Gradient materials formation by laser cladding of powder compositions

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Abstract. In this paper we consider the possibility of creating gradient materials using laser cladding technology. Laser cladding was carried out using a continuous fiber laser system. Copper and iron-chromium-nickel powders were used as powder materials. Samples of each powder material directed into one and several layers were obtained. Optimum deposition regimes for these powders were selected and gradient material samples from consistently surfaced copper powder, iron-chromium-nickel powder were obtained. Metallographic studies of the obtained samples by means of optical microscopy were carried out. The phase composition of the obtained powders was studied using x-ray diffractometry on the D8 ADVANCE device, the ratio of elements within the deposited layer was revealed.

1. Introduction
Laser cladding is a method of applying a material using laser radiation, which is used to melt and mix the filler material with the surface. As an additive, powders, wires, various pastes can be used. The physicomechanical properties of the deposited layer are determined, first of all, by the choice of the grade of the surfacing material (powders, wires, pastes). The properties of the surfaced layer, such as homogeneity, density, contact with the surface of the part, depend on a number of technological parameters: the power density in the laser spot, the presence of fluxes, the nature of the deposited material, the form factor of the deposited material, the composition of the deposited material, the state of the surface of the processed material, the scanning speed over the surface, the surface temperature maintained, and the degree of preheating of the workpiece [1].

Laser cladding makes it possible to deposit wear-resistant, heat-resistant, corrosion-resistant gradient and composite coatings on geometrically complex product surfaces. It can also be used for restoring worn parts, applying protective coatings, manufacturing volumetric objects. High cooling rates with laser surfacing lead to the formation of a unique structure and properties in the deposited material. Laser surfacing makes it possible to increase the life of the tool and thereby make the technological process more efficient. The wear resistance of the cutting tool is determined by the ability to resist fractures on the surfaces of its contact with the material being processed, under the influence of high temperatures and contact stresses. With this action, heat accumulates in the treatment zone, and when certain temperatures are reached, the structure of the tool material changes and, as a consequence, its performance and processing quality deteriorate. Thus, it is necessary to create conditions that enhance the redness and efficient removal of heat from the cutting edge of the tool. These conditions can be realized using refractory materials with high thermal conductivity, hardness and toughness. Papers [1–
3] were devoted to laser surface modification of various metals and alloys is considered. Thus, in work
[4] the basic metal-research methods of increasing the service life of the die tooling were presented and
the process of laser cladding of powder material with addition of the reinforcing phase of titanium
carbide was studied.

The main benefits for laser applications over traditional methods are possibility of processing in hard-
to-reach places, reducing the processing time, local high radiation intensity, possibility of creating a
layer of material with specified properties. Improved properties of material can be obtained by
optimizing the cladding parameters and selecting suitable powder materials [5]. Fabrication of
multilayer coatings also contribute to improving the performance of the processed product. To obtain a
multilayer coating, the powder composition is placed and melted in turn, thus achieving the formation of
several layers of different materials. Due to this method of surfacing, it is possible to modify many
characteristics of the surface layer of the workpiece, such as: increased resistance to wear and oxidation,
corrosion resistance; increasing the hardness of the product; change in the natural frequency of the
product’s vibration, redness, thermal conductivity, and so on. The advantages of this method consist in
the simplicity of the technology and the design of the required equipment. The advantages of this method
consist in the simplicity of the technology and the design of the required equipment. The main
drawbacks include the high labor intensity and unevenness of the coating caused by the surface tension of
the molten liquid metal formed during the formation of coating layers. When using a laser source the
complexity of multilayer surfacing of various materials is significantly reduced. This is achieved by the
properties of laser radiation, in particular the ability to produce a local melting of the powder material
followed by rapid cooling.

The melting of substrate material ensures a good metallurgical bond between the cladding layer and
the substrate material. However, the melting of the substrate material causes dilution. Therefore, the
melting of the substrate material should be controlled and kept at a minimum because high substrate
melting causes an increase in the dilution which may degrade the mechanical and corrosion properties
of the cladding layer [6, 7].

2. Experimental work
Laser cladding was performed on a steel substrate using a continuous laser fiber laser system LS–02
having a maximum power of up to 200 W and operating at a wavelength of 1060 nm. The wavelength
of the ytterbium fiber lasers is an order of magnitude smaller than that of CO2 lasers, which provides
better absorption of the incident radiation for most metals and alloys and, consequently, improves the
efficiency of the treatment. For focusing, an optical head was used, equipped with a galvano scanner
system. The beam diameter in the processing area was from 100 to 300 μm. The scheme of the
experiment is shown in figure 1.

Copper powder, iron-chromium-nickel powder were used as powder materials. A powder layer
(100±10 μm) was applied to the surface of the processed sample. For this type of processing is
characterized by the formation of significant stresses in the material, which in turn leads to deformation
of the substrate. To avoid this, the treatment was carried out with a rigid fixation of the sample in a
special holder. This approach is necessary to preserve the geometric characteristics of the substrate
during processing, since the change in the location of the treated surface, as a result of bending, there is
a shift of the treated surface relative to the focus point, which entails a change in the power density and
as a consequence there is a violation of the processing mode.

In general, to determine the optimal mode, such parameters as the radiation power, scanning speed,
thickness of the applied powder layer are changed. Depending on the scanning speed of the laser beam,
the energy contribution to the selected area as well as the total heating of the treated area changes. At
small scanning velocities, the increase of energy input in the area of irradiation, including possible
significant bulk heating of the treated sample. As the scanning speed increases, less radiation energy
enters the area due to the faster passage of the beam through the area, which contributes to the
localization of processing, this approach is often used in the processing of thin-walled products [8, 9].
Figure 1. Scheme of a continuous laser system: 1 – power supply unit; 2 – laser (LS-02-T); 3 – galvano scanner system; 4 – laser beam; 5 – vertical linear translator; 6 – computer.

Thus, by adjusting these parameters, it is possible to select the optimal treatment mode to achieve various physical and mechanical properties of the metal surface. In this study, the scanning speed changed 40–150 mm/s, laser power 20–150 watts. The process of surfacing of powder materials is shown in figure 2.

Figure 2. The process of cladding of powder materials: 1 – steel substrate, 2 – iron-chromium-nickel layer, 3 – copper layer, 4 – powder material, 5 – laser, 6 – focusing system.

By increasing the scanning speed from 100 to 130 mm/s powder material is rolled into drops, at 140 mm/s and above the drops begin to break away from the substrate and burn out. This phenomenon often manifests itself in lack of power of laser irradiation. Therefore, when the scanning speed is increased at a constant power, there is an insufficient heating of the melted powder material. The area of laser radiation exposure is warmed up to the melting temperature of the granule, but it is not enough to form a homogeneous melt bath. This phenomenon is a kind of limitation of the use of many metals and alloys.
The next negative factor is the «bad» shape of the granules, including the developed surface topography, which is characterized by high gas saturation. When using multicomponent powder systems, a significant impact on the quality of the coating has a large difference in melting temperatures. These factors prevent the formation of a continuous track. It is not uncommon in the melt path is the Marangoni effect, manifested in the form of convective flows caused by the surface tension gradient [10, 11]. The effect is manifested by the formation of individual drops of melt, which tightens the nearby powder particles, which leads to the formation of unfilled cavities around the treated area of impact, which ultimately leads to the formation of porosity and violation of the homogeneity of the structure of the material. The values of the parameters contributing to the formation of a uniform roller of the deposited material on the surface of the sample were as follows: for iron-chromium-nickel powder \( P = 130 \) W, scanning speed \( \nu = 60 \) mm/s., for copper \( P = 100 \) W, \( \nu = 60 \) mm/s. with these parameters, layers are formed with good adhesion resistance.

Cladding of powders was carried out in one or several layers. At optimal parameters the powder was applied in 5 and 10 layers. First, the first layer is applied, after which this layer is sintered with a laser, then the powder is again applied over the first layer, and so on until the desired number of layers of the deposited powder is achieved. At each stage of layer formation, the strategy of the beam passing in the direction of the cross-previous layer was changed and the focal length changed accordingly to the thickness of the applied layer. Using a similar algorithm, gradient material samples were obtained, where a layer of iron-chromium-nickel and a copper layer alternated. The sample consists of 10 successive layers deposited under the following conditions: layer of iron-chromium-nickel – 130 W, copper layer – 100 W, scanning speed was unchanged – 60 mm/s.

3. Research

To investigate the composition of the deposited powders, a D8 ADVANCE diffractometer was used. This diffractometer operates on the principle of measuring the dependence of the intensity of X-rays scattered by powder samples, films, glasses, etc., on the diffraction angle \( 2\theta \) at temperatures from 77 to 1270 K.

The diffractogram of a crystalline object is a distribution of peaks of a certain shape and intensity, depending on the energy of the characteristic radiation of a particular phase. If you have this information, you can make a conclusion about the parameters of the sample and obtain the following information: density of phase distribution, number of phases, texture, residual stresses, structure of crystallite, microstructure. If the object consists of several phases, then each phase will have its own diffraction pattern. In this case, the peaks of all phases of the sample are present on the diffractogram. The intensity of the reflexes of each phase will depend on its amount in the test mixture and the degree of crystallization. Each phase of the sample corresponds to its X-ray diffraction peaks. Sharp peaks are obtained from the crystalline phases of the sample, and the nonlinear background is obtained from the amorphous phase. The diffraction pattern contains peaks from all phases of the sample irrespective of their number. From the position of the peaks in the diffractogram, it is determined which crystalline phases are present in the sample the phases are identified. Identification is achieved by finding in the database the same X-ray peaks as in the diffractogram of the sample under study. The height (intensity) of the peaks is a quantitative analysis of crystalline phases that is the concentration of each crystalline phase of the sample is determined. The total content of amorphous phases is determined from the intensity of the nonlinear background.

With the help of a diffractometer, the ratio of elements within the deposited layer was revealed. The result is a diffractogram (figure 3, figure 4) - the dependence curve of the scattered beam intensity on the scattering angle. For the iron-chromium-nickel sample, the ratio of the elements is shown in figure 3.
Figure 3. Diffractogram of cladding layer 1 – iron-chromium-nickel.

After analyzing the diagram of the ratio of elements inside the cladding layer of iron-nickel-chromium, it can be concluded that the cladding powder consists of 50.06% of iron, 48.91% of the alloy of chromium and nickel and contains 1.03% of cobalt.

Figure 4. Diffractogram of cladding layer 2 – copper.

Based on the data of the diffractogram, it is clearly seen that the powder deposited on the sample is pure copper.

The obtained samples were subjected to metallographic studies. The cross sections of the samples were grinded, polished in several times and etched in acid. Metallographic microscope MMN-2 was used to obtain micrographs of the obtained thin sections. In an optical microscope with a resolution of up to 40 μm, images of the surface of the samples were obtained (figure 5).
4. Conclusion
The possibility of creating gradient materials by means of laser surfacing was considered. For processed materials, a certain treatment regime was selected to avoid cracking of the formed material. Laser cladding was carried out using a continuous fiber laser system. Optimum deposition regimes for these powders were selected and gradient material samples from consistently surfaced copper powder, iron-chromium-nickel powder were obtained. Samples of each powder material deposited in 1, 5, 10 layers were obtained. Metallographic studies of the obtained samples by means of optical microscopy were carried out. The phase composition of the obtained powders was studied using x-ray diffractometry, the ratio of elements within the deposited layer was revealed.

The use of laser cladding technology allows to create on the surface of the part as a homogeneous coating and coating containing a number of layers of different materials. In the course of the work, a number of features of this type of processing were established, including the need for constant changes in the processing mode. It is assumed that this is due to the constantly changing thermal conductivity of the material formed, consisting of alternating layers having different thermal conductivity. Since the change in the temperature regime is decisive, the main contribution of this physical quantity is assumed. Subsequently, it is planned to conduct studies of wear resistance and manufacturability of the tool using this approach. Also, the team faced difficulties associated with the study of physical and mechanical properties of the formed material. The formed layers have a rather small thickness, which entails a number of difficulties in conducting studies of the properties of the formed layers. In the future, it is planned to conduct extended studies of this type of processing, to assess the adhesive properties of the formed layers, the amount of heat and electrical conductivity.

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