Simulation of laser cladding of a wear-resistant coating hardened with Al$_2$O$_3$ particles

V V Alisin and M N Roshchin*
Mechanical Engineering Research Institute of the Russian Academy of Sciences
4, Malyi Kharitonevskii lane, Moscow, 101990, Russian Federation

*E-mail: roschin50@yandex.ru

Abstract. The article is concerned with the matters of formation of heat fluxes during laser fusion of coating of the NiCrBSi system hardened with the addition of aluminum oxide fine powder. It is based on the simulation of the process of heating and melting of the CW coating with a laser and the specified thermophysical properties of the base material, coating and hardening additive of aluminum oxide powder. The numerical solution of the differential equations system is obtained and the temperature distribution in the coating over the thickness is determined depending on the power and time of action of the heat source. The obtained diagrams are analyzed, on the basis of which it is proposed to choose the parameters of laser processing. The prospects of applying a coating using the laser cladding technology to protect against wear of steel friction surfaces and restore hardened steel parts of friction assemblies are shown.

1. Introduction
Conventional surface hardening technologies, including gas-thermal ones, are not always able to meet the growing requirements of mechanical engineering to improve the tribological characteristics of machine assemblies and units operating under extreme conditions in terms of loads, temperatures and sliding speeds. One of the most important advantages of plasma coating is the possibility to apply almost any materials and compositions, with high process performance and a high material utilization rate. The main disadvantage of plasma coatings is low adhesion strength to the base material, which does not exceed 80...100 MPa at the initial temperature of the $T \leq 400^\circ C$ base material, as well as insufficient reliability. The probability of crack formation during operation is very high. The structure of plasma coatings does not have a high endurance limit, which imposes limits on their use in heavy-loaded tribocouplings. Laser fusion of coatings allows to obtain more developed metallurgical bonds of the coating with the base, flexibly adjust the width of the transition zone, refine the coating structure, create additional hardening phases, reduce porosity and, as a result, significantly increase the strength and tribological properties of the "coating - base material" system. Laser cladding of wear-resistant coatings is one of the promising hardening technologies. Technology of laser cladding of the surfaces is used to harden rails and wheels [1, 2], to perform restoring repair of friction surfaces [3], to protect aluminum alloys from wear, especially at high temperatures [4], to increase the resistance of iron surfaces to corrosion [5], and to increase the wear resistance of tool alloys [6]. Laser cladding technologies are diverse. One of the developing areas is the fusion of plasma powder coatings [7]. In [8] paper, the
tribological behavior of NiCrBSi coatings fused with a CW CO\textsubscript{2} laser of 1700 W was investigated. The influence of the geometric properties of partially molten surfaces, such as the angle of the laser tracks and the fraction of the molten surface, is investigated. It is shown that the best percentage of molten surface to reduce the wear rate is 46\%, while the track angle is not considered as the main factor affecting the wear rate. Laser melting of coatings imposes certain restrictions on the materials used, both in terms of thickness and thermophysical properties. To solve the problems of increasing the wear resistance and reliability of heavy-loaded friction assemblies, the composite coating material must have a plastic matrix, fine grain, high hardness of the fine-dispersed hardening phase, at its optimal concentration. Experiment on remelting of Al\textsubscript{2}O\textsubscript{3} + 13 wt.% TiO\textsubscript{2} coating using laser and the results of the study of tribological properties are described in [9] paper. The tribological test was performed on a tribometer with a ball on a disk under dry sliding conditions, the coefficient of friction and the wear rate of the coating decreased. In [10] paper, it is noted that when applying composite coatings with a nickel-based matrix reinforced with WC carbides, the adhesion and damage resistance are also improved due to laser cladding. The dependence of wear resistance on the concentration of carbides is found, and the microstructure, hardness, and internal stresses are studied. As a plastic matrix, nickel- or cobalt-based alloys, solid solutions, Ni-Al, Ni-Ti, Ti-Al intermetallides, low-melting eutectics, thermostetting materials, etc., as well as compositions based on them are used. The cobalt-based matrix has a high plasticity. The use of eutectic alloys of the Ni-Cr-B-Si system as a plastic matrix is a promising composite material for heavy-loaded tribocouplings. In [11] paper, the cladding of the NiCrBSi coating on wheels and rails using the a-hybrid laser-induction technology was tested. It is found that the new technology can reduce the wear rate and the degree of contact fatigue damage to the rails at a higher contact stress and maintain the surface profile. The economic interest and shortage of tungsten make it particularly attractive to use Al\textsubscript{2}O\textsubscript{3} as a hardening phase, with its content from twenty to forty percent, by weight. In [12] paper, the laser-melted Al\textsubscript{2}O\textsubscript{3} - 40\% TiO\textsubscript{2} coating was studied with methods of electron microscopy and X-ray analysis of changes in the microstructure. Tests for wear, microhardness and adhesion strength of the coating were performed. It was found that the coating melted by the laser becomes denser, and its microhardness and adhesion strength are significantly improved, and wear resistance increases. In [13] paper, the influence of the surface texture in combination with various solid lubricating coatings on the tribological properties of Al\textsubscript{2}O\textsubscript{3} / TiC ceramics was investigated. The mechanical properties of the laser-cladded NiCrBSi coating hardened with Al\textsubscript{2}O\textsubscript{3} powder depend on the resulting coating structure, which is completely determined by the temperature distribution over the coating thickness.

The objective of the paper is to determine the temperature distribution in the NiCrBSi coating, hardened with Al\textsubscript{2}O\textsubscript{3} powder, occurring during the laser treatment using a CW CO\textsubscript{2} laser at the set processing parameters - the power density of the heat source, the thermal properties of the materials and the speed of movement.

2. Materials

Material of the base is 30KhGSA steel with the following thermophysical properties: $\lambda = 37 \text{W/(m}\cdot\text{C}); \ \alpha = 9.4*10^{-6} \text{m}^2/\text{s}; \ c = 504 \text{J/(kg}\cdot\text{C});$ the coating material PG-10N-01 + 20\% Al\textsubscript{2}O\textsubscript{3}, $\lambda = 16, 4 \text{ W/(m}\cdot\text{C}); \ \alpha = 4, 2*10^{-6} \text{ m}^2/\text{s}; \ c = 618 \text{ J/(kg}\cdot\text{C}),$ where "$\lambda$" is the thermal conductivity, "$\alpha$" is the thermal conductivity and "$c$" is the specific heat capacity.

3. Calculation method

The paper uses a mathematical model and an algorithm for the numerical solution of a system of partial differential equations of the heating and melting process, a surface heat source, a two-layer semi-bounded body with Stefan boundary conditions, developed in [14] paper.

4. Results
Figure 1 shows the temperature distribution over the coating thickness at different times of exposure to the heat flow of $q_0 = 1 \times 10^7$ W/m$^2$. Coating material is PG-10N-01 + 20% Al$_2$O$_3$, $\lambda = 16.4$ W/(mK); $\alpha = 4.2 \times 10^{-6}$ m$^2$/s; $c = 618$ J/(kg°C).

The surface temperature will reach the melting point of the coating material $T_{\text{mel.}} = 1080°C$ in time of $t = 0.785$ s. The coating with a thickness of 0.6 mm is completely melted in time of $t = 1.77$ s. At the same time, the surface temperature reaches $T = 1277°C$, which is much lower than the boiling point of the coating. With a further increase in the heating time, the temperature at the "coating-base" interface will reach the melting point of the base material $T = 1535°C$ in the time of $t = 2.65$ s.; see figure 2, curve 1. The surface temperature is $T = 1705°C$. With a further increase in the heat flow, the heating time decreases and the surface temperature increases.

At a heat flow of $q_0 = 5 \times 10^7$ W/m$^2$, the surface temperature exceeds the melting point of the hardening fraction of the Al$_2$O$_3$ coating material by 330°C. For this composite material, with a coating thickness of $h = 0.6 \times 10^{-3}$ m, the heat flow $q_0 = 5 \times 10^7$ W/m$^2$ is the maximum permissible. With a further increase
in the heat flow, the hardening fractions of the coating will decompose. With an increase in the surface temperature above $T = 2300^\circ C$, which corresponds to the heat flux of $q_0 = 5 \times 10^7$ W/m$^2$, the process of decomposition and oxidation of boride and carbide phases is intensified, which adversely affects the tribological characteristics of the coating. Therefore, it is not advisable to use heat fluxes higher than $q_0 = 5 \times 10^7$ W/m$^2$, at $h = 0.6 \times 10^{-3}$ m for this composite material. On the basis of physicomathematical modeling of the process of laser fusion of the coating, taking into account the dependence of thermophysical parameters on temperature, the technology of cladding of metal-ceramic coatings for protection of hydraulic equipment parts against wear was developed and tested. Figure 3 shows samples of parts after finishing machining.

For the preliminary application of powder compositions, an optimized plasma deposition process was used. The coatings on the working surfaces were applied using a supersonic plasma generator developed at Mechanical Engineering Research Institute of the Russian Academy of Sciences. The powder material was injected into the subsonic region of the plasma flow. The alloys of the Ni-Cr-B-Si system (the PGSR-4OM powder material is nickel-based, 13.5-16.5% of chromium, 2.5-3.5% of silicon, 2.0-2.8% of boron, and iron no more than 5%; hardness is 52-58 HRC) were used as a plastic matrix. Al$_2$O$_3$ powders with a fraction of 5...20 microns were used as the hardening phase. The concentration of the hardening phase varied in the range of up to 20% (by weight). The coatings were melted using a CO$_2$ laser at a continuous radiation power of 3.5 kW, a processing speed of $6 \times 10^{-3}$ m/s, and a laser beam scanning frequency of approximately 200 Hz. Process parameters of the laser treatment excluded the thermal decomposition of the coating components. Pilot operation of the parts showed an increase in the service life of the products by more than 2 times. The performance of this hardening technology depends on the speed of the laser beam movement. The dependence of time of the coating fusion in depth on the heat flow power for the PG-10N-01 + 20% Al$_2$O$_3$ coating material is shown in figure 4.

With an increase in the power of the heat flow, the speed of the melting front increases, and the melting time of the coating decreases. An important factor is to prevent the tempering of the base material. The obtained characteristics of fusion of the coating show that the heating time of the base material is not sufficient to change the structure of the base material. In the process of laser cladding of a wear-resistant coating, within the studied laser processing modes, it is impossible to heat the material to the tempering temperatures, for example, for 30KhGSA steel, the tempering temperature is equal to $T = 550^\circ C$. Therefore, laser cladding of friction surfaces is promising for hardening and restoring high-quality hardened steels. The calculation established the process parameters of laser fusion of the coating containing fine particles of aluminum oxide.
5. Conclusion
A numerical analysis of the heating and melting of a two-layer semi-bounded body with Stefan boundary conditions is performed to determine the value of the heat flux and the exposure time during the melting of wear-resistant composite coatings based on a Ni-Cr-B-Si plastic matrix with a hardening phase based on aluminum oxide on high-strength steel. The prospects of laser cladding process of coatings containing aluminum oxide particles to protect the friction surfaces of hardened steels from wear are confirmed.

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