IMPROVEMENT OF CYCLIC FATIGUE LIFE OF METALLIC MATERIALS AND WELDED JOINTS BY TREATMENT BY PULSED ELECTRIC CURRENT

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The paper presents experimental data on improvement of cyclic fatigue life of stainless steel and aluminium alloy samples as a result of treatment based on direct passage of electric current through the material, as well as data of calculation-experimental studies of residual welding stress relaxation under the impact of induced electric current. Results of investigation of the influence of current treatment on residual stresses in the coating and in the material after grinding are given.

Keywords: *metallic materials, welded joints, protective coatings, pulsed electric current, fatigue, residual stresses, relaxation, cyclic fatigue life*

Results of investigation of the influence of treatment by pulsed electric current (PEC) on mechanical properties of metallic materials are indicative of its positive impact on fatigue resistance characteristics [1–3]. However, no significant progress has been achieved in understanding the mechanism of the influence of PEC treatment on these characteristics, so that obtaining new experimental data is urgent.

Also known is the influence of residual stresses (RS), in particular, residual welding stresses (RWS), on fatigue of structural elements: under the conditions of cyclic loading, particularly at loading with a low stress level, RWS influence is manifested in an essential lowering of endurance limit of welded joint material and increase of fatigue crack propagation rate [4, 5].

Operations on lowering of RWS in structures usually are difficult to perform, require considerable expenses, and are reduced mainly to thermal and force (mechanical) impact on welded joint metal or to a combination of these impacts. Each of these methods has certain drawbacks. For instance, local application of high-temperature tempering leads to formation of areas with high residual stresses in the structure after its complete cooling, as such treatment essentially reproduces the thermal cycle of welding. A similar situation arises at heat treatment of some kinds of coatings. Thus, development of new methods to lower RS, devoid of the drawbacks inherent to the currently available methods, also is an urgent task.

This work gives the results of investigation of the influence of PEC treatment on fatigue of 10Kh18N10T steel and D16T aluminium alloy, as well as results of experimental assessment of PEC influence on RWS and RS relaxation in the coating and ground material.

PEC influence on fatigue of 10Kh18N10T steel and D16T aluminium alloy. Investigations were performed on samples of 10Kh18N10T stainless steel (Figure 1, *a*) and similar samples of aluminium alloy D16T 3.7 mm thick (unlike 4 mm for steel). In fatigue testing the sample was supported in cantilever (Figure 1, *b*) in the grip of the machine (electrodynamic vibration testing facility) [6]. Nine sample groups were tested altogether: one each — without treatment (as-delivered) and seven — after PEC treatment in different modes (Table).

At PEC treatment samples were connected to the taps of pulsed current generator [7]. Three current pulses were applied to each of the samples.

Testing results (Figure 2) are indicative of an essential influence of PEC on fracture resistance characteristics of the material. Treatment of steel samples

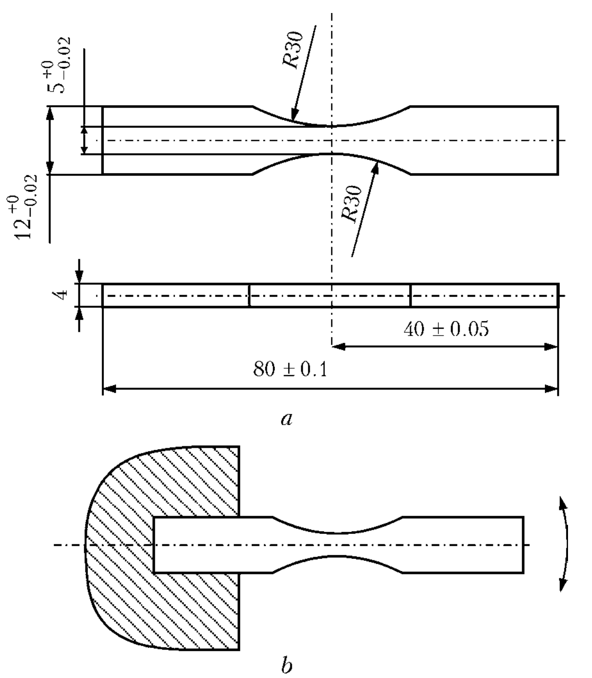

Figure 1. Sketch of a sample for fatigue testing (*a*) and its loading schematic (*b*)

Modes of PEC treatment of samples

Mode No.	j, kA/mm^2	C, μF	U, kV	I, kA
10Kh18N10T steel				
1	1	150	1.8	20
2	2	150	3.63	40
3	4	600	3.46	80
4	5.75	600	5.0	115
D16T alloy				
5	1.35	150	2.25	25
6	2.60	100	5.0	48
7	4.32	600	3.46	80

at current density j = 1 kA/mm^2 (mode 1) leads to a slight increase of these characteristics. At j = = 2 kA/mm^2 (mode 2) endurance limit of steel rises by 30 %. Increase of current density at treatment up to j = 4 kA/mm^2 (mode 3) leads to an increase of endurance limit by more than 50 %. However, further increase of current density up to j = 5.75 kA/mm^2 (mode 4) causes a lowering of fatigue resistance characteristics.

A similar tendency is observed also in the case of treatment of D16T alloy: treatment at j = = 1.35 kA/mm^2 (mode 5) does not change the fatigue characteristics compared to the initial state of the material. At j = 2.60 kA/mm^2 (mode 6) D16T alloy endurance limit increased by 40 %. Further increase of current density up to j = 4.32 kA/mm^2 (mode 7) does not cause any change of fatigue resistance characteristics compared to the initial condition.

It follows from the results of X-ray structural analysis of samples from steel that a certain change of orientation of crystals making up the grains occurs at treatment, which is indicative of ordering of the material crystalline structure in the direction of current action. In addition, according to the data of metallographic investigations, treatment results in precipitation of carbides (complex carbides $(Cr, Fe)_7C_3$) in the metal grain bulk (Figure 3). Here, the maximum density of the precipitating carbides in the grain body is observed in mode 3 corresponding to a maximum increase of endurance limit (Figure 3, *c*). Further increase of current density leads to intensive evolution

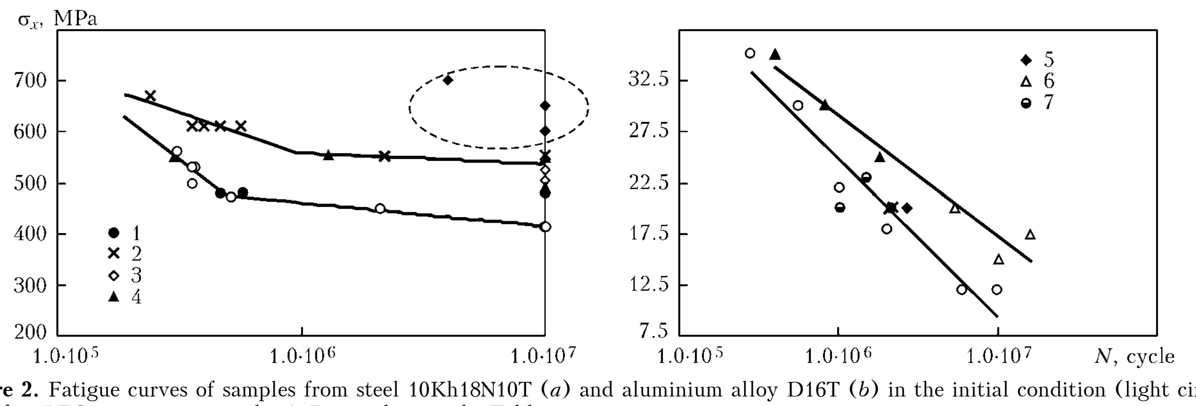

Figure 2. Fatigue curves of samples from steel 10Kh18N10T (*a*) and aluminium alloy D16T (*b*) in the initial condition (light circle) and after PEC treatment in modes 1–7 according to the Table

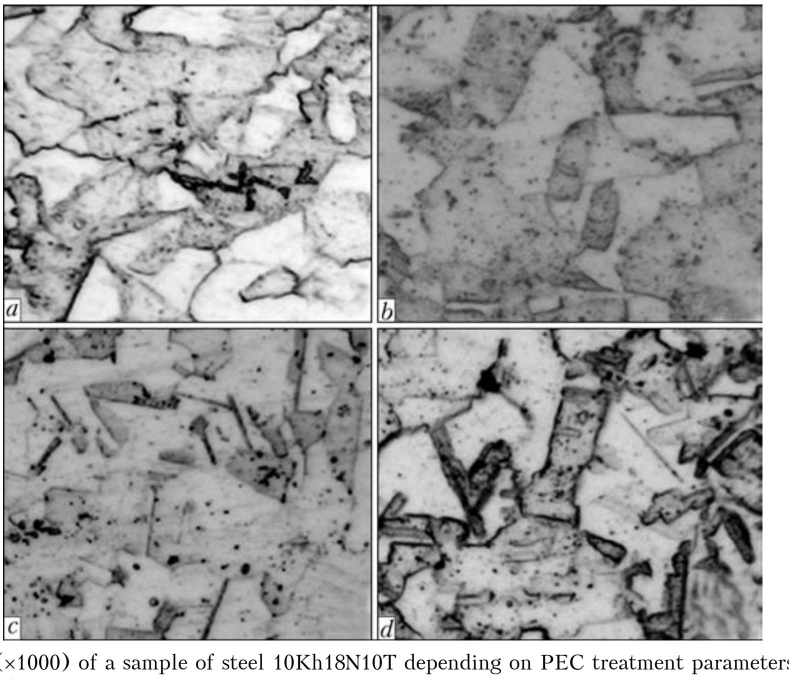

Figure 3. Microstructures (×1000) of a sample of steel 10Kh18N10T depending on PEC treatment parameters: *a* — initial state; *b* — I = 40; *c* — 80; *d* — 115 kA

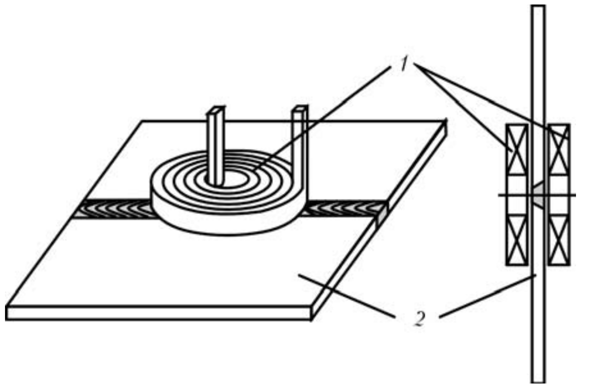

Figure 4. Schematic of PEMF treatment: *1* — inductors; *2* — plate with a weld

of carbides along the grain boundaries (Figure 3, *d*) and, as a consequence, to material softening.

Influence of induced current on RS in the welded joint. Treatment by pulsed electromagnetic field (PEMF) of a plate from aluminium alloy AMg6 made by butt welding of two parts 360 mm long, 250 mm wide and 3.7 mm thick (butt weld is along the long side, melting zone width B is about 12 mm), was made by the schematic given in Figure 4. At treatment the co-axially mounted inductors with outer diameter of 45 mm were shifted along the weld axis by 15 mm after each discharge and the bank of capacitors of 600 μF capacity was discharged through the inductors connected in series, at 3 kV voltage. Results of RWS measurement made by the method of speckle-interferometry are shown in Figure 5.

PEC influence on RS redistribution in the coating. Adverse influence of tensile RS on fatigue and wear resistance of structural elements with coatings is well known. However, considerable compressive RS in the subsurface layer do not always provide the maximum effect of improvement of fatigue life of parts. In study [8] it is shown that lowering of compressive RS induced in the subsurface layer of a titanium alloy after vibration-amplitude strengthening leads to a considerable increase of the number of cycles to fracture.

Therefore, increase of fatigue strength and wear resistance of structural elements ensured at optimum level and distribution of RS for the specified mode of thermomechanical loading and development of effective methods of technological treatment, providing formation of optimum level of RS in the coating–base system, are an urgent task.

Samples in the form of bars 10 mm wide, 80 mm long and 3 mm thick from tool steel of Cr–Mo–V system with one-sided coating from chromium nitride CrN of thickness b_c = 3 μm applied by magnetron sputtering, were studied. Coating was applied in two modes inducing, by the data of sample manufacturer, RS on the level of 0.5 and 1.5 GPa in the coating. At treatment two current pulses with maximum amplitude of about 40 kA (discharge of a bank of capacitors of 300 μF capacity at initial voltage of 2.5 kV) were applied to the sample.

Assessment of PEC influence on the stress-strain state of the coating was performed on samples without

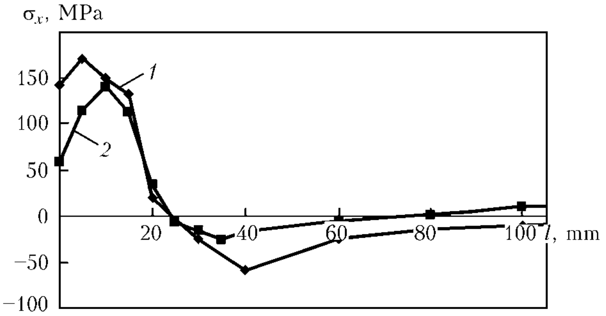

Figure 5. Dependence on RS in a sample of AMg6 alloy (normal to weld axis, plate middle) on distance from weld axis x before (*1*) and after PEMF treatment (*2*)

treatment and after treatment at complete removal of the coating, comparing the data of recording the change of strain on the opposite side relative to the coating. By the results of measurement, sample treatment by PEC application causes a lowering of the level of strain recorded by resistance strain gauges and, therefore, the level of compressive RS in the coating by approximately 20 % (Figure 6).

PEC influence on residual stresses after grinding. Strips from 10Kh18N10T steel 10 mm wide and 2 mm thick were used for investigations. Strips were attached by screws to a rigid pre-ground steel base, which, in its turn, was mounted on the table of a planogrinding machine tool, ensuring the coincidence of the grinding direction with the strip axis. At the first stage pre-grinding of the strips to the thickness of 1.9 mm was performed, using lubricoolant and low feed across the thickness. At the second stage lubricoolant feeding was overlapped and a 0.1 mm layer was removed in two passes at corundum wheel speed of 30 m/s. After such a «tough» grinding and removal from the base, the strips had a pronounced bend — result of action of tensile stresses in the layer adjacent to the ground surface (Figure 7). Strips were cut into samples of about 70 mm length, and then strain gauges were glued onto the sample ground surface in the central part.

At PEC treatment the sample was pressed by current taps of pulsed current generator to the flat surface

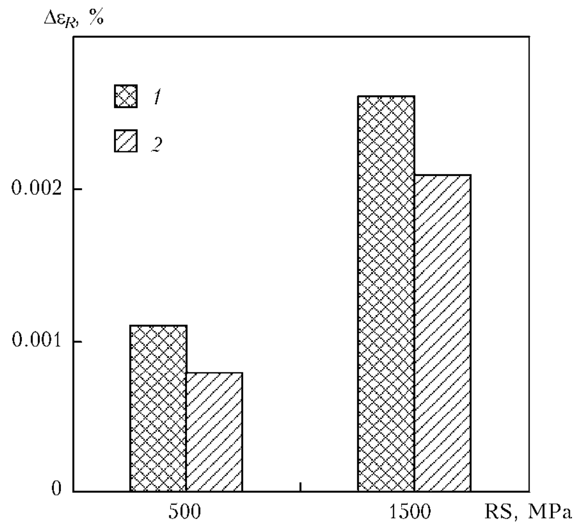

Figure 6. Change of strain in samples with a coating after its removal: *1* — without PEC; *2* — after PEC treatment

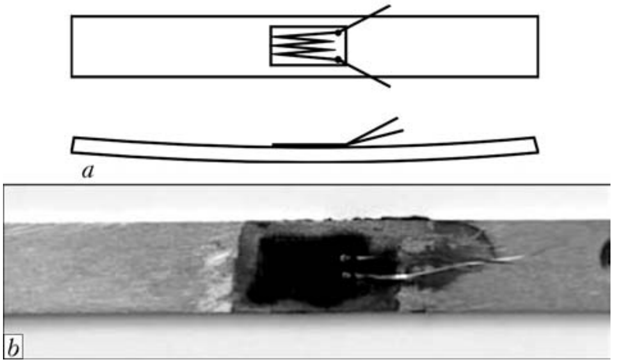

Figure 7. Schematic (*a*) and appearance (*b*) of a sample after grinding

of the massive textolite guide so that there were a sample section of about 40 mm (treated part of the sample) between the current taps with a strain gauge in the central part. One current pulse with 50 kA amplitude was applied, temperature rise being equal to 110 °C, which is essentially lower than the temperature required for RS lowering in regular heat treatment.

During investigations the strain gauge initial resistance was recorded in the free (bent) condition of strip A_1, in its straightened condition, pressed to textolite surface A_2, after PEC treatment (current passing and subsequent cooling) A_3 and in the released state after treatment A_4. Experimental results were used, allowing for calibration coefficient k, to determine the value of tensile strain caused by strip straightening in the initial condition $\varepsilon_b = k(A_2 - A_1)$ and after PEC treatment — $\varepsilon_b^{\rm PEC} = k(A_3 - A_4)$, as well as treatment-induced longitudinal compression $\Delta\varepsilon = k(A_2 - A_3)$ and lowering of bending deformation in the free state $\Delta\varepsilon_b = \varepsilon_b - \varepsilon_b^{\rm PEC}$.

The given results of strain recording were used to assess PEC influence on RS in the ground layer. Plastic compression of metal in layer δ_1 overheated as a result of grinding, causes tensile σ_1 (Figure 8) and compressive RS σ_2 in the layer (base metal layer unaffected by overheating) after cooling. From the condition of equality of forces in the layers before and after treatment and compatibility of deformation of the layers as a result of PEC action we can show that the change of stress in the first layer is equal to

$$\sigma_1^{\rm PEC} = [(\delta - \delta_1)/\delta_1]\Delta\varepsilon E, \quad (1)$$

where E is the modulus of elasticity.

At the same time, the level of stresses and strains in the surface layer after sample fixing on the flat textolite base is proportional to initial stresses after grinding. It can be shown that the change of bending deformation caused by PEC treatment, is equal to $\Delta\varepsilon_b = [1 - 3(\delta_1/\delta]\sigma_1^{\rm PEC}/E$, therefore,

$$\sigma_1^{\rm PET} = \frac{\delta}{\delta - 3\delta_1}\,\Delta\varepsilon_b E. \quad (2)$$

Then the thickness of ground layer δ_1 is determined by equating expressions (1) and (2):

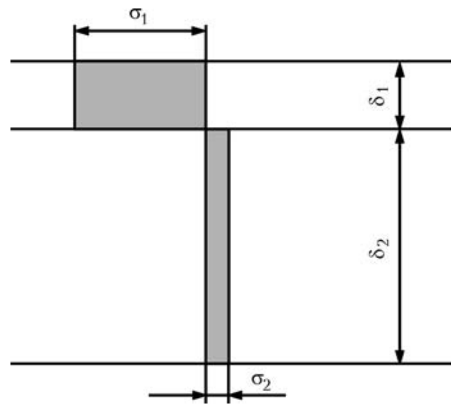

Figure 8. Schematic distribution of RS in a sample straightened after grinding ($\delta_1 + \delta_2 = \delta$)

$$\frac{\delta}{\delta - 3\delta_1}\Delta\varepsilon_b = [(\delta - \delta_1)/\delta_1]\Delta\varepsilon,$$

and finally

$$\delta_1 = \frac{\delta}{6}\,[\xi + 4 - (\xi^2 + 8\xi + 4)^{1/2}], \quad (3)$$

where $\xi = \Delta\varepsilon_b/\Delta\varepsilon$.

From the recorded data for $\Delta\varepsilon_b$ and $\Delta\varepsilon$, value ξ can be determined as $\xi = 0.57576$. At strip thickness $\delta = 1.8$ mm using equation (3), thickness of deformed layer can be determined as $\delta_1 = 0.48$ mm, here the calculated lowering of RS as a result of current passage through the sample determined from equation (1) or (2) is equal to $\sigma_1^{\rm PEC} \approx 40$ MPa.

CONCLUSIONS

1. Treatment modes were determined allowing an essential improvement of the endurance limit of a number of metallic materials at cyclic loading.

2. It is shown that this treatment leads to an essential redistribution of RS in the weld, coating or material after grinding, that in case of its application on structural elements allows their cyclic fatigue life to be extended.

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