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STRESSES IN COATINGS OBTAINED BY ELECTRO-SPARK ALLOYING AND LASER PROCESSING (REVIEW)

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High-energy treatments (electric-spark alloying, laser processing) give rise to residual stresses in the surface layers of processed materials. Their distribution during the electric-spark alloying depends on the applied alloying metal. Under laser treatment the stress distribution depends on the radiation power, the treatment speed and the distance between the sections to be processed. The value, the sign, and regularities of stress distribution significantly affect the working properties of machine parts.

The development of modern industries demands that the quality and reliability of manufactured products be improved. It is the development and wide use of new hardening technologies that is one of means for the solution of this problem. Electric-spark alloying (ESA) and laser processing are among the promising and economically expedient techniques [1]. Residual stresses have a substantial effect on mechanical and, accordingly, performance properties. Below, we examine the following problems: (i) the mechanism of formation of residual stresses in surface layers of materials after ESA and laser processing and (ii) effects of both alloying metal in ESA and laser processing parameters (radiation power density, speed of laser processing) on regularities of residual stress distribution in the depth of a hardened layer.

It is well known that residual stresses in coatings are induced by deformation due to a rigid cohesion of material with the base [1–4]. With base deformation under external loads, the coating is transferred through an adhesion bond. In the case of temperature or force loading of coatings, the adhesion bond between the coating material and the material of base is subjected to considerable mechanical actions that weaken the initial adhesion strength.

The residual stress distribution in the surface layer is tested as a rule by the method of chemical stripping (Davidenkov method) and the X-ray method. The experimental determination of residual stresses in the surface layer by the Davidenkov method is based on the detection of relocation of the free end of a flat specimen after surface layer stripping. The residual stress is calculated by the formula

$$\sigma = \frac{Ed^2}{3l(1-\mu)}\frac{\Delta f_k}{\Delta h}, \tag{1}$$

where E is the elasticity modulus, μ is the Poisson's coefficient, d is the specimen thickness, l is the specimen length, f is the sag, and h is the thickness of the removed layer.

To achieve the correctness of the results, hardening should be conducted throughout the specimen surface. The value calculated by the formula is an averaged for a stripped volume.

The Davidenkov method is unfit for testing residual stresses in coatings formed by electric spark and laser processing because of both the temperature drop in the thickness and width of the zone of action and structure inhomogeneity that lead to nonuniform residual stress distribution.

The X-ray method for residual stresses determination is based on a precise measurement of the lattice constant. In a state of plane stress the variation of the lattice constant in some grains in a certain random direction is proportional to deformation in this direction. In this case, the residual stress and the variation of the lattice constant must be connected by the relation

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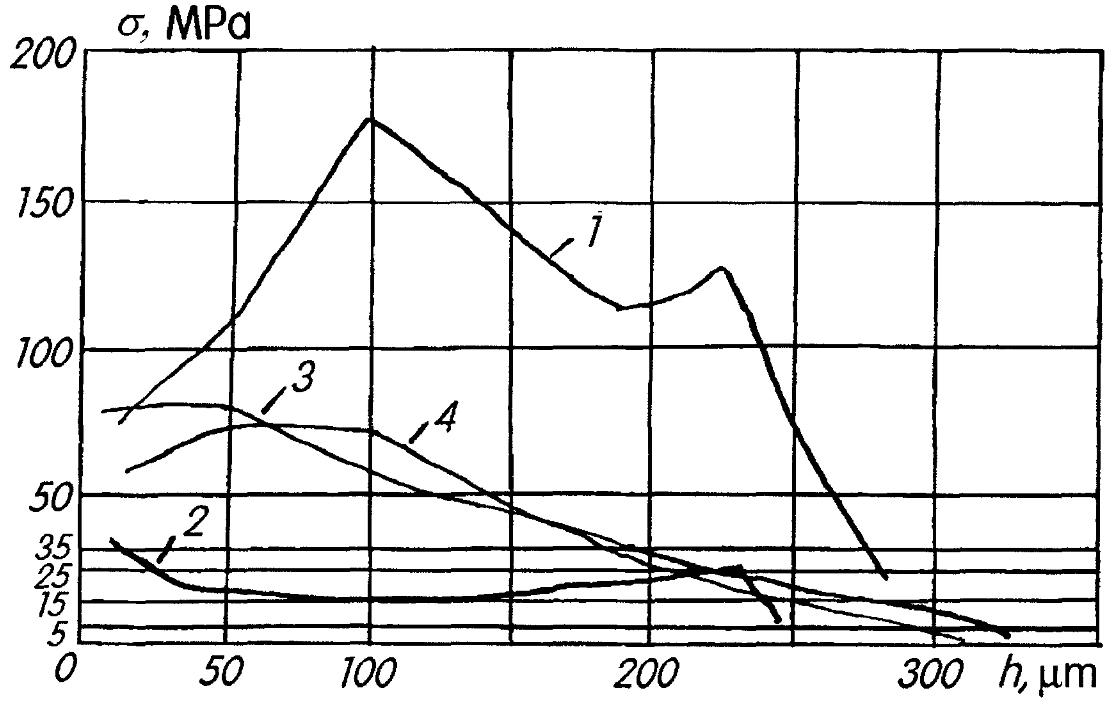

Fig. 1. Residual stress distribution in the depth of alloyed layer while alloying 45 steel by ESA with tungsten (1), chromium (2), zirconium (3) and molybdenum (4).

$$\varepsilon = \frac{\Delta d}{d_1} = \frac{1+\mu}{E}\sigma \sin^2\psi, \qquad (2)$$

where ε is the elastic deformation, σ is the residual stress, d is the interplanar distance, Δd is the interplanar distance variation, μ is the Poisson's coefficient, E is the elasticity modulus, and ψ is the slope angle of the X-ray beam toward the specimen surface.

The X-ray test is carried out without surface damaging, the stresses being determined in a thin presurface layer 30–50 μm deep, the X-ray beam width on the surface being about 0.5 mm [5, 6].

Residual stresses during ESA depend much on the nature of the alloying metal [1, 2]. In the series Ti, Zr, V, Nb, Ta, Cr, Mo, W, Fe, Ni, under otherwise equal conditions, the values of maximum residual stresses drop from 150 MPa for titanium to 4 MPa for nickel. As thickness increases, in the alloyed layer cracks are formed due to residual stresses in a coating that lead to the generation of pronounced stresses on the boundary surface. Only tensile stresses were detected. Minimum residual stresses (180–450 MPa) in the layer are generated under ESA with metals that form unlimited solid solutions with iron (V, Cr). High residual stresses (600–1000 MPa) in the layer in the course of alloying with titanium or zirconium are explained by the surface heating up to temperatures of polymorphic transitions.

The analysis of residual stress distribution in the thickness of a layer demonstrates the local behavior of maximum stresses in a coating [1, 2, 7–9]. In alloying with metals that form limited solid solutions with backings, the maximum stresses are generated near the interface "white layer"–the transition layer (Fig. 1). In this case, in the upper zone of the transition layer a certain increase in stresses is detected, too, bound up with the change of physical and mechanical state of cathodic material owing both to multiple α- and γ-transitions in iron and to diffusion of anodic material into the cathode. The residual stresses in alloying with titanium and zirconium are particularly high. In addition to the mutual insolubility of coating materials and backing, this fact is explained by data of spectral seaming analysis, which show deepest penetration of the metals of the IV group into iron. Moreover, titanium and zirconium, when heated, undergo polymorphic transitions which at the repeatedly varying heat loads in the process of alloying also stimulate the residual stresses increase. The residual stress distribution in the coating thickness depends on ESA conditions. Residual stresses can be diminished by application of argon and light air for inter-electrode medium, which decrease the embrittlement of the layer [10, 11].

The effect of sequential heat treatment on residual stresses in the alloyed layer was studied on specimens of 45 steel hardened by heating up to 840°C in water and tempered at temperatures from 0 to 500°C. It is known that the value and the sign of residual stresses govern the thickness and working properties of the alloyed layer [12]. ESA was carried out in the air with the alloy W62 (65% W, 38% Ti). The internal stresses in the surface layer were established to be 500–600 MPa. Their further increase causes the destruction of the coating. The depth of residual stresses penetration depends on steel cathode heat treatment: with an increase in tempering temperature it decreases (Fig. 2). A slight diminution of stress value in the direction toward the surface in some specimens is due to the presence of cracks near the surface [12]. Tungsten carbide WC is shown to be the basic phase component in the alloyed layer. Iron and cobalt are also present in moderate amounts. The tungsten monocarbide content, rather small in untempered specimens, increases with an increase in tempering temperature. At ESA performed with solid alloys, residual stresses diminish along the depth, just as in the case of alloying with metals.

Thus, in the process of ESA with metals that form unlimited solid solutions or chemical compounds with the material of the cathode, minimum internal stresses are induced in the coatings in the entire range of the modes of treatment, which ensures the high strength of cohesion [1, 2].

Surfaces treated by the method of ESA are not characterized by high wear resistance because of high roughness and high internal tensile stresses in the surface layer. To eliminate these disadvantages, we smooth out the alloyed surface with a superhard material. The maximum values of tensile stresses in nonsmoothed electric-spark coatings are as high as 500–600 MPa. Smoothing substantially decreases internal stresses in the coating. Tensile stresses with a value of 30–40 MPa formed in the "white layer" in the transient layer turn into compressive stresses with the value of about 50 MPa in tempered specimens and about 30 MPa in specimens hardened prior to ESA. It is the tensile stress relaxation as a result of plastic deformation by smoothing that is responsible for such a diminution. Smoothing with a superhard material removes the microasperities of the coating and flattens its surface. Thus, smoothing of electric-spark coatings diminishes residual tensile stresses and roughness [13].

In laser treatment of a material, from the very beginning of the process in the area of beam action there occurs a volume expansion whose intensity and size are governed by the rate and temperature of heating [14, 15]. Cold layers surrounding the heating zone reduce the volume expansion, as a result, in the heat-affected zone (HAZ) compressive stresses are generated, increasing with higher temperature. They increase until the heated metal becomes plastic, after which they partially or even completely relax [14–17].

Initially the surface layers subjected to laser action cool down most intensively. In the underlying layers, the temperature increases owing to heat ingress from upper layers. As a result of surface cooling, the heated volume decreases, but the expected increase of compressive stresses is not observed. This fact is due to high material plasticity in the HAZ depth [14]. Over the course of time, rates of material cooling throughout the volume of HAZ are equalized and layers adjacent to the cold mass of matrix metal intensively cool down. As metal in HAZ solidifies, it loses its damping property, and tensile stresses begin to generate intensively, often exceeding the ultimate stress of the material, with the result that, on the surface treated with laser radiation, a net of microcracks can develop. In this case, thermal stresses govern the formation of stressed state of the hardened layer [14–17].

With further cooling in the material, there occur structural transformations attended by alteration of specific volume. Particularly, in the examined period of time martensite transformations in steel take place that increase the volume and cause the generation of structural stresses directed opposite to heat-removal, i.e., toward the surface of hardened material [14–17].

Volume expansion of the material undergoing structural transformation generates compressive stresses that to some extent can decrease formerly generated tensile thermal stresses. Hence, the stressed state of a material is governed by thermal, residual, and purely structural stresses of the opposite sign. The character of the final distribution of residual stresses in the material depends on the predominant stress type [14–17].

With an increase in laser radiation power accompanied by formation of a thin layer of melted metal on the surface, tensile stresses decrease equalizing in the depth. Later on, the metal melts, the residual stresses in the surface layer change their sign, i.e., compressive stresses appear, and tensile stresses increase in the depth of HAZ [18–20].

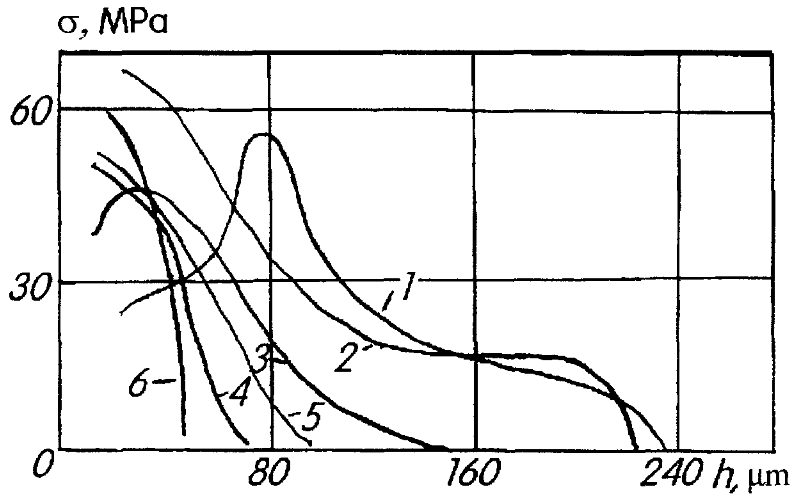

Fig. 2. Residual stress distribution in the depth of layer of the original specimen (1) and specimens tempered at temperatures T = 100°C (2), 200°C (3), 300°C (4), 400°C (5), and 500°C (6).

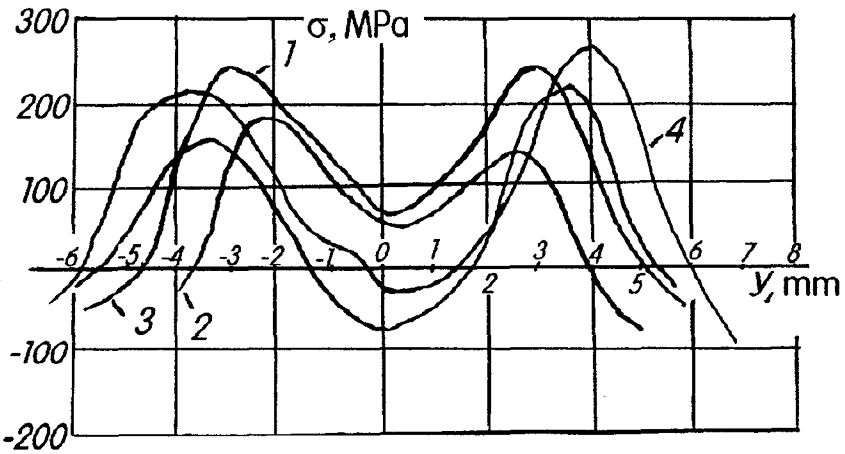

Fig. 3. Residual stress distribution at the armco-iron surface transverse to the hardened streak after laser treatment with the speed v = 33.3 mm/sec and power P = 0.9 kW (1), 1.3 kW (2), 2.3 kW (3), and 3 kW (4).

The study of residual stresses of the first kind in U8A, KhWG, Kh12M steels and armco-iron showed that stress value and the nature of stress distribution are strongly affected by the laser radiation power density [21]. At the power density of 2–10 W/cm, compressive stresses in the surface layer of KhWG steel reach the value of 250 MPa. Residual stresses extend to a depth comparable to the HAZ depth. In the periphery of the hardened zone tensile stresses occur. The laser treatment was carried out on the pulsing installation "Kwant-16" and by continuous CO_2 lasers at a radiation power from 0.5 to 3.5 kW. The results of the research have been plotted as curves of residual stress distribution in armco-iron transverse to the surface at different distances from the center of the hardened streak and various radiation power densities (Fig. 3). At the surface of specimens treated by continuous CO_2 laser, the residual stress distribution is rather nonuniform, being symmetrical with respect to the streak center. Under treatment conducted without surface melting with the power of 0.9 and 1.3 kW, tensile stresses in the streak center are small (up to 70 MPa). On the boundary of the laser-affected zone (LAZ) and the nonirradiated surface, tensile stresses increase up to 170–270 MPa, and passing into the nonirradiated zone they start to drop smoothly to values of −50 to −70 MPa. With laser treatment with surface melting, stresses in the streak center drop down to nearly zero at $P = 3$ kW and to −90 MPa at P = 2 kW, rising at the boundary to 240–290 MPa. Furthermore, the power and the hardened streak width increased, and the region of tensile stresses moves from the center of the streak [21].

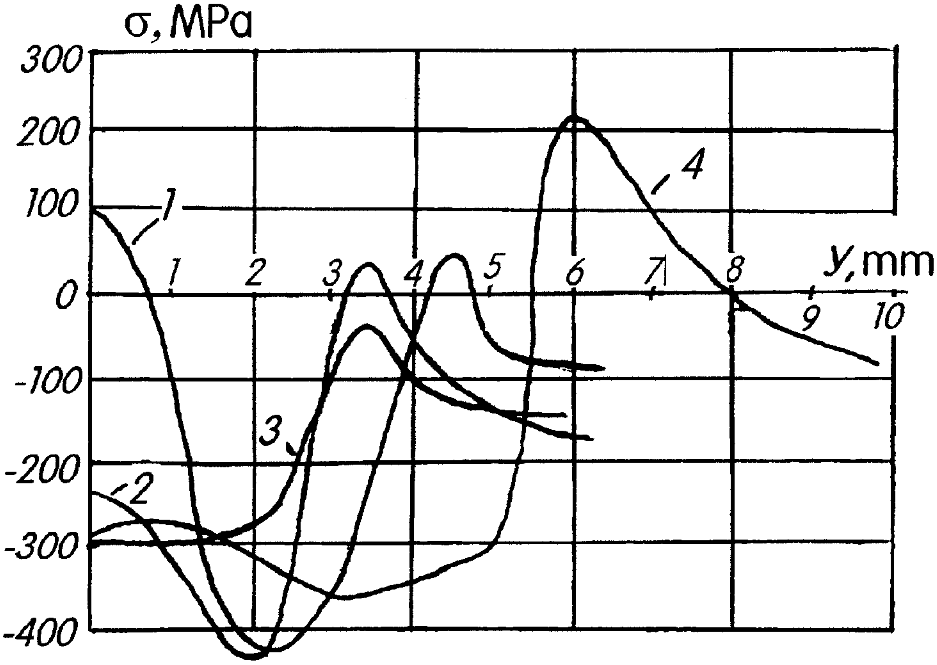

Fig. 4. Alteration of residual stresses transverse to a hardened streak for 40Kh steel after treatment without scanning at the power P = 1 kW and speeds v = 8.3 mm/sec (1), 16.7 mm/sec (2), and 25.0 mm/sec (3), and with scanning at the power P = 2.5 kW and speed v = 20 mm/sec (4).

Laser processing under the conditions: P = 0.5 kW and v = 33.3 mm/sec does not augment the steels' hardness in the irradiated streak, i.e., it heats them below transition temperature [22]. Tensile stresses as high as 200–380 MPa are formed on the streak surface only due to the thermal action of layers. The volume expansion at the martensite transition owing to the increase of carbon concentration or cooling rate in steels results in an increase of compressive stresses proportion. In 45 and 40Kh steels in the center of the laser melted streak, compressive stresses are as high as 100–260 MPa. They are maximum at P = 1 kW, minimum volume of liquid bath and maximum cooling rate. At P being 2–3.5 kW, the stresses on the surface of 45 and 40Kh steels exceed those on armco-iron surface by 100–150 MPa. The curve of stress alteration in the center of the melted streak as a function of radiation power for U8 steel is located somewhat higher than that for 45 and 48Kh steels. This can be associated with the residual austenite generation in the ZLV that diminishes the volume effect during hardening [22].

As the laser radiation power increases, there is a change not only in the stress values in the streak center but also in the character of their distribution across the layer [19]. Thus, at P = 1 kW, the curve of transverse residual stress distribution for 45 steel is close to that for armco-iron. At P = 2 kW the curve shape turns into a very complex one: in the center of streak of melting the curve almost reaches zero; on its edges there are deep minima at –370 to –410 MPa, and on the boundary of ZLV with the nonirradiated surface we see regions with small tensile stresses. The appearance of a maximum in the melted streak center can be explained by the self-tempering or the increase in the amount of residual austenite. With P being 3 and 3.5 kW, the melted zone is rather expansive, and the curve of residual stress distribution transverse to the streak passes near zero values with small deviations on both sides [19–22].

The value and the character of residual stress distribution are also significantly affected by the speed of laser treatment [20, 21]. The speed being 8.3 mm/sec, in the melted streak center of 45 and 40Kh steels tensile stresses are generated with a value from 100 to 140 MPa (Fig. 4). At a 2 mm distance from the melted streak center, residual stresses have a value in the range of –200 to –400 MPa. As the speed of laser treatment increases, tensile stresses in the streak center change to compressive.

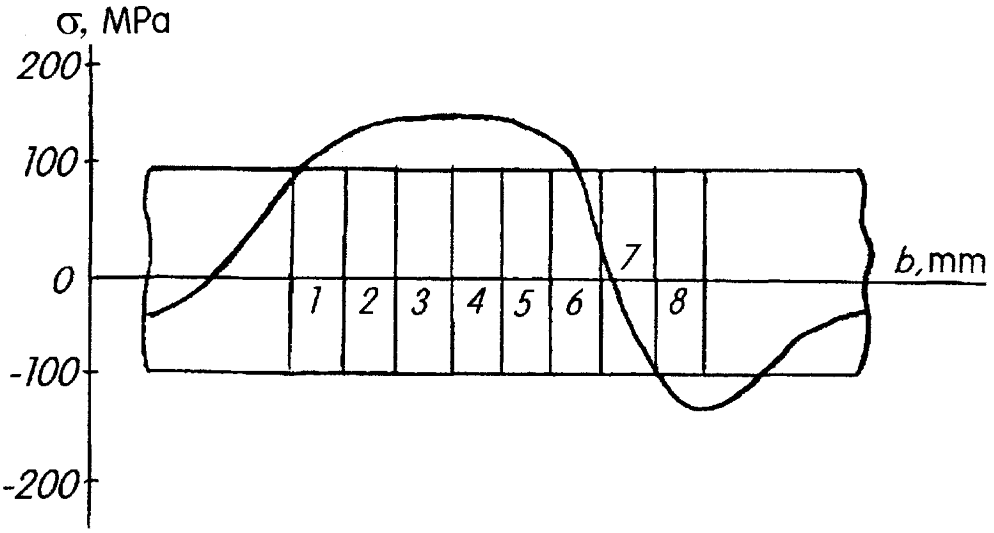

Fig. 5. Residual stress distribution transverse to the streaks of hardening on the surface of a 40 Kh steel bar after treatment with continuous CO_2-laser.

In U8 steel, stresses in the streak center and the shape of the curve of transverse stress distribution change slightly at various speeds. For the KhWG steel, they are reverse to those observed for 40 and 45Kh steel; at low speeds, compressive stresses are formed in the streak center and, at high speeds, we observe the formation of tensile stresses. In this case the influence of residual austenite self-tempering is perceptible. In the R18 steel with low martensite content in the region of melting, high speed laser treatment not only forms tensile stresses in the streak center, just as in the KhWG steel, but also changes the shape of the curve of transverse distribution. At the speed 25 mm/sec the stresses in the melted streak center are as high as 140 MPa, on the edge they fall to the minimum value of 20 MPa, and on the boundary they reach again the maximum value of 230 MPa. At the speed 33.3 mm/sec the shape of the curve is preserved but the stress values displace in the region of tensile stresses. At the speed 41.6 mm/sec residual stresses equalize and fall in the range of 260–370 MPa [22].

The value, the sign and the character of the residual stress distribution substantially change under processing with spots and streaks overlapping [22, 23]. Stress distribution was examined at the 40Kh steel bar surface transverse to the hardened streaks applied to the surface along a spiral with turns overlapping during hardening with continuous CO_2-layer (Fig. 5). On the surface of the first six streaks tensile stresses were detected, whereas at the two last streaks the compressive ones were found. This fact demonstrates that the value and the sign of residual stresses are decisively influenced by the interaction between the volume changes in the metal of the irradiated streak and the metal of the precedent streak. Such an interaction inevitably results in formation of sequential tensile stresses when streaks and spots overlap. The value and the range of changes in tensile stresses at irradiation with overlapping depend on treatment conditions and, first of all, on the overlapping extent and radiation power. When overlapping extent increases, the range of changes in tensile stresses all through the surface decreases [20–22]. Deformation of parts under heat treatment depends on the values of total stresses. Under laser treatment, it is affected both by the irradiation conditions and by the density of streaks to be hardened. An evaluation of this parameter has been conducted on specimens with only one streak previously put on the surface, i.e., 30% of the surface hardened [22]. The value of residual stresses was determined to diminish not by a factor of 3–4, but by a factor of 2. Hence, with continuous hardening during application of every next streak, there occur both tempering and a partial relaxation of internal stresses generated by a preceding irradiation.

Working characteristics of machine parts and mechanisms are governed by material strength properties, corrosion resistance, and stressed state [22]. In the surface layers of machine parts, high technological residual stresses can develop, sometimes exceeding the material ultimate stress. This results in formation of a net of microcracks. This may occur just after finishing treatment as well as somewhat later due to the common action of residual and working stresses.

CONCLUSIONS

At ESA, tensile stresses are generated in the surface layers. Minimum stresses are generated in alloying with metals that form unlimited solid solutions with iron. High residual stresses developing in alloying with tungsten and chromium are associated with their polymorphic transitions.

The laws of residual stress distribution depend on the power density of laser radiation, treatment speed, and the distance between the areas to be processed.

The value, sign, and character of residual stress distribution along the depth of the surface layer significantly affects the working properties of machine parts and mechanisms.

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