Electroexplosive and Electron Beam Combined Treatment of AISI 1045 Steel[1]

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Abstract – Complex researches of system metal (aluminium) coating – AISI 1045 steel substrate formed by methods of electroexplosive alloying and following pulse electron-beam treatment were made by using methods of optical microscopy, SEM, TEM and microhardness measurement. The mode of electron-beam treatment which allows decreasing the surface roughness of coating-substrate composition (to obtain mirror surface) and increasing microhardness of treated surface and near-surface layer was revealed.

1. Introduction

The last decades particular interest in the technologies combining various methods of coating formation and their electron-beam treatment, their combinations and sequence are increased [1]. Such combined technologies have functionally different influence on surface and often result in significant increase of material characteristics: fatigue strength (up to 40%), corrosion resistance (up to 200%), heat-resistance (up to 200%), and wear resistance (up to 1000%) [2].

Analysis of structure transformation regularity and mechanical characteristics modification of near-surface layer of carbon steel at electroexplosive alloying (EEA) and following pulse electron beam treatment is the purpose of present work. Pulse plasma jets formed during the capacitor discharge through conductors are the instruments of influence on surface in EEA method. In the case working matter of plasma accelerator serve as for heating of surface layers of metals, and for their alloying [3]. Data presented in [3] show the increase of microhardness, wear-, heat-resistance, and other exploitation properties of wide nomenclature of machine components, constructions and tools exposed by EEA. But there are some restrictions for practical use of EEA. The products of electric explosion represent polyphase system including plasma component and condensed particles of different size. During formation of jet, its front forms the plasma component. The condensed particles have greater inertness and therefore they are located in the jet back. This process leads not only to surface alloying but also to coating formation. The formed coatings are high-porous, contain large number of droplets, microcraters and microcracks. All of these significantly decrease the exploitation properties of treated details. Usually given coatings are removed by mechanical polishing, that results in loss of valuable alloying elements (up to 50%) and consequently rise in price of EEA process occurs. In the present work, the irradiation of surface after electroexplosive treatment by electron beam with submillisecond pulse duration was carried out for elimination of the given negative consequences [4].

2. Experimental procedure

AISI 1045 steel with ferrite-perlite structure was used as substrate material. The electroexplosive alloying was made using electric explosion of aluminium foils with thickness of 20 μm. The parameters of EEA were the followings: charging voltage of storage element – 2.3 kV, diameter of nozzle channel – 20 mm, and distance from nozzle cross section to a sample – 20 mm. Depth and alloying zone radius were maximum under these conditions. The time of treatment – 100 μs, the absorbed power density on jets axis – 4.5 GW/m^2, pressure in shock-compressed layer near the surface – 11.2 MPa. Thickness of alloying zone in its central part was 25 μm [3]. Electron-beam treatment of alloying surface was carried out on setup “Solo” [4] under following irradiation parameters: energy density of electron beam 10…30 J/cm^2; pulse duration 50 μs; repetition frequency of pulses 0.3 Hz; number of pulses 2…200. Research of structure of irradiated surface and fracture surface, element composition of near-surface layer of modified samples were made by using techniques of optical and SEM, phase composition was determined by methods of X-ray diffraction analysis. Changing of mechanical characteristics of material was characterized by microhardness determined with using Vickers approach under loading of 1 N.

3. Results and discussion

Owing to products of electric explosion of conductor are multiple-phase system including both plasma

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component and condensed particles of different size, the EEA is accompanied by forming coatings on treated surface. The coatings are high-porous, contain large number of droplets, microcraters and microcracks (Fig. 1).

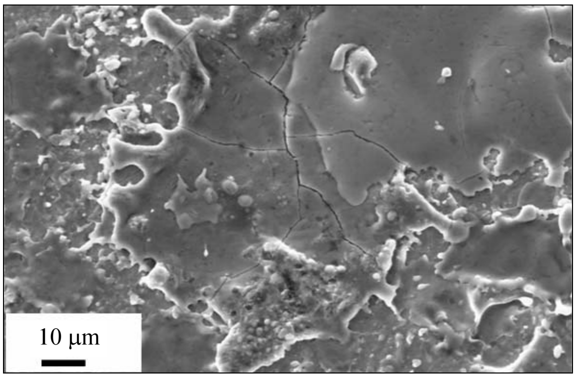

Fig. 1. SEM image of surface structure of AISI 1045 steel subjected to electroexplosive alloying by aluminium

Obviously that given fact essentially decreases exploitation properties of EEA treated details. In the present work, elimination of these negative effects on the surface treated by EEA was realized by electron beam irradiation with submillisecond pulse duration.

With the purpose of optimization of irradiation parameters, electron-beam treatment of samples was carried out on two experiment series. At first, energy density of electron beam (E_S) was changed from 10 to 30 J/cm^2 under invariable pulse duration (τ = 50 μs), repetition frequency of pulses (f = 0.3 Hz) and number of pulses (N = 10). Secondly, number of pulses N was varied in the range of 2 … 200 pulses under invariable energy density of electron beam (E_S = 20 J/cm^2), pulse duration (τ = 50 μs) and repetition frequency of pulses (f = 0.3 Hz).

3.1. Surface modification at variation of energy density of electron beam

As a result of realization of first series of experiments was founded that pulse electron-beam treatment of samples subjected to EEA leads to melting of surface layer with the depth of 2…10 μm. The level of smoothing of EEA surface relief is increasing with electron beam energy density rising. The maximum of smoothing was reached at E_S = 20 J/cm^2 (Fig. 2).

The multiple crater formation was registered under high values of electron beam energy density. The given process can be partially suppressed by increasing energy density of electron beam. However, we failed to completely remove the craters.

Simultaneously with EEA surface modification by electron beam the strength characteristics of surface layer were changed. Microhardness measurements of surface layer shows that maximum values of given material characteristic are achieved in two cases: E_S = 10 and 20 J/cm^2. Taking into account the level of surface roughness, we can think that optimal mode of irradiation in given experimental series is the mode with electron beam energy density E_S = 20 J/cm^2. In this connection next experimental series were carried out at E_S = 20 J/cm^2 under conditions of variation of electron beam pulses number (N = 2…200).

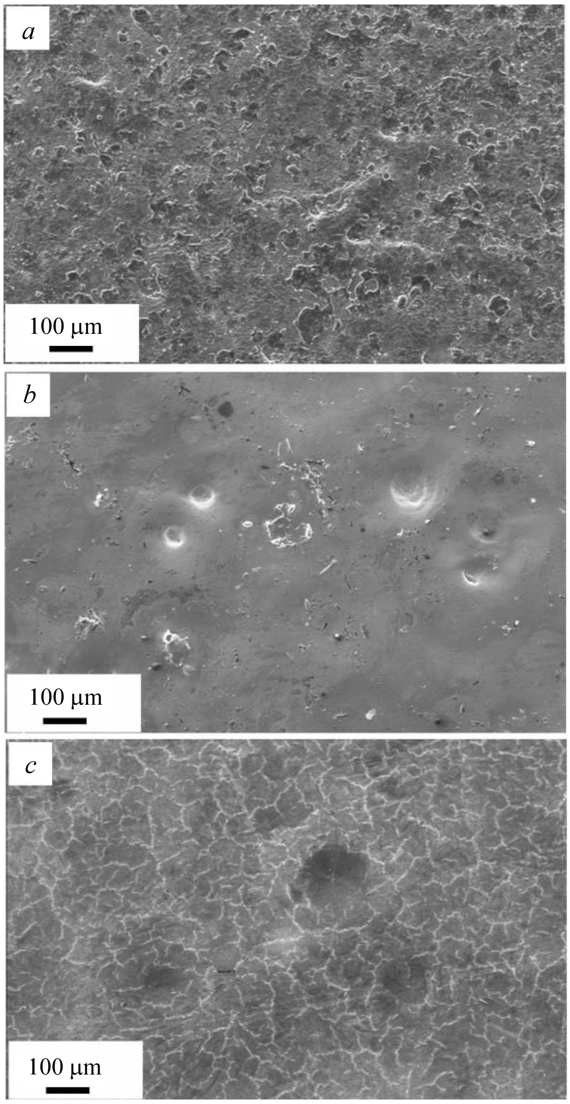

Fig. 2. SEM image of surface structure of AISI 1045 steel subjected to electroexplosive alloying by aluminium and electron beam treatment: *a* – E_S = 10; *b* – 15; *c* – 20 J/cm^2

3.2. Surface modification at the variation of pulses number of electron beam

Treatment of samples by pulse electron beam with energy density E_S = 20 J/cm^2 leads to melting of surface layer with a depth of 5…8 μm. The increase of pulse number from 2 to 10 is accompanied by decreasing of roughness level of treated surface. Microcraters are begun to form on the surface when number of pulses reached 50. The increase of pulse number up to 200 results in significantly decrease of craters number on treated surface.

High-speed melting with following cooling is accompanied by formation of microcracks system breaking the surface on blocks with average size $D = 60$ μm (Fig. 3, *a*).

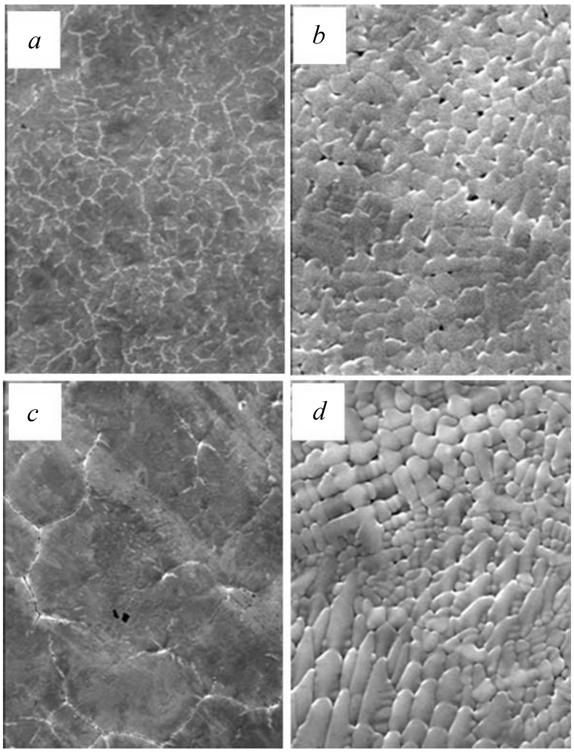

Fig. 3. SEM image of surface structure of AISI 1045 steel subjected to electroexplosive alloying by aluminium and electron beam treatment: *a*, *b* – $N = 10$; *c*, *d* – 200 pulses; *a*, *c* – × 70; *b* – × 8000; *d* – × 3100

In the bulk of blocks the structure of dendrite crystallization is observed; the average size of dendrite is 250 nm (Fig. 3, *b*). The increase of pulse number up to 200 leads to bulk heating of sample, decreasing cooling rate of surface layer. The last leads to particular relaxation of elastic stresses in surface layer, significant decrease of microcracks number on the surface of sample ($D = 60$ μm) (Fig. 3, *c*), increase of average dendrite cross section sizes ($d = 650$ nm) and changing of their morphology (Fig. 3, *d*).

The modification of surface layer structure leads to increase of steel microhardness reaching the maximum values (exceeding in ~3.8 times of steel microhardness values without coating) at $N = 10$ pulses. (Fig. 4).

The increase and decrease pulse number of electron-beam treatment is accompanied with decreasing of surface layer microhardness. In first case it indicates a liquid-phase mixing of substrate and coating; in second case – a weak thermal treatment of coating.

Distribution of microhardness values of coating surface changes remarkably. At small number of pulses ($N = 5$), bimodal distribution of microhardness is observed. This is the result of comparatively low level of thermal modification of coating surface by electron beam (presence of residual microporous regions). At $N \geq 10$ pulses microhardness distribution

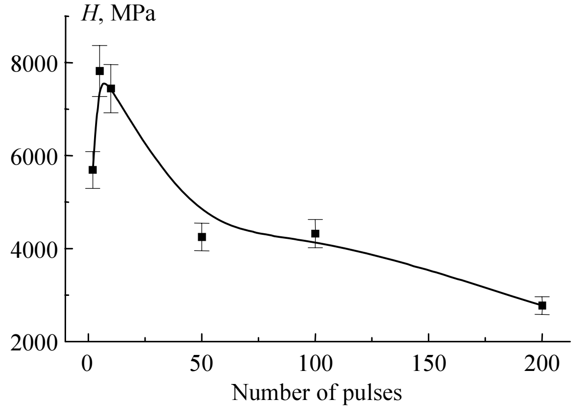

Fig. 4. Dependence of average values of surface layer microhardness of AISI 1045 steel subjected to EEA on pulses number of electron beam treatment ($E_S = 20$ J/cm^2; $\tau = 50$ μs; $f = 0.3$ Hz)

is single-mode. It indicates on good electron-beam thermal surface treatment. To increase the pulse number the maximum of microhardness distribution displaces to the side of lower value.

The range of microhardness values decreases showing on forming of strength homogeneous surface layer.

As it was already marked, the electron-beam treatment of AISI 1045 steel alloying by an electroexplosive method is accompanied with surface layer melting, i.e., liquid-phase mixing of substrate and coating. The last shows on possible modification of steel surface layer structure and change of its microhardness.

Analysis of surface layer microhardness profiles shows that material hardening at EEA quickly decreases with increase of distance from the surface on depth of ~20 μm, reaching hardness of initial steel (Fig. 5, curve *4*).

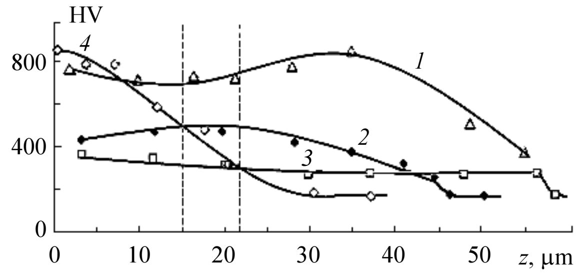

Fig. 5. Microhardness profiles of AISI 1045 steel subjected to electroexplosive alloying by aluminium (curve *3*) and electron beam treatment ($E_S = 20$ J/cm^2; $\tau = 50$ μs; $f = 0.3$ Hz): *1* – $N = 10$; *2* – 50; *3* – 200 pulses

Thickness of hardened layer is increased to 55–60 μm (Fig. 5, curve *2*) after electron-beam treatment. Absence of an abrupt difference of microhardness values near the coating/substrate interface shows on absence of dangerous stress concentrators which are able to decrease system mechanical properties.

4. Conclusions

Electroexplosive alloying by aluminium of AISI 1045 steel with the following electron-beam treatment was carried out. The modes for liquid-phase mixing of coating/substrate system allowing forming surface layer with lower roughness, high value of microhardness and absence of concentrators of stress on coating/substrate interface were revealed.

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