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Laser surface treatment of aluminum: correlation between thermal modeling and experimental study

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Abstract. In recent years, laser surface treatment was widely used to improve the properties of aluminum coatings. This paper implements a thermal model to simulate the laser treatment effects on a cold-sprayed aluminum coating and St3 substrate. As a result of the work, a model has been developed to evaluate the thermal fields and the melt pool during the laser surface treatment process, and laser treatment modes have been identified, with the help of which a high-alloyed aluminum layer on the surface of steel has been obtained.

Keywords: laser surface treatment, aluminum, intermetallides, thermal fields, thermal modeling

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Лазерная обработка поверхности алюминия: тепловое моделирование и экспериментальное исследование

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Аннотация. В последние годы для улучшения свойств алюминиевых покрытий широко применяется лазерная обработка поверхности. В данном исследовании разработана тепловая модель для изучения процесса лазерной обработки алюминиевого покрытия, нанесенного методом холодного напыления на подложку из стали Ст3. В результате работы создана модель для оценки тепловых полей и ванны расплава в процессе лазерной обработки поверхности, а также выявлены режимы лазерной обработки, с помощью которых на поверхности стали формируется высоколегированный алюминием слой.

Ключевые слова: лазерная обработка поверхности, алюминий, интерметаллиды,

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тепловые поля, тепловое моделирование

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Introduction

The laser surface treatment (LST) of metals enables the production of a surface layer with a thickness of under a millimeter to several millimeters and with special functional properties: high hardness and wear resistance, while maintaining the properties of the substrate material [1-4]. This makes it possible to obtain various compounds of materials for scientific research [5–9]. This is confirmed by the study of materials on various devices [10–13].

Currently, LST is widely used to improve the properties of aluminum coatings, since aluminum has a high specific strength, thermal and electrical conductivity, and corrosion resistance [14, 15]. Laser power and speed conditions the structure and properties of the surface layer [16].

An important step in laser surface treatment is the mode selection. The mismatch of the process parameters leads to various adverse outcomes, such as inefficient processing, in which the conditions necessary for the formation of intermetallides are not met, and damage to the processed sample [17]. It is advantageous to select the modes of the laser surface treatment process using computer modeling. With the help of modern numerical simulation packages, it is possible to calculate thermal fields in a sample during surface treatment. This significantly saves time and production resources [18-22].

The aim of the study was to better understand the behavior of aluminum deposited by gas dynamic spraying during laser treatment. At the modeling stage, treatment modes are identified in which the conditions for the formation of intermatallic compounds are fulfilled. For this purpose, a thermal finite element model of laser processing was implemented to evaluate the thermal fields occurring in the deposited coating. Using the selected modes, heat treatment of aluminum deposited by gas-dynamic spraying on a steel substrate is carried out.

Materials and Methods

Fig. 1 schematically depicts the process of laser surface treatment. When a laser beam interacts with a material, part of the heat is dissipated as a result of convective and radiative heat transfer. The remaining laser energy is absorbed by the material. The main mechanisms of heat transfer during laser treatment are the thermal conductivity of the sample and thermal convection between the material and the environment [18].

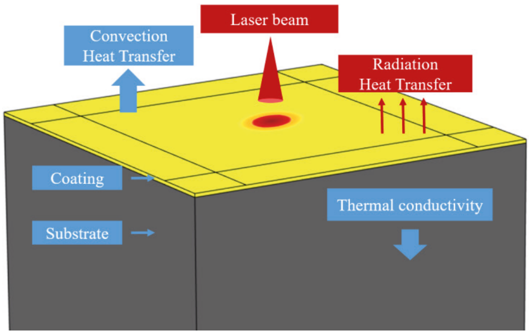

Fig. 1. Schematic illustration of the LST process

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In general, heat transfer can be described by the heat conduction equation:

$$\rho C_p\left(\frac{\partial T}{\partial t}+\left(\vec{u}\cdot\vec{\nabla}T\right)\right)=\vec{\nabla}\cdot\left(k\vec{\nabla}T\right), \tag{1}$$

where ρ is the material density, C_p is the heat capacity, T ist he temperature, u is the fluid velocity vector, k is the thermal conductivity.

The laser source is represented by a heat source with a Gaussian distribution:

$$Q_{in}=\frac{2PA}{\pi r^2}\exp\left(-\frac{2\left(x-vt\right)^2+y^2}{r^2}\right), \tag{2}$$

where P is the laser power, A is the laser energy absorption coefficient, r is the radius of the laser beam, and v is the laser speed.

When the laser interacts with the material, heat losses due to convection and radiation are taken into account:

$$-k\frac{\partial T}{\partial t}=Q_{in}-\alpha\left(T_w-T_0\right)-\sigma\varepsilon\left(T_w^4-T_0^4\right), \tag{3}$$

where α is the heat transfer coefficient, T_w is the surface temperature, and T_0 is the ambient temperature, σ is the Stefan-Boltzmann constant, and ε is the surface absorption coefficient.

The phase transition of melting and evaporation is considered in the equation of heat capacity [23]:

$$C_p^{eq}=C_p+D_mL_m+D_vL_v, \tag{4}$$

where C_p is the heat capacity as a temperature dependent function, L_m is the latent heat of fusion, D_m and D_v is the Gaussian function normalized around the melting and evaporation temperature T_m and T_v.

In the process of heating and cooling, the thermophysical properties of materials change, since they depend on temperature. The model has the ability to set such properties as thermal conductivity, heat capacity, density, as a function of temperature. Also, before starting the calculation, you can change the values of process parameters, such as power, scanning speed, laser beam diameter, hatch spacing, sample dimensions and coating thickness.

The Comsol Multiphysics package and 3D finite element method are used to model thermal effects. A three-dimensional numerical model was built with dimensions of 2 mm x 2 mm x 4 mm. Aluminum was chosen as the coating material, and St3 steel as the substrate material. Steel St3 was chosen for modeling, since its physical properties are known from open sources, and it is similar to steel 09G2S. The studies were carried out for speeds of 100–800 mm/s and for the thickness of the aluminum coating from 20 μm to 180 μm. The hatch spacing, power and diameter of the laser beam were set constant for all modes and were equal to 75 μm, 180 W and 100 μm, respectively.

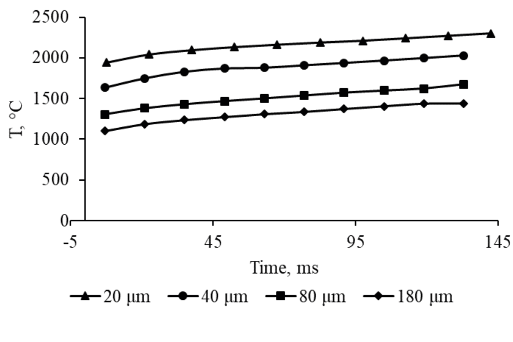

Fig. 2. Dependence of the maximum surface temperature on the scanning time for different coating thicknesses at a laser speed of 100 mm/s

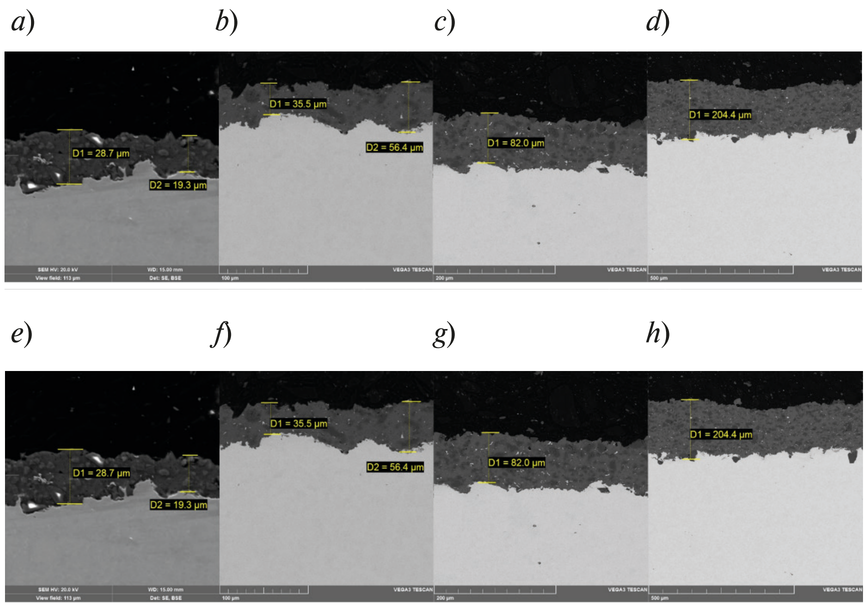

Fig. 3. Cross section of a coating 20 thick (*a*, *e*); 40 (*b*, *f*); 80 (*c*, *g*) and 180 μm (*d*, *h*) after cold spraying (*a*–*d*) and after subsequent laser treatment (*e*–*h*)

The experiment consists of two stages. At the first stage, the cold spraying method [24] forms an aluminum coating with a thickness of 20–180 μm. PA-VCh grade aluminum powder was used as the starting powder material. For applying coatings by cold spraying, a Dimet-403 installation was used. The 09G2S steel substrate was coated with different thicknesses: 20, 40, 80, and 180 μm.

The second stage includes laser surface treatment to form a coating with improved characteristics [25]. Laser surface treatment is performed at the Russian SLM Factory using an ytterbium fiber laser in a protective argon atmosphere.

Results and Discussion

Ten laser beam passes were simulated for samples made of St3 steel with different thickness of aluminum coating. The maximum temperatures for each pass of the laser beam are found (Fig. 2). It has been found that with increasing coating thickness, the maximum temperature on the surface decreases. This is due to the high thermal conductivity of aluminum.

The melt pool depth was measured for all modes under study. It has been established that at a laser speed of 400 mm/s, 800 mm/s and a power of 180 W, there is no mixing of the components in the laser impact zone, since the energy input is insufficient. For a coating thickness of 20 μm and 40 μm, the components are mixed in a ratio of 2:1 and 1:2, respectively, at a scanning speed of 100 mm/s and a power of 180 W, from which it can be assumed that under these modes, intermetallic compounds are formed in the resulting coating.

As a result of the experiment, samples were made in two stages. At the first stage, an aluminum coating was applied by gas-dynamic spraying, after which the surface was treated with a laser to change the microstructure, reduce the level of porosity, and improve the mechanical properties of the coating (Fig. 3). The cross section of a coating were studied by scanning electron microscopy using the TESCAN Vega 3.

Table 1

Comparison of the melt pool depth obtained from modeling and experimental study for a scanning speed of 100 mm/s

	20 μm	40 μm	80 μm	180 μm
d, μm (modeling)	70	58	80	180
d, μm (experiment)	63.3	62.9	74.2	230.3

As a result of the study, the dependence of the size of the melt mixing zone on the scanning mode (different scanning speeds and coating depth) was established. Table 1 compares the melt pool depth obtained from the simulation with the mixing zone of the components measured in the experimental samples.

It was found that for a coating thickness of 20 μm and 40 μm, a scanning speed of 100 mm/s, and a power of 180 W, intermetallic compounds are formed in the mixing zone of the components.

The discrepancies with the simulation results when comparing the values in Table 1are caused by the uneven distribution of the precursor coating over the substrate, as well as the presence of corundum in the coating, which was not taken into account in the simulation.

Conclusion

As a result of the work, a model was developed for estimating thermal fields in an aluminum coating deposited by gas-dynamic spraying during laser treatment. It was found that for a coating thickness of 20 microns and 40 microns, a scanning speed of 100 mm/s, and a power of 180 W, intermetallic compounds are formed in the mixing zone of the components.

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