTE (*d*) (*1–4* — sequence of EDT cycles)

cycle, consisting of five to six successive electrodynamic impacts, was performed in the weld localized zone (LOC schematic) (Figure 2, *b*; Table 1, Nos. 1, 4, 7), in the second variant — EDT cycle was run on the weld face in the pass direction (PASS schematic) (Figure 2, *c*; Table 1, Nos. 2, 5, 8). Third variant was realized by means of application of four EDT cycles along the weld line in the direction «from the middle to edges» (FME schematic) (Figure 2, *d*; Table 1, Nos. 3, 6, 9).

At realization of LOC schematic the weld central part was treated (Figure 2, *b*), allowing concentration of electrodynamic impact on a limited weld area, applying it in the zone, corresponding to maximum value of longitudinal deflection — f_2 (Figure 2, *a*). This schematic is characterized by minimum labour consumption, because of absence of the need for electrode displacement, but EDT effectiveness becomes lower with each subsequent current impact, applied to a fixed area of weld surface. This, according to the data of [4], is related to the fact that effectiveness of electrodynamic impact directly depends on the level of initial stresses σ_0 in the treated metal. Thus, each subsequent current discharge in EDT cycle makes its impact on the metal, σ_0 value of which decreased as a result of the previous discharge, and, therefore, electrodynamic impact on the stress-strain state of the plate becomes smaller.

Analysis of residual form changes in welded plates from AMg6 alloy treated by LOC schematic showed that before treatment the samples had the characteristic parabolic shape of longitudinal deflection of up to 2.5 mm, and that of transverse ones — from 2.5 up to 3.5 mm. After treatment, residual values of longitudinal and transverse deflection decreased by 60 % on average (Table 1, No.1).

Before treatment by LOC schematic samples from 30KhGSA steel had values of longitudinal deflection of 4.3–6.5 mm on the edges and 6.7 mm on the weld. After EDT residual values of deflection along longitudinal edges and weld decreased by 40 and 60 %, and along the transverse ones — by 50 %, respectively (Table 1, No.4).

Values of residual longitudinal deflection of welded plates from steel St3 reached 6.9–9.4 mm, and those of transverse one — 12–16 mm. After treatment by LOC schematic, residual values of longitudinal and transverse deflection decreased by 45 and 50 %, respectively (Table 1, No.7).

At comparison of values f_2 and f_{2e} one can see that maximum effect of treatment determining residual deflection of plates after EDT, is achieved in welded joint zone — in the area, where deflection values are maximum, as is the level of residual welding stresses, that is confirmed by the data given in [9].

At EDT by the PASS schematic (Figure 2, *c*) changes of plate deflection values were studied at progressive motion of the electrode in «the pass» direction from the joint start to its finish (shown by arrow). Longitudinal displacement of electrode end face was performed along the weld line with 15 mm step so that one electrodynamic impact was applied to each section of the treated surface. This

Table 1. Longitudinal f and transverse Δ deflection of welded plates before and after EDT

Plate number	Welded plate material	f, mm			Δ, mm		EDT schematic	f_e, mm			Δ_e, mm	
		f_1	f_2	f_3	Δ_s	Δ_f		f_{1e}	f_{2e}	f_{3e}	$\Delta_{s.e}$	$\Delta_{f.e}$
1	AMg6	2.5	2.5	2.5	2.5	3.5	LOC	1.1	1.0	1.2	1.1	1.2
2	AMg6	2.5	2.6	2.4	2.4	3.2	PASS	2.2	2.0	2.2	2.2	3.9
3	AMg6	2.4	2.6	2.6	2.6	3.4	FME	−0.5	0	−1.1	−2.3	−0.6
4	30KhGSA	4.3	6.7	6.5	9.3	12.6	LOC	3.3	2.8	3.2	4.1	6.4
5	30KhGSA	4.4	6.9	6.6	9.8	12.1	PASS	2.4	3.9	3.2	7.5	12.4
6	30KhGSA	6.3	6.8	4.9	9.4	12.9	FME	1.5	1.3	1.9	1.9	2.8
7	St3	7.3	9.4	6.9	16.0	12.1	LOC	4.6	4.0	4.2	8.1	6.0
8	St3	7.2	9.2	5.7	16.7	11.7	PASS	4.5	5.2	3.6	10.2	14.8
9	St3	7.0	9.1	6.8	15	11.3	FME	1.6	1.5	1.7	1.5	0.9

EDT schematic is the most labour consuming from all the enumerated ones, as it requires multiple positioning of electrode along weld line.

Analysis of values of residual displacements of welded plates from AMg6 alloy at EDT by PASS schematic showed that after treatment samples demonstrated a slight lowering of longitudinal deflection to 2.0 mm at increase of transverse deflection to 3.9 mm (Table 1, No.2).

It should be noted that at lowering of longitudinal deflection at treatment by PASS schematic of plates from steels of 30KhGSA and St3 grades transverse deflection increases up to 12.4–14.8 mm (Table 1, Nos. 5, 8). A similar effect was observed also on plates from AMg6 alloy (Table 1, No.2). Comparison of initial values of form change Δ_s and Δ_f with similar parameters $\Delta_{s.e}$ and $\Delta_{f.e}$ after EDT showed that during treatment a certain increase of transverse deflection is found at electrode motion along the butt in «the pass» direction.

Application of FME schematic (Figure 2, *d*) combines the advantages of earlier described LOC and PASS schematics. So, LOC schematic has the advantage of its low labour consumption (no need for electrode displacement along the butt), and the advantage of PASS schematic is the capability of weld surface treatment along its length.

FME schematic was realized by treatment of four sections of weld surface on welded plates in the sequence «from middle to edges». EDT cycle (five current discharges) was performed in each section.

Analysis of values of residual form changes in welded plates of AMg6 alloy at EDT by FME schematic showed that after sample treatment their longitudinal deflection in the weld decreased to zero values, and transverse deflection changed up to reaching form change of an opposite sign (Table 1, No.3).

Values of residual longitudinal deflection in the weld of welded plates from 30KhGSA and St3 steels after EDT by FME schematic decreased by 80 and 85 %, and those of transverse deflection — by 80 and 90 %, respectively (Table 1, Nos. 6, 9).

Conducted experiments lead to the conclusion that selected EDT schematics, such as the impact of series of current pulses on the zone «in weld center» (LOC schematic) and EDT along «the pass» (PASS schematic) do not provide complete elimination of residual distortion of welded plates from steels of St3 and 30KhGSA grades. Application of FME schematic at EDT of AMg6 alloy provides a slight reverse curvature of the studied plates at concurrent residual deflection of transverse edges.

Analyzing the data from Table 1, one can see that FME sequence is the most effective schematic of electrodynamic straightening.

Earlier performed research [11] showed that pre-loading of the HAZ of sheets to be welded by elastic bending, which is created by forces applied normal to the sheet plane, allows regulation of residual form changes of sheet structures from AMg6 alloy.

Data from [11] lead to the conclusion that pre-bending of welded plates before EDT allows improving the treatment capabilities, in order to reduce distortion of sheet structures. This is related to the fact that at realization of reverse bending an external load is applied to the welded structure, stimulating transformation of the elastic component of welded plate deformation into the plastic component at realization of electrodynamic impact. Here the force loop assigns the parameters of the restrained plate bending with the specified accuracy.

To assess the influence of parameters of metal stressed state at pre-bending on the effectiveness of straightening by EDT method treatment of stretched flat samples from aluminium alloy AMg6 and St3 steel with gauge area of 30 × 4 mm was first conducted. Sample tension was performed in TsDM-10 testing machine in the «stringent» loading mode at deformation rate of 0.1 mm/s up to specified σ_0 values. Testing temperature was equal to 293 K. Influence of electrodynamic impact on treatment effectiveness determined as the ratio of values of material deformation resistance $\Delta\sigma$ to initial stress σ_0 was assessed. $\Delta\sigma$ value was determined as the difference of σ_0 value and current value of stress recorded after electrodynamic impact. σ_0 values were assigned both in the elastic and elastoplastic load ranges that allowed determination of the stressed state parameters corresponding to optimal magnitude of outward bending.

Comparative assessment was performed of the influence of electrodynamic impact at various σ_0 levels on EDT relative effectiveness $(\Delta\sigma/\sigma_0)\cdot 100$ % for AMg6 alloy and St3 steel, which was determined after single current discharge. Values of EDT energy were assigned in the range of 130–800 J, and σ_0 value for AMg6 alloy — from 55 up to 294 MPa, for St3 steel it was from 180 up to 310 MPa. Selection of values $\sigma_0 > 1.5\sigma_{0.2}$ for samples from AMg6 alloy is dictated by the need for assessment of the influence of material strain hardening on EDT effectiveness in the elastoplastic loading range. Performance of similar research on samples from St3 steel is difficult, because of impossibility of ensuring stable σ_0 values after initial load values exceeding $1.2\sigma_{0.2}$ as a result of local yield of metal.

It should be noted that as $\sigma_{0.2}$ values are significantly different for steel and aluminium alloy, plotting $(\Delta\sigma/\sigma_0)\cdot 100\ \% = f(\sigma_0)$ dependence will make it difficult to compare the characteristics of EDT effectiveness from the level of initial stresses for the studied materials in the set range of charge energies. For a more correct comparison of obtained values, relative load $\sigma_0/\sigma_{0.2}$ was used, showing the ratio of initial stress to yield limit of St3 steel and AMg6 alloy.

Dependencies of $\Delta\sigma/\sigma_0$ on $\sigma_0/\sigma_{0.2}$ at different values of stored charge energy for AMg6 alloy and St3 steel are given in Figure 3. It is seen from the Figure that maximum EDT effectiveness corresponds to the level of initial stresses, which are close to $\sigma_{0.2}$ for AMg6 alloy (curves *3*, *5*). In this case lowering of $\Delta\sigma/\sigma_0$ values at $\sigma_0/\sigma_{0.2}$ increase is attributable to the influence of strain hardening earlier noted in [4]. For St3 steel at E increase the effectiveness increased monotonically with load increase (curves *1*, *4*) that is probably related to high ductility. It should be noted that at E = 130 J the effectiveness of EDT of St3 steel is close to zero.

Analysis of the data (Figure 3) leads to the conclusion that for AMg6 alloy plates bending parameters should correspond to σ_0 values in the elastic loading region close to $\sigma_{0.2}$. Considering the monotonic nature of increase of $\Delta\sigma/\sigma_0 = f(\sigma_0/\sigma_{0.2})$ dependence for St3 steel (Figure 3, curves *1*, *4*) it is rational to study the parameters of pre-bending of plates, corresponding both to elastic and to elastoplastic σ_0 ranges.

Considering the data (Figure 3 and [11]), effectiveness of straightening welded plates by EDT method was studied with preliminary assigning of the values of longitudinal deflection f_1^* in the direction opposite to that of deflection caused by welding. Plate pre-bending was performed in welded joint center, using a fixture (Figure 1, *a*) and deflection value was assigned by regulation of the height of supports mounted along plate edges. Here f_1^* was determined as deflection of plates after vertical load application.

Bending was applied by clamping electrode end face to plate surface in the joint central part.

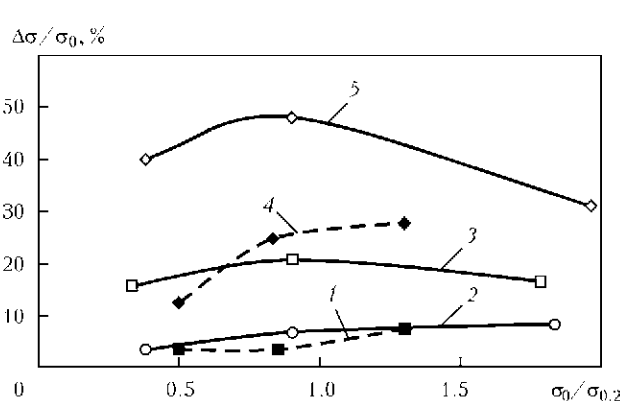

Figure 3. Influence of magnitude of relative load $\sigma_0/\sigma_{0.2}$ for samples from steel St3 (*1*, *4*) and AMg6 alloy (*2*, *3*, *5*) on EDT effectiveness at different stored charge energy: *1* — E = 300 J; *2* — 130; *3* — 300; *4* — 800; *5* — 800

After specified f_1^* values have been reached, longitudinal component of compressive stresses σ_{xx} along the fusion line was controlled, these stresses arising on plate surface as a result of bending. Here $\sigma_{xx} = 0$ value corresponded to deflection f_2 of the plate in the weld zone as a result of welding. It should be noted that evaluation of the influence of initial load on EDT effectiveness was performed by assigning σ_0 values for flat samples in the tensile region (Figure 3), and compressive stresses σ_{xx} were found on plate surface after bending. Data of [12] lead to the conclusion that dependencies $\Delta\sigma/\sigma_0 = f(\sigma_0/\sigma_{0.2})$, derived at tension of aluminium alloy and low-carbon steel, are valid also in the region of compressive stresses, but with an opposite sign.

Recording of σ_{xx} values was conducted using a wire strain gauge, pasted on the plate surface in EDT zone, and stub of IDTs-10 strain gauge unit. f_1^* and σ_{xx} values are given in Table 2. EDT cycle, similar to previous experiments, consisted of five current discharges applied to the plate by LOC schematic, with subsequent recording of its form change as a result of treatment. Values of initial longitudinal deflection of plates f_1–f_3 and after treatment f_{1e}–f_{3e} (f_2, f_{2e} is deflection in weld zone) are given in Table 2. Initial values of transverse bending of plates in the zone of weld start and finish Δ_s and Δ_f, and after EDT — $\Delta_{s.e}$ and $\Delta_{f.e}$ are also shown in Table 2.

It should be noted that assigned f_1^* values at $\sigma_{xx} = -0.3\sigma_{0.2}$ do not lead to any noticeable lowering of parameters of residual distortion of the plates for all the studied materials.

Proceeding from the data (Tables 2, No.1), we can see that at achievement of value $\sigma_{xx} = -0.6\sigma_{0.2}$ on a sample of AMg6 alloy and respective deflection $f_1^* = -2.5$ mm the longitudinal and transverse components of form change decrease by 70 and 60 %, respectively. Maximum values of residual deflection components were obtained at EDT at $\sigma_{xx} = -\sigma_{0.2}$ (Table 2, No.2) that corresponds to $f_1^* = -5.5$ mm, where form change reduction ensured practical straightening of the plates. This is confirmed by the data in Figure 3, which shows that maximum effectiveness of electrodynamic impact for AMg6 alloy is achieved at initial stress values close to $-\sigma_{0.2}$.

After bending 30KhGSA steel plate up to value $\sigma_{xx} = -0.45\sigma_{0.2}$ (Table 2, No.3) and subsequent EDT, values of longitudinal and transverse components of deflection decreased by 70 and 65 %, respectively. EDT influence was maximum at $\sigma_{xx} = -0.5\sigma_{0.2}$ and $f_1^* = -20$ mm (Table 2, No.4) where reduction of longitudinal and transverse components of plate form change reached 80 %. Further increase of values σ_{xx} and f_1^* did not lead to any essential change of plate deflection characteristics.

Table 2. Influence of preliminary longitudinal bending f_1^* on residual form change of welded plates at EDT

Plate number	Welded plate material	f, mm			Δ, mm		f_s^*, mm	σ_{xx}, MPa	f_e, mm			Δ_e, mm	
		f_1	f_2	f_3	Δ_s	Δ_f			f_{1e}	f_{2e}	f_{3e}	$\Delta_{s.e}$	$\Delta_{f.e}$
1	AMg6	2.5	2.6	2.5	2.4	3.8	−2.5	−90	0.7	0.8	0.7	1.0	1.4
2	AMg6	2.4	2.7	2.6	2.6	3.4	−5.5	−145	0.1	0	0.2	0.2	0.2
3	30KhGSA	4.4	7.2	5.9	9.0	11.8	−1.0	−430	2.2	2.2	2.4	3.5	4.2
4	30KhGSA	4.8	7.1	6.6	9.2	12.0	−2.0	−475	1.4	1.3	1.6	1.5	1.6
5	St3	7.4	9.8	6.1	15.9	12.1	5	−250	2.1	3.8	1.5	3.1	3.6
6	St3	7.3	9.4	6.9	16.3	12.1	3	−330	1.0	2.5	0.9	1.7	1.3

For St3 steel when $f_1^* = 4.0$ mm was reached (Table 2, No.5), σ_{xx} increased to $\sigma_{0.2}$ values. In this case EDT led to lowering of deflection component values to 85 %, respectively.

The rationality of studying EDT influence on form change of welded plates from St3 steel under the conditions of plastic outward bending is substantiated by data of Figure 3, which shows the comparative assessment of the influence of initial load on EDT effectiveness for St3 steel and AMg6 alloy. These data (Figure 3) lead to the conclusion that while for AMg6 alloy EDT effectiveness decreases at transition of initial load into elastoplastic stress region, for St3 steel it rises monotonically. With this purpose residual deflection $f_1^* = 3.0$ mm was created in the plate, at which σ_{xx} value on the plate outer surface reached 330 MPa that is equal to $1.4\sigma_{0.2}$ for St3 steel. Lowering of transverse deflection is maximum — up to 90 % (Table 2, No.6).

These data (Table 2) lead to the conclusion that EDT with pre-bending of welded plates inducing on plate surface stresses on the level of material yield point, allows practical elimination of residual distortion of longitudinal welded joints from AMg6 alloy and lowering it by an order of magnitude in structural steel joints.

Comparison of the data in Table 1 (Nos. 3, 6, 9) and Table 2 (Nos. 2, 4, 6) leads to the conclusion that EDT under the conditions of pre-bending at σ_{xx} values close to $-\sigma_{0.2}$ is comparable in its effectiveness for the studied metals to treatment by FME schematic, but more readily adaptable to fabrication, due to absence of the need of inductor positioning along the weld line.

EDT labur consumption is lower at application of outward bending than of FME schematic, as this does not require repeated repositioning of the electrode along the weld line.

Conclusions

1. It is established that different variants of the sequence of weld EDT performance lower the level of residual distortion of welded sheets from AMg6 alloy and from structural steels of 30KhGSA and St3 grades.

2. It is shown that both EDT of a localized weld section and EDT of weld in «the pass» direction are comparable in their effectiveness and lower the values of longitudinal and transverse deflection of welded plates several times. Maximum EDT effectiveness is found at weld surface treatment in the direction «from middle to edges».

3. Application of «reverse» bending of plates inducing on weld surface stresses on the level of material yield point, in combination with EDT, allows practically eliminating residual distortions of longitudinal welded joints from AMg6 alloy and essentially lowering it in structural steel joints.

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