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Specifics of the Surface Structure of Steel Products After Various Laser Alloying Methodics

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Abstract— In modern conditions, volumetric alloying of steels is becoming an increasingly less economically viable process. However, the level of performance properties of unalloyed steels cannot cover the current industry needs. One of the ways to solve this problem – usage of various surface alloying methods of steels, makes it possible to obtain the required properties of the working surface of the alloyed part with minimal consumption of expensive alloying elements. Over the course of the study, combined method of laser-plasma alloying of steel surfaces was analyzed, its technological capabilities were determined, and the structural-phase state of surface layers, formed during laser and hybrid laser-plasma processing was compared. During comparative studies of samples obtained by both methods of surface alloying, it was found that in the case of laser-plasma alloying, the observed structure and carbide phases are smaller in size, with a low density and uniform distribution of dislocations in the metal of the alloyed layer. After various analysis, it was established that during both laser and laser-plasma methods of surface alloying, the crack formation tendencies was mostly attributed to various structural and concentration changes associated with the redistribution of elements, leading to the formation of sharp grain-boundary concentration gradients. An increase in the number of cracks is observed in regimes with higher heating temperatures, increased duration of exposure to high temperatures and reduced cooling rates.

Keywords— surface alloying; laser alloying; hybrid laser-plasma alloying; steel; structural study.

I. Introduction

In modern conditions of continuous cost growth of alloying various components, the volumetric alloying of steels is becoming an increasingly less economically viable process. However, the level of performance properties of unalloyed steels is not sufficient to cover the needs of the modern industry. One of the ways to solve this problem – usage of various surface alloying methods of steels, makes it possible to obtain the required properties of the working surface of the alloyed part with minimal consumption of expensive alloying elements [1-3].

The development of surface engineering at the present stage involves the development of novel technological processes that allow for modification of the surface layer [4], as well as radical changes in its structure and properties [5], utilizing concentrated energy flows such as ion, laser, ultrasonic, electrical and etc. [6-8]. At the same time, during usage of concentrated heating sources, the problem of accumulation of internal stresses in the treated layers arises, leading to the formation of microcracks [9].

One of the current directions in solving this problem is the development of new combined and hybrid surface treatment processes based on the simultaneous use of two different sources of thermal energy for heating, for example, laser radiation and electric arc plasma [6, 8]. Recently, more and more publications on the use of combined processes for applying coatings based on the combined use of laser radiation and a plasma arc have appeared in the modern scientific and technical literature [1-10]. This combination of processes, due to the incomplete overlap of the plasma spraying zone with the laser heating zone, provides a surface preparation effect and eliminates the need for abrasive jet postprocessing. A characteristic result of this process is the ability to obtain a continuous alloyed layer with increased adhesive strength. By correcting the technological parameters of the process, we deem it possible to move from the process of applying a surface coating to the technology of surface alloying.

The purpose of this study is to analyze the combined method of laser-plasma alloying of steel surfaces, determine its technological capabilities and compare the structural-phase state of surface layers, that are formed during laser and laser-plasma processing.

II. Experimental Methodic

For experimental studies, steel 38KhN3MFA (GOST 4543-71) was chosen. This metal is used for the production of turbogenerator rings, as well as the most important and heavily loaded parts of pipeline fittings. In the railway industry, this steel has found its application in the manufacture of crankshafts for four-stroke medium-speed engines with gas turbine supercharging and charge air cooling, widely in the post-Soviet countries; on top of that, they were exported with various export diesel locomotives to Germany, Bulgaria, France, Mongolia, Syria and other countries.

A laboratory stand for conducting experiments on laser and laser-microplasma surface alloying was organized on the basis of a three-coordinate manipulator manufactured at the PEWI (Paton Electric Welding Institute, Ukraine).

The Nd:YAG laser “DY044” by “ROFIN-SINAR” (Germany) with a laser radiation wavelength λ=1.06 μm was used in this study. Laser radiation was transmitted to the treatment site via an optical fiber with a diameter of 600 microns and a length of 20 meters. From the optical fiber, laser radiation entered the collimator, where it was transformed using a system of optical elements, acquired the required geometric dimensions and then fell on a focusing quartz lens ∅ = 50 mm with a focal length F = 200 mm. The surface alloying was carried out by varying the laser radiation power within the range P=3.0...4.4 kW, processing speed V=400...750 mm/min and defocusing value ΔF=+30...+45 mm.

The outer surface of cylindrical samples made of structural alloy steel 38KhN3MFA underwent post-processing. For laser alloying, a mechanical mixture of powders with granulation of 0...40 μm with the following composition (wt. %) was used: (WC-W_2C) + Cr + Al + Si = 46% + 46% + 4% + 4%. For laser-plasma alloying, a mechanical mixture of powders of similar granulation with the composition (wt.%) was used: (WC-W_2C) + Cr + Al = 48% + 48% + 4%.

When carrying out laser alloying experiments, the sample was placed on the object table and fixed in a stationary manner, while the laser focusing head was located on the movable carriage as a part of a three-coordinate manipulator. The design of the laser focusing head made it possible to process the sample with a coaxial delivery of both laser radiation and filler powder. The filler powder was transported directly into the nozzle part of the laser head using argon. Filler powder dosing was carried out using a vibrating feeder device, developed at the PEWI. To prevent any possible laser radiation reflecting back into the optical path from the surface of the liquid metal, the laser head was tilted 10° forward along the movement of the carriage.

When conducting experiments on laser-plasma surface alloying, the laser focusing head and plasmatron were mounted on a fixed support. The samples were fixed in grippers, specifically mounted inside the movable carriage of a three-axis manipulator. During processing, straight alloyed tracks were obtained due to the longitudinal movement of the carriage. A melt pool up to 2 mm deep was formed on the surface of the sample, into which a mechanical mixture of powders was supplied by a jet of laminar argon-arc plasma. To power the plasmatron, an MPU-4 source was used in the experiments. The welding current was 40...50 A at a voltage of 32...38 V. The distance from the plasma torch nozzle to the processing zone was 120...150 mm. The flow rate of the plasma-forming gas (argon) was chosen to be 1.5...2 l/min, the flow rate of the shielding gas (argon) was 4...5 l/min. The convergence angle of laser radiation and plasma jet was 30...45°. The filler powder consumption was varied within 0.1…1 g/s.

Templates measuring 10 × 10 × 10 mm were cut out from the obtained samples. For 12 groups of samples that differed in the parameters of technological modes, metallographic studies of each sample were carried out in areas of the alloy layer, the fusion line zone and the base metal.

The studies included light microscopy using Versamet-2 by Unitron (USA), analytical scanning electron microscopy utilizing SEM-515 by PHILIPS (Holland), as well as microdiffraction transmission electron microscopy using JEM-200CX by "JEOL" (Japan).

Structural changes, microhardness, chemical composition at local points and its distribution along the depth of the layer from the outer surface of the alloyed layer to the base metal, dislocation structure, and the formation of phase precipitates were studied. Based on this set of studies, estimates of the dislocation density were made, the nature of the distribution and level of local internal stresses, as well as their gradients, were established. Particular attention was paid to the nature of the formation of microcracks, namely their distribution, size and establishing the cause of their appearance.

III. Results and discussion

Over the course of the study, experiments have shown, that as a result of surface alloying by both methods, the alloyed layer has a clearly defined crystalline structure (Fig. 1, 2), directed perpendicular to the fusion line. The thickness of the alloyed surface layers, obtained by laser and laser-plasma methods decreases from 2250 µm to 1580 µm, with an increase of the alloying speed from V = 400 mm/min to V = 750 mm/min.

On the side of the base metal, near the fusion line, a heat-affected zone (HAZ) was observed, the width of which increases from 1300 µm to 1650 µm, when respective alloying speed decrease, from V = 750 mm/min to V = 400 mm/min.

In the case of hybrid laser-plasma surface alloying (Fig. 1), the crystallites are both more extended and more cellular in nature. They are smaller in size compared to those obtained by laser surface alloying (Fig. 2). During both laser and laser-plasma alloying, microcracks - one of the main defects of interest, were recorded in almost all of the analyzed samples. However, while microcracks may be present in the alloy layer, the fusion zone (Fig. 3) and even inside the base metal layers after using the laser surface alloying methodic, similar microcracks were not detected in neither the fusion zone nor the base metal after hybrid laser-plasma surface alloying.

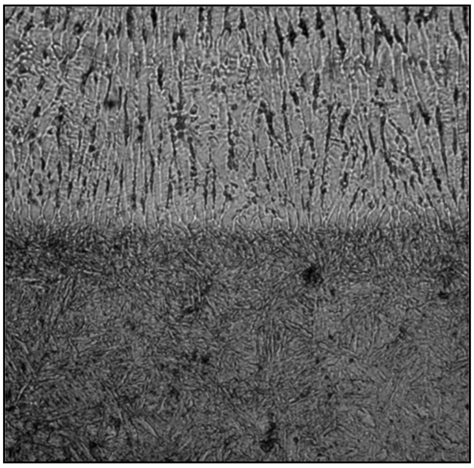

Fig. 1. Microstructure at the fusion line (×500) of a 38KhN3MFA steel sample with a surface layer obtained by laser-plasma alloying (V=500 mm/min, P=3.0 kW, ΔF= +30 mm).

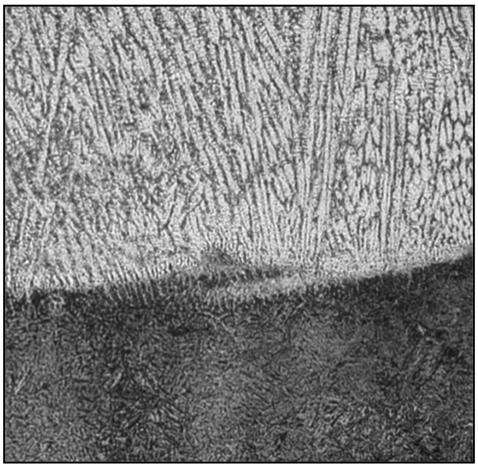

Fig. 2. Microstructure at the fusion line (×500) of a 38KhN3MFA steel sample with a surface layer obtained by laser alloying (V=400 mm/min, P=4.4 kW, ΔF = +30 mm).

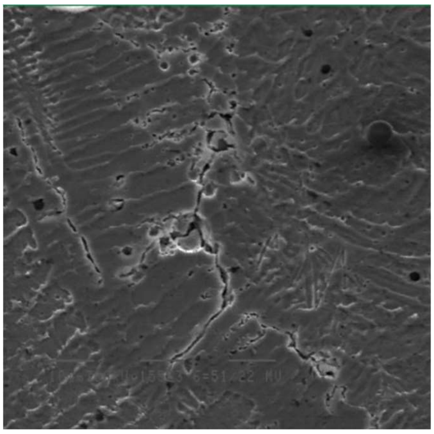

Fig. 3. Microstructure with a microcrack near the fusion line (×1550) of a 38KhN3MFA steel sample with a surface layer obtained by laser alloying (V=400 mm/min, P=4.4 kW, ΔF = +30 mm).

At the same time, samples obtained by laser alloying (P = 4.4 kW, V = 400 mm/min, ΔF = +30 mm) are characterized by a needle-like structure inside the crystallites, saturated with extended carbides of various sizes and, accordingly, with different internal structure, formed mainly along the grain boundaries of crystallites. Phase deposits have a complex linear “parquet-like” structure (Fig. 4). A sharp gradient is observed, both in structure and in dislocation density ρ, which varies from 8×10^8 cm^{-2} to 1×10^{12} cm^{-2}. The chromium concentration in places with formed cracks and microcracks increases up to 25%.

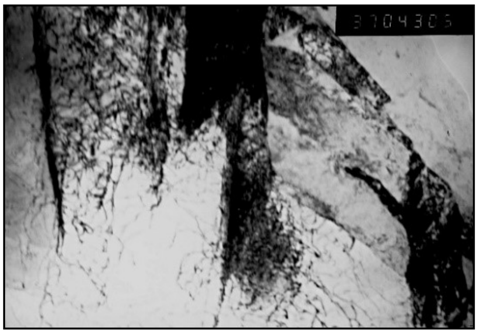

Fig. 4. Crystallite structure near the fusion line (×37000) of a 38KhN3MFA steel sample with a surface layer obtained by laser alloying (V=400 mm/min, P=4.4 kW, ΔF = +30 mm).

It has been established that it is the gradient in dislocation density $\Delta\rho$ that is the main reason for the formation of sharp local concentrators of internal stresses $\tau_{L/IS}$ components from $\tau_{IS} \approx 14.9$ MPa to 18500 MPa, which causes formation of the cracks and a sharp deterioration in surface quality of produced layers.

The length of cracks in both the alloyed layer and in the fusion zone is 50...550 μm.

The study of concentration changes in the alloyed layer showed that in the case of processing speed V = 400 mm/min in the volumes of crystallites, a chromium content of 7...7.5%, tungsten 1.3...2.5% is observed, and at the boundary crystallites, their content increases to 9.5...10.4% and 3.6...4.15%, respectively. The amount of iron in the volumes of crystallites is 85...87%, while at the boundaries it decreases to 80...82%. The gradient of concentration changes between the crystallite boundary and the volume (bou/vol) is up to 6% $\Delta Fe_{(bou/vol)}$, up to 3% $\Delta Cr_{(bou/vol)}$ and up to 3% $\Delta W_{(bou/vol)}$.

When the alloying speed is increased to V=500 mm/min, a similar trend of concentration changes and an increase in the percentage of elements compared to V=400 mm/min is observed. In the volume of crystallites, the chromium content is on average 14%, tungsten 6.7...7.3%, and at the boundary there is an increase in chromium content to 15%, and tungsten to 9%. In the volume of crystallites, iron constitutes an average of 81%, and at the boundary it decreases to 75...78%. The gradient of concentration changes in crystallites at V=500 mm/min is smaller compared to V=400 mm/min and amounts to $\Delta Fe_{(bou/vol)}$ up to 2.5%, $\Delta Cr_{(bou/vol)}$ up to 2% and $\Delta W_{(bou/vol)}$ up to 1.5%. A local study of the microhardness of crystallites, carried out in this sample, showed that the microhardness both in depth and at the boundary equaled to 2500...3480 MPa.

With an increase in the laser alloying speed to V = 750 mm/min in the volume of crystallites, the content of chromium is on average 10.5%, tungsten 3%, and at the boundary it increases on average for chromium to 12%, for tungsten to 7%. The gradient of concentration changes in crystallites is $\Delta Fe_{(bou/vol)}$ of up to 6.5%, $\Delta Cr_{(bou/vol)}$ of up to 2% and $\Delta W_{(bou/vol)}$ of up to 3%.

Such an important feature as the presence or absence of cracks was also considered.

During surface alloying at both V=400 mm/min (see Fig. 3) and V=750 mm/min speeds, the formation of cracks in the alloyed layer near the fusion line is observed. At V=400 mm/min, the crack propagation length is 50...450 μm with a volume fraction V_f of up to 2%. At a higher laser alloying speed of V=750 mm/min, an increase in both the length of cracks up to 500 μm and their volume fraction V_f up to 10% was noted. In both cases, the chromium content in areas with cracks increased to 20...26%, and the tungsten content – to 2...5%.

In the case of laser-plasma alloying in the mode: P=3.0 kW, V=500 mm/min, ΔF= +30 mm; the structure and carbide phases are observed to be more discrete in size (Fig. 5), with a low dislocation density in the alloyed layer $(1...8) \times 10^9$ cm^{-2} and without the sharp gradient, present in other samples. This indicates the absence of structural conditions for the formation of internal stress concentrators at $\tau_{IS} \approx 148...370$ MPa. The latter characterizes the structural state of the surface as optimal and is confirmed by the practical absence of microcracks.

Studies of concentration changes during laser-plasma alloying showed a slight change in the iron content during the transition from the alloyed surface layer to the fusion line and then to the base metal. The chromium concentration level varies from 9% to 13% in the alloyed layer and, with increasing laser alloying speed to 750 mm/min, gradually decreases as it approaches the fusion line (to a value of 8% in the transition zone).

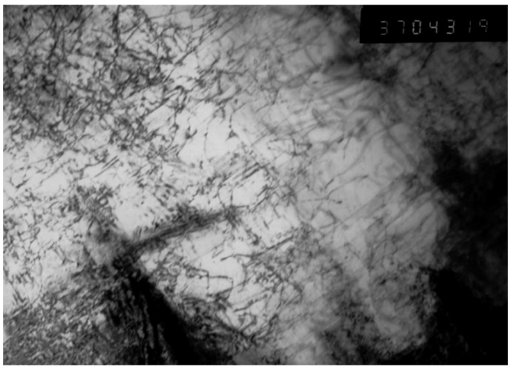

Fig. 5. Crystallite structure near the fusion line (×37000) of a 38KhN3MFA steel sample with a surface layer obtained by hybrid laser-plasma alloying (V=500 mm/min, P=3.0 kW, ΔF = +30 mm).

The size of the transition zone decreases from 60 to 40 μm as the alloying speed increases from 400 mm/min to 750 mm/min.

IV. Conclusions

Over the course of the study, it was established that when using both laser and laser-plasma methods of surface alloying, the tendency to formation of cracks is attributed, first of all, to structural and concentration changes associated with the redistribution of elements, namely an increase in the concentration of chromium along the grain boundaries. This, in turn, leads to the formation of sharp grain-boundary concentration gradients, which contributes to the formation of carbide phases in the border zones and, accordingly, sources of initiation and propagation of cracks. An increase in the number of cracks is observed in regimes with higher heating temperatures, increased duration of exposure to high temperatures and reduced cooling rates.

When comparing samples obtained by both methods of surface alloying, it was found that in the case of laser-plasma alloying, the observed structure and carbide phases are smaller in size, with a low density and uniform distribution of dislocations in the metal of the alloyed layer. This indicates the absence of structural conditions for the formation of internal stress concentrators. The latter characterizes the structural state of the surface as optimal and is confirmed by the practical absence of cracks.

When comparing both methods of surface alloying, it was found that hybrid laser-plasma method is the best at speeds of the order of 500 mm/min and radiation power of up to 3 kW. This is explained by the absence of cracks, a low level of internal stress concentrators, high wear resistance, and also higher microhardness values (HV microhardness averaged about 6000 MPa) compared to laser processing without cracks (HV microhardness averaged about 3500 MPa).

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