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INFLUENCE OF PULSED ELECTROMAGNETIC FIELD TREATMENT ON STRESS-STRAIN STATE OF CIRCUMFERENTIAL WELDED JOINTS OF ALUMINIUM AMg6 ALLOY

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At present a growing interest in pulsed electromagnetic field treatment technologies is observed to improve the mechanical properties of metals, alloys and welded joints. Based on the pulsed electromagnetic field treatment, effective methods can be developed to optimize the stress-strain state of aluminium alloy products in order to extend their residual life for the use in aircraft and rocket, shipbuilding and other industries. The aim of the work is to study the influence of pulsed electromagnetic field treatment on the stress-strain state of circumferential welded joints of aluminium AMg6 alloy. An original experimental procedure was developed to study the kinetics of the electrodynamic pressure force during treatment of metallic materials with a pulsed electromagnetic field. It is shown that as a result of treatment with a pulsed electromagnetic field in the same conditions, the value of P increased with the use of the screen, which is predetermined by the increase in the active additional volume of the electric conductive medium. It was established that the use of the screen during treatment by a pulsed electromagnetic field helps to reduce the level of residual tensile welding stresses and improve the accuracy of circumferential welded joints. 8 Ref., 3 Tables, 8 Figures.

K e y w o r d s : pulsed electromagnetic treatment, aluminium alloy, circumferential welded joints, stress-strain state, residual welded joints, additional screen

The development of modern industry need the study of advanced energy-saving technologies to improve the service properties of metal structures. In this regard the development of methods for treatment of metal materials and welds is promising, which is based on the effect of a pulsed electromagnetic field (PEMF). These are electrodynamic treatment (EDT) and direct pulsed electromagnetic field treatment (PEMFT). The advantages of EDT are given in [1], and its disadvantages, unlike PEMFT, include the need for contact interaction with the surface of the treated metal.

At present, an increased interest in PEMFT technologies is observed in various fields of metal treatment [2], such as forming, reduction, welding, calibration, etc. In [3] the calculations and designs of inductor systems for straightening buckling of automobile body structures at PEMFT are considered.

Based on the results [2, 3], it should be noted that PEMF is an effective instrument for influencing the shaping and mechanical properties of metals and alloys [4], as well as welded joints [5]. On the basis of PEMFT, effective technologies can be developed to control the stress-strain state of thin-sheet metal materials, which include aluminium alloys used in the aircraft and rocket, shipbuilding industries, which is relevant for modern production.

The aim of this work is to study the effect of PEMF on the residual stress state of welded joints of nonferromagnetic materials on the example of aluminium AMg6 alloy.

Procedure, equipment and specimens for investigations. As is known, electric current pulse (ECP) passing through the conductors of an inductor in an approximate electric conductive medium excite eddy currents. As is proved in [6], regardless of how the inductor is located relative to the plane of the electric conductive medium, the circuits of the induced current are located parallel to the plane of the surface (medium). As a result of interaction of induced currents with a pulsed magnetic field, that excited these

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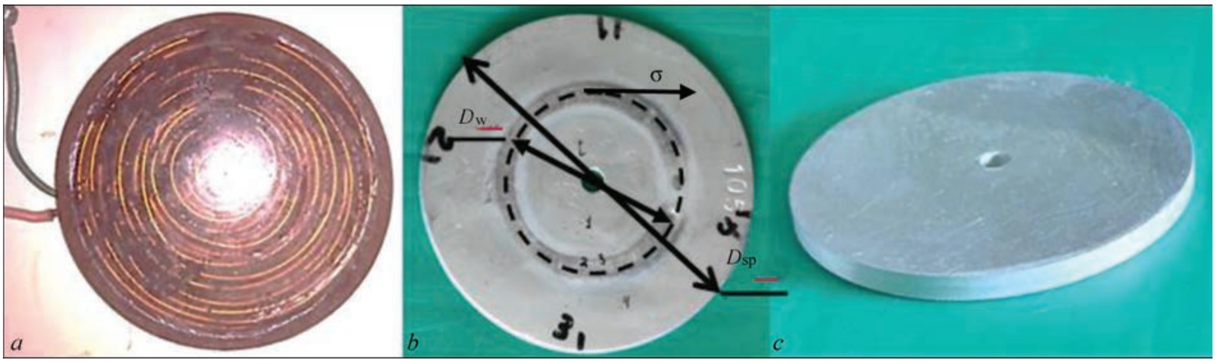

Figure 1. Appearance: *a* — flat multiturn inductor; *b* — specimen of circumferential welded joint of AMg6 alloy with a thickness δ = 1.0 mm, where D_{sp} = 90 mm and D_w = 45 mm are, respectively, the diameters of the specimen and the weld; σ is the normal component of residual stresses; *c* — screen conducting current with 90 mm diameter and 5 mm thickness

Table 1. Characteristics of flat inductor for PEMFT

Inductance* L, μH at the frequency f; kHz 1.0	Outer diameter d_{ind}, mm	Inner diameter d_{ind}, mm	Height h_{ind}, mm	Material of winding	Diameter of winding, mm	Number of turns, n
121	95	5	14	Wire, copper of M1 grade	1.0	50
*The values of inductance are determined at the value of air gap of 0.1 mm between the inductor and the specimen of AMg6 alloy with a thickness δ = 5 mm.						

Table 2. Modes of TIG surfacing of circumferential «idle» beads on the specimenns of AMg6 alloy for PEMFT

Thickness δ, mm	Arc stickout, mm	Argon consumption, l/min	Diameter of W-electrode, mm	Welding speed v_w, m/h	Welding current I_w, A
1.0	1.5	10	1.6	13.4	39

currents, an electrodynamic force arises that has three spatial components, but only one normal component of the electrodynamic force reveals to be much higher than tangential components. This force exerts an active load on the area with a pressure of force P and, as a consequence, changes the stress state of the treated material. Provided that the density j of the induced electric current reaches the value $j \geq 1$ kA/mm^2 in the treated metal, the conditions are created to realize the electroplastic effect (EPE) [4]. This contributes to the intensification of plastic deformation of the material and, as a consequence, a controlled change in its stress state. The EPE mechanism operates according to the theory of electron-dislocation interaction, in which at $j \geq 1$ kA/mm^2 in the material conditions for the interaction of conduction electrons with dislocations are created, resulting in the breakthrough of the last structural barriers, their reproduction and advancement.

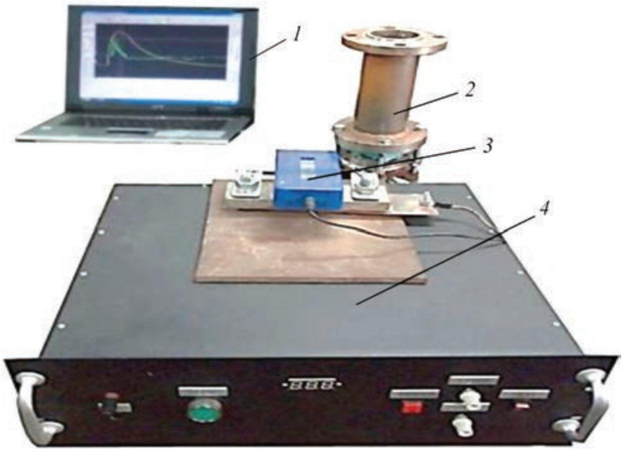

Figure 2. Appearance of hardware complex for registration of time distributions of ECP — *I* and *P* at PEMFT of metal materials: *1* — device for processing and visualization of measurement results; *2* — device for fixing the inductor for PEMFT and registration of values of the force *P*; *3* — digital device for registration of values of ECP amplitude and duration; *4* — power source for PEMFT

To generate PEMF, a flat multiturn inductor was used (Figure 1, *a*), and to realize charged and discharged cycles of PEMF, the power source is used based on a capacitor system with a total capacity C = = 5140 μF, a charging voltage of up to 800 V and a stored energy E_s ~ 1.6 kJ. The characteristics of the inductor are presented in Table 1.

To evaluate the efficiency of PEMFT, plane specimens in the form of a disc with a thickness and diameter of relatively δ = 1.0 and D_{sp} = 90 mm of aluminium AMg6 alloy were used. The circumferential welded joints were simulated by automatic TIG surfacing in the Ar atmosphere on the surface of the discs of the «idle» beads on the mode (Table 2) along the circle line with a diameter D_w = 45 mm. The method of elec-

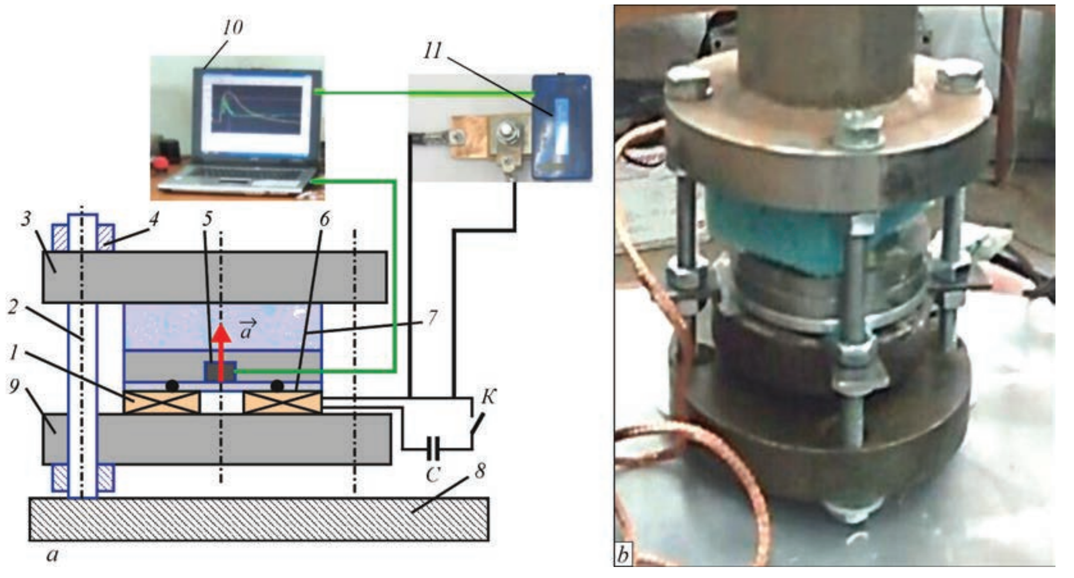

Figure 3. Device for registration of time distributions of ECP and *P* included in the hardware complex for PEMFT (Figure 2): *a* — structural design where *1* — inductor; *2* — pin; *3* — upper plate; *4* — pressing nut; *5* — acceleration sensor; *6* — specimen-simulator of welded joint; *7* — pressure damper; *8* — base support; *9* — lower plate; *10* — system for registration and processing of received data; *11* — digital device for data processing; *C* — power source; *K* — key for starting discharge cycle; *a* — acceleration vector; *b* — appearance of the device

tron speckle interferometry [1] was used to evaluate the normal component σ (Figure 1, *b*) of the residual stressed state of welded joints and vertical movements of the disc edges before and after PEMFT. During treatment, an electric conductive screen in the form of a disc of AMg6 alloy with a diameter and thickness of 90 and 5.0 mm, respectively was used (Figure 1, *c*).

The parameters of ECP were studied using a measuring digital device on the base of an noninductive shunt, designed to record the amplitude value of unipolar ECP. In addition to the value of the current amplitude, the device measured the pulse duration and the number of ECPs from the beginning of operation. The time distribution of the force *P* was recorded using Kistler 8042 acceleration sensor [7]. The appearance of the hardware complex for registration of time distributions of ECP — *I* and *P* is shown in Figure 2.

The structural design and appearance of the device *2* (Figure 2) are shown in Figure 3. The scheme of registration of PEMF parameters works as follows. Closing the discharge circuit with the key *K* starts the transient process of the discharge capacitive accumulator on the active-inductive load. The parameters of the power source and its electrical circuit provide an aperiodic type of a transient process with unipolar current pulses, the parameters of which are registered by the digital device *11*. The discharge current excites PEMF during passing through the inductor *1*. In the specimen of metal *6*, which is located above the inductor at the interaction with PEMF, eddy currents are induced, the result of which interaction with PEMF is the formation of electrodynamic force *P*, which causes repulsion of the specimen of a finite mass *m* from the inductor (which is rigidly fixed) with acceleration *a*. The time distribution *a* is registered by the acceleration sensor *5*, which is fixed on the specimen. On the top of the «sensor-specimen» assembly, pressure damper *7* made of sparse elastic material is installed, which almost does not hinder the free acceleration of the assembly. The measuring system is fixed by clamping nuts *4* and studs *2* between the upper *3* and lower *9* plates, which are mounted on the base support *8*. The force *P* is calculated by hardware as a result of multiplying mass by acceleration. The conditions for fixing the specimens, which provided their acceleration, were set by the power circuit, shown in Figure 3, *a*.

The registration of the time distributions of ECP — *I* and *P* after a single discharge of the capacitor was performed at a charging voltage $U = 200$–800 V under the conditions of acceleration of the specimens with a thickness $\delta = 1.0$ mm without a screen conducting current (Figure 1, *c*) and with its application — $\delta = 1 + 5$ mm.

After registration of $I(t)$ and $P(t)$, PEMFT of the specimens was performed, the scheme of which (with the use of the screen) is shown in Figure 4. To provide the conditions of treatment, the damper and acceleration sensor were removed. With the use of fixing elements 5 and *6*, a rigid fixation of the specimen *4* and the screen *9* between the lower *7* and upper *2* plates was provided, which are placed on the base support *8*. During the discharge of the capacitor a repulsive force *P* arised, which exerted pressure on the specimen.

PEMFT of the specimens with a thickness $\delta = 1.0$ mm and assembly of the specimen $\delta = 1.0$ mm

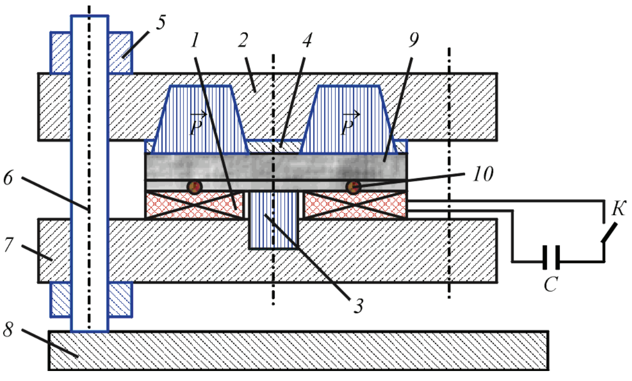

Figure 4. Structural design of PEMFT of metal materials: *1* — inductor; *2* — upper plate; *3* —axis for mounting inductor; *4* — specimen of welded joint of AMg6 alloy δ = 1.0 mm; *5* — clamping nut; *6* — pin; *7* — lower plate; *8* — base support; *9* — current-conductive screen (Figure 1, *c*); *10* — specimen-simulator of welded joint; *P* — diagram of the distribution of electrodynamic force on the specimen surface; *C* — source of PEMF; *K* — key for starting discharge cycle

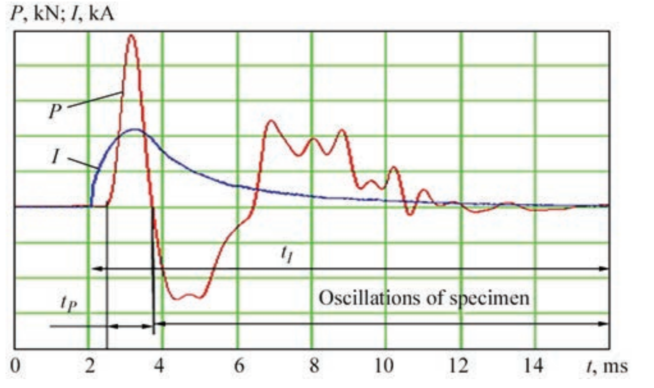

Figure 5. Time distributions of electrodynamic pressure force *P* and current force *I* at PEMFT of specimens of AMg6 alloy δ = 1.0 mm without a screen at the charge voltage U = 800 V, where t_1 and t_p are respectively periods of action of *P* and *I*

with a current-conductive screen δ = 5.0 mm (Σδ = = 6 mm) was performed. The treatment was performed by a series of eight ECPs on the mode with increasing the values of *U* in the following sequence: U_1 = 200 V, U_2 = 400 V, U_3 = 600 V, U_4–U_8 = 800 V. ECPs at U_1–U_3 contributed to the gradual reaching the nominal mode, and ECPs at U_4–U_8 — generation of PEMF for specimens treatment. The choice of the number of ECPs at a voltage of 800 V is based on the data of [4].

Results of experiments and their discussion. The time distributions of the oscillograms $I(t)$ and the force $P(t)$ at PEMFT of the disc δ = 1.0 mm without the screen are shown in Figure 5. It should be noted that the pressure *P*, which determines the change in the stress state of the specimens, acts during the period of the first half-wave of the force. The subsequent damped oscillations of *P*, which is a consequence of the contact of the specimens with the damper *7* (Figure 3) and which are reflected in Figure 5, were not taken into account when estimating the amplitude values of the force. This is associated with the fact that damped oscillations occur only during the registration of the values of *P* and are excluded under the conditions of rigid fixation of the specimens (Figure 4), under which PEMFT was performed in order to affect the stress-strain state of welded joints. When the possibility of movement of the specimen under the conditions of its fixing is excluded, the action of the force *P* initiates relaxation of stresses in the metal.

The amplitude-frequency characteristics of the pressure force *P* and the current force *I* are given in Table 3, according to which in the investigated range of treatment modes the time period t_I of the action of ECP provided the duration of the current pulse, which corresponds to the frequency at which the depth of current penetration into the AMg6 alloy reached a value higher than 10 mm. Therefore, during treatment of the specimens with a thickness δ = 1.0–6.0 mm with the pulses of such duration, PEMF is revealed on the back side of the specimen. The attenuation of the induced current occurs according to the solution of the nonstationary problem for distribution of electromagnetic field vectors [8]. In any case, at the selected parameters of the inductor, the thickness of the specimen treated by the pulsed electromagnetic field will have little effect on running the transient process of the discharge of the capacitor. The electromagnetic force *P* will grow with increasing thickness, as it is determined as an integral value in a certain volume, which is confirmed by the data in Table 3 and the dependence $P = f(I)$ at the variation δ, which are shown in Figure 6. At the growth of δ to 6.0 mm as a result

Table 3. Amplitude-frequency characteristics of *P* and *I* at PEMFT of specimens of AMg6 alloy at different values of *U* and δ

Number	Characteristics of PEMFT of specimens	*U*, V	Δ, mm	*P*, kN	t_p, ms	*I*, kA	t_I, ms
1	Without the screen	200	1.0	0.234	0.3	0.733	8.8
2		400		0.812	0.28	1.427	10.8
3		600		3.694	0.48	2.199	11.9
4		800		4.871	0.48	2.864	12.6
5	With the screen	200	1.0 + 5.0	1.267	1.36	0.82	7.7
6		400		3.589	1.2	1.593	9.4
7		600		6.690	1.2	2.316	10.0
8		800		10.999	1.0	2.952	10.58

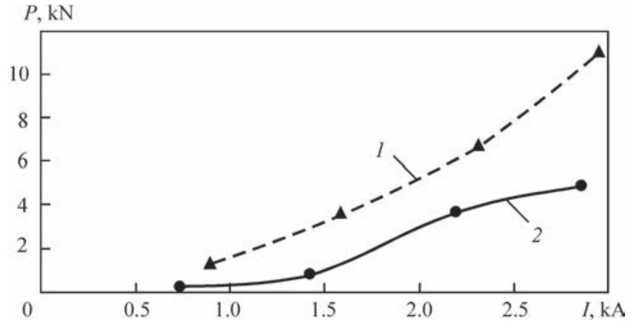

Figure 6. Influence of amplitude values of ECP — *I* on the pressure force *P* at PEMFT of specimens of circumferential welded joints δ = 1.0 mm of AMg6 alloy: *1* — PEMFT without the screen; *2* — PEMFT with the screen

of applying the screen (curve *2*), the values of *P* are increased twice as compared to PEMFT of specimens without the screen δ = 1,0 mm (curve *1*). The decrease in the pressure force *P* with a decreasing thickness δ of the disc is predetermined by the surface effect, i.e. nonuniform distribution of the density of induced currents in depth and reduction of the active volume of the electric-conductive medium, which is the electromagnetic load of the inductor. Therefore, for efficient treatment of thin specimens, it is necessary to reduce the duration of the current pulse. This path, obviously, requires a change in the parameters of the discharged circuits, which is not appropriate. The paper proposes the simplest and the most effective way in the form of installing additional layers of a related material, in which the equivalent thickness will be optimal in terms of achieving the highest value of the force *P* of the electromagnetic pressure.

The effectiveness of PEMFT effect on the residual distortion of the specimens treated under the above-mentioned conditions is confirmed by the data shown in Figure 7, *a*–*c*. The values of vertical movements of the disc edges *f* (Figure 7, *a*) were recorded according to the procedure [1] at the points Nos *1*–*4* (Figure 7, *c*) with a fixed angular distance l_α of 90° between the adjacent points. Performance of PEMFT without the screen (Figure 7, *d*, curve *2*) and with its use (curve *3*) allows reducing the value of edges movements *f* of the discs, respectively, to two and eight times as compared to the specimens that were not subjected to PEMFT.

Figure 8 shows the results of the PEMFT effect on the normal component σ of the residual stresses in the center of the weld zone (WZ) and in the zone around the weld (AWZ) at a distance of 10 mm from the weld line. Taking into account the bending of the discs (Figure 7), the consequence of which is the imbalance of the residual stress diagrams, as an estimate of the PEMFT effect on the stress state, the peak values of σ in WZ and AWZ in the specimens in the initial state and under the set treatment conditions were determined. It can be seen that in general PEMFT has

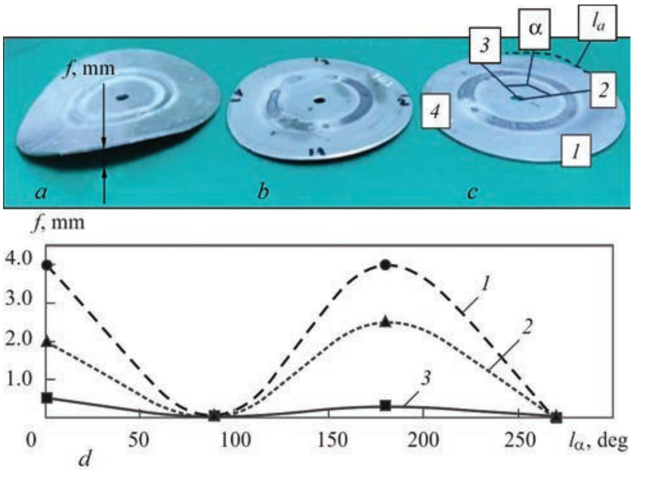

Figure 7. Residual distortions of specimens of circumferential welded joints of AMg6 alloy: *a* — appearance (A) of the disc without treatment, where *f* is the movement of the edges of the disc; *b* — A after PEMFT without the screen; *c* — A after PEMFT with the screen, where *1*–*4* is the number of the point of measurement of displacements, α and 1_α are respectively the angle and angular distance between the points *2*–*3*; *d* — vertical displacements f of edges of the disc, where the curve *1* — without PEMFT; *2* — after PEMFT without the screen; *3* — after PEMFT with the screen

a positive effect on the residual stress state of circumferential welded joints of AMg6 alloy with a thickness δ = 1 mm.

Although the initial (before PEMFT) values of σ during treatment without a screen (Figure 8, *a*) and with a screen (Figure 8, *b*) differ, which is related to low rigidity of the discs, it can be seen that the use of the screen has a positive effect on relaxation of stresses at PEMFT. This is confirmed by the comparison between the diagrams *a*, *b* and *c*, *d*. Thus, treatment without and with the use of the screen led to a decrease in the initial values of σ in the active zone of tension (WZ) by 36 and 56 %, respectively, and reactive compression (AWZ) by 50 and 80 %. The obtained results are explained by the influence of the field on the intergranular boundaries and local heating

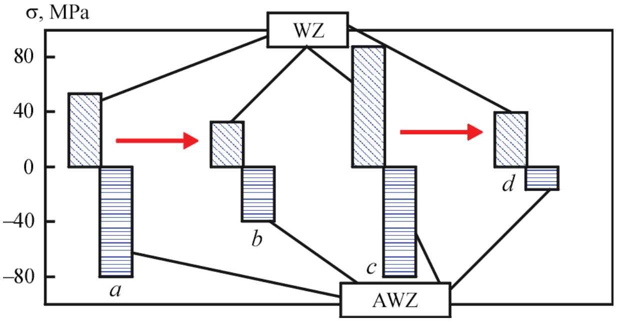

Figure 8. Influence of PEMFT on the normal component σ of residual stresses in welds (W) and in the zone around the weld (AWZ) of circumferential welded joints of the specimens of AMg6 alloy with a thickness δ = 1 mm: *a* — peak values of specimens in the initial state; *b* — σ after PEMFT without the screen; *c* — σ of specimens in the initial state; *d* — σ after PEMFT with the screen

of the grains [3], but require a more detailed study of the evolution of the fine structure of nonferromagnetic materials under the action of PEMF.

Taking into account the abovementioned, it should be noted that PEMFT can be an effective mean of improving the accuracy of manufacturing elements of thin-sheet welded structures of aluminium alloys, and also the control of their residual stress states. The advantages of PEMFT over the general heat treatment include its much lower energy consumption and the absence in the need for special equipment. It is known that the local heat treatment (LHT) of aluminium alloys is not effective because of a high thermal conductivity of the latter, and the use of PEMFT, which is characterized mainly by nonthermal mechanism of action, is more effective.

For application of PEMFT in the industrial production, in particular in aircraft and «white» shipbuilding, it is advisable to determine several branches that allow increasing the efficiency of treatment:

- optimization of electrophysical parameters of PEMFT, which will provide the maximum efficiency of the influence of field components on the stress-strain state and structure of nonferromagnetic materials;
- development and manufacture of inductor systems of increased strength and thermal stability;
- development and manufacture of energy-efficient pulsed power sources with optimal characteristics of charging and discharging cycles;
- development of PEMFT technologies for regulation of stress-strain states of welded, surfaced and sprayed structures of conductive materials.

Conclusions

1. On the basis of using the acceleration sensor, the experimental procedure of studying kinetics of electrodynamic pressure force on the specimens of circumferential welded joints during their treatment by a pulsed magnetic field was developed (PEMFT).

2. It was established that a decrease in the pressure force of the pulsed electromagnetic field with decreasing thickness of specimens of circumferential welded joints of AMg6 alloy is predetermined by a nonuniform distribution of density of induced currents and a decrease in the active volume of the electric-conductive medium, which is electromagnetic load of the inductor.

3. A method was proposed to increase the efficiency of PEMFT by forming additional layers of a related material by installing a screen that conducts a current at which the equivalent thickness will be optimal to achieve the highest value of the electromagnetic pressure.

4. It was established that realization of PEMFT without a screen that conducts current and with its use allows reducing the value of vertical movements of specimens of circumferential welded joints by respectively two and eight times as compared to the specimens that were subjected to treatment.

5. It was found that PEMFT without and with the use of the screen leads to a decrease in the initial tensile welding stresses by 36 and 56 %, respectively, and compression stresses by 50 and 80 %, which is explained by the effect of the field on intergranular boundaries and local grain heating and requires additional investigations.

6. The directions of increasing the PEMFT efficiency for its faster use in industrial production were formulated, in particular: optimization of electrophysical parameters of PEMFT, development of advanced induction systems, pulsed power sources and technologies of regulation of welded, surfaced and sprayed structures by stress-strain states.

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