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Determination of the influence of changes to the laser surface alloying process technological parameters on the formation of the surface layer geometry

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ABSTRACT:

This study is dedicated to establishing the possibility of improving physical and mechanical properties of the surface layers of cylindrical and flat structural steel products via application of laser alloying processes. As a result of the research, it was established that the influence of the wavelength of laser radiation on the parameters of the alloying process of steel samples is linear. Thanks to the use of laser radiation from the Nd:YAG laser under the same initial conditions (power of laser radiation, size of laser radiation defocusing distance, usage rate as well as the type of implant material, etc.), it was possible to increase the speed of laser alloying by 30-70% while maintaining a similar depth of alloying compared to the usage of CO_2 lasers. It was also established that a decrease in radiation power to that of less than 1 kW leads to a nonlinear relationship between the laser power and the diameter of the laser spot. Since reduction of the diameter of the laser radiation spot to less than 1 mm can lead to undesirable processes in the laser focus spot, that is characterized by an increase in burning of some implant material elements, as well as pore formation. Therefore, during laser alloying of thin-walled cylindrical and small flat samples, it is necessary to observe the lower limit of the specified range of the ratio between the power and the diameter of the laser radiation spot. On the contrary, when alloying thick-walled (with a wall thickness of more than 10 mm) flat and tubular samples, as well as solid cylindrical samples with a diameter of 40 mm or more, it is advisable to observe the upper limit of the P-d_n range, and in some cases, utilize lasers capable of emitting radiation power in excess of 4.5 kW.

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NOMENCLATURE

Symbol	Description	Unit
P	Laser power	*kW*
d_n	Efficiency coefficient	%
w_e	Radiation power density	W/cm^2
Q_n	Implanting powder mixture consumption speed	*g/s*
K_p	Alloying track overlap coefficient	%
ΔF	Defocusing distance	*mm*

I. INTRODUCTION

The scientific and technical progress in mechanical engineering, instrumentation engineering and other branches of industry is connected, first of all, with the creation of new structural materials and the improvement of technologies for improving their physical, mechanical and operational properties [1]. Thanks to the improvements in modern materials science, a wide range of materials with high operational characteristicshas been created for various purposes. Due to this, the share of plastics and composites increased, and the share of metal materials decreased to 60...65% [2]. However, in the near future, alloys based on iron and, first of all, steel will remain the most common among metal structural materials [3]. Therefore, the problem of improving technological methods of improving the operational properties of parts made of structural steels remains relevant.

Since the end of the 20th century, more attention has been paid to the development of surface strengthening technologies, rather than volume strengthening [4]. This is related with a new approach in assessing the material role in ensuring the structural strength of products, according to which the leading role belongs to the surface, and not to the volume, as it was accepted before. In this approach, it is the condition of the surface that largely determines the level of structural strength and operational properties of machine parts. This led to the emergence of a new direction - surface engineering, carried out by methods of combined energy and physio-chemical influence. The development of surface engineering involves the development of technological processes of a new level, which allows for modification of the surface layer, radically changing its structure and properties. In modification of the surface of metals, the preference is given to methods of control processing that use concentrated energy flows as a heat source, such as: ion, laser, and others. In this regard, the development of affordable, economical, highly effective and environmentally safe technologies for strengthening the surface layers of structural steel products, which ensure the necessary operational and physical-mechanical properties is an urgent task.

With the growth of requirements for the surface layer quality, indicators of the economic efficiency of processes, as well as the selection of materials depending on the surface properties and cross-section of parts, as well as due to the increase in the volume fraction of complex alloyed steels in the production process of products, the tasks related to usage of applying resource-saving technologies to increase the operational resource of steel products are becoming urgent. One of such technologies is alloying [5-7].

Alloying is the process of introduction of additives into metals, alloys and semiconductors to give them certain physical, chemical or mechanical properties. Various metals, non-metals and ligatures are used for this [8]. When alloying metals and alloys, solid solutions, mixtures of two or more phases, intermetallids, carbides, nitrides, oxides, sulfides, borides, and other compounds of alloying elements can be formed with the base of the alloy or with each other [9].

As a result of alloying, the physical and chemical characteristics and, first of all, the electronic structure of the original metal or alloy change significantly [10]. Alloying elements affect the melting temperature, the nature of crystal lattice defects, the formation of grains as well as its fine crystal structure, the area of allotropic modifications existence and the kinetics of phase transformations, the dislocation structure, heat resistance and corrosion resistance, electrical, magnetic, mechanical, diffusion and many other properties of alloys [11-15].

A large number of brands of steels and alloys, for which it is not possible to find a universal method of processing the surface layer that is effective enough for various operating conditions, are known [16]. In connection with the growing operational requirements for pre-loaded steel parts of various assemblies and mechanisms, the tasks of increasing heat resistance and crack resistance are becoming urgent. However, the classical chemical and thermal treatment with additional hardening and tempering, while greatly affecting the properties of the product, is clearly insufficient in many cases. It is most suitable for increasing wear resistance, corrosion resistance, and to a lesser extent for increasing heat resistance, as well as resistance to the appearance and propagation of cracks [17]. It has been established that a number of factors related to the condition of the surface layer of the part have a decisive influence on the crack resistance of high-strength steels [18-20]. They include local corrosion, microstructure defects, residual stresses, areas of stress concentration, etc. To improve crack resistance, the surface treatment must be carried out in such a way as to create a stressed surface layer characterized by the action of compressive stresses. All this requires the development of new progressive methods of surface treatment and alloying.

At the current stage of technology development, special attention is paid to new methods of surface alloying, that make it possible to eliminate the listed disadvantages of the aforementioned classical chemical-thermal treatment methods. The basis of these new methods is the use of local heating sources. To modify the surface of metals, preference is given to such methods that use concentrated energy flows as a heat source, for example, laser.

Laser technologies allow us to successfully solve the issue of creating materials with a given set of properties through targeted formation of a specific structure. With laser alloying, it is possible to form surfaces with such properties: a high level of hardness, heat resistance, wear resistance, corrosion resistance and other characteristics. Local alloying processes can be implemented using both pulsed and continuous laser radiation. At the same time, various processing schemes "with and without overlapping" can be used. The results of the process also depend on the method of supply of the alloying composition to the processing zone, the type of alloying element(s), the properties of the matrix material as well as many other factors.

Laser alloying fundamentally differs from liquid hardening [21] in that it changes the chemical composition of the hardened layer. As it turns out, the usage of laser alloying makes it possible to create local areas with high service characteristics on parts from simple structural materials instead of making these parts entirely from scarce alloys. The economic factor is important here: the part is made of inexpensive material that is easily processed by mechanical means, and expensive and scarce components are used only in a thin layer on the important load-bearing part of the product. Methods of laser surface treatment, including laser alloying, have seen a recent surge in intensity of its development, as evidenced by the large number of scientific works by multiple author teams. This allows us to conclude, that in the near future laser alloying will undoubtedly be added to the list of highly efficient industrial technologies for the production of high-quality tools and machine parts.

Surface laser alloying consists of the production of surface layers with the forced supply of implant material directly into the heat-affected zone, created by focused laser radiation. The scheme of the laser doping process is shown in Fig. 1. A sample with a thin layer of alloying coating when moving under the laser beam is locally melted, the alloying components pass into the volume of the liquid bath of the metal, which then crystallizes.

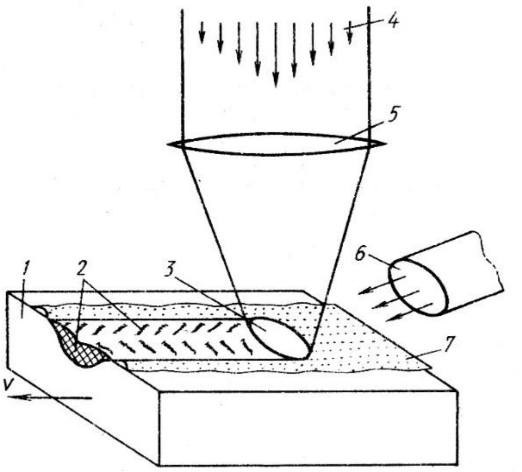

Fig. 1. Scheme of the laser alloying process:

1 – sample, that is moving with speed (V); 2 – alloy track; 3 – melt bath; 4 – laser beam; 5 – focusing system; 6 – shielding gas output; 7 – resulting alloying coating.

Studies of the process of laser surface alloying [5-7, 13-15, 20, 22] show that laser radiation, directed at the treated surface, is partially absorbed by the filler and base materials, and partially reflected outside.

As a result of absorption in the heat-affected zone of laser radiation, an intense source of heat begins to act. At the values of radiation power density of $w_e=10^5...10^6$ W/cm^2, an active local heating of the implant material happens, during which a vapor-gas phase is formed on the surface of the melt bath (liquid phase). During laser alloying, interconnected processes of heat and mass transfer, as well as various micrometallurgical processes occur at the same time. During the movement of the laser beam, the molten metal is pushed into the tail part of the bath due to the phenomenon of mass transfer (integral action of vapor pressure, the difference in surface tension forces in the central and tail parts of the melt bath, turbulent flows of the melt) [23]. At the moment of the existence of liquid metal, thanks to Marangoni thermocapillary convection [24], the molten alloying composition is mixed with the metal matrix. At the same time, the steel surface is saturated with alloying elements from the added compositions, chemical compounds are formed, and partial homogenization occurs in the liquid metal zone. During the crystallization of the metal of the melt bath, an alloyed layer is formed. When the radiation power density is increased to more than $w_e=10^6$ W/cm^2, a transition to the local “keyhole” melting regime is observed, which is characterized by the formation of a steam-gas channel in the melt bath [25].

The purpose of this study is to establish the possibility of improvingthe physical and mechanical properties of surface layers of cylindrical and flat structural steel products by applying laser alloying processes.

II. EXPERIMENTAL SETUP

Several laboratory stands were created to conduct research on laser alloying. A CO_2TRIAGON "TR-100" laser as well as Nd:YAG ROFIN-SINAR "DY044" laser were used in the study. Two laboratory stands were created for each of them – one for processing flat parts and another for processing rotating bodies. For processing rotating parts, stands were created on the basis of recycled lathes, and for processing flat parts – they were created on the basis of three-coordinate manipulators.

Laboratory stands for laser surface alloying of steel parts based on “TR-100” and “DY044” lasers are shown on theFig. 2, (a, b). The mounting system was created to be universal for each of the stands, allowingfor fastening of the optical systems elements for both the “TR-100” CO_2 laser as well as those of the “DY044” Nd:YAG laser. Radiation from the “TR-100” laser was transmitted to one of the two created technological stands using a system of copper water-cooled mirrors.

a

b

Fig. 2. Laboratory stands, created for laser alloying of different parts:
a – stand for processing of flat parts utilizing laser radiation from “TR-100” CO_2 laser and “DY044” Nd:YAG laser;

b – for processing of rotational utilizing laser radiation from “TR-100” CO_2 laser and “DY044” Nd:YAG laser.

Processing of the rotational parts was carried out on a laboratory stand created on the basis of the "K-163" lathe. Processing of flat-faced parts was carried out on a stand created on the basis of the three-coordinate manipulator "Lastivka". Experiments were carried out on laboratory standson flat and cylindrical samples made out of 08kp, St3, St20, 38KhN3MFA, 38KhM2MYuA, 40KhN, 4X5VMF, 45L and 65G steels. Powder mixtures of the Ni-Cr-B-Si system (PG-10N-01, PG-12N-02, PG-10N-04, PG-12N-01), Fe-Cr-B-Si system (PG-C27, PG-AN1), as well as chromium, relite and mixtures based on them with additives of other elements.

During the experiments, the power (P) of the laser radiation was varied from 0.5 to 6.0 kW when using the

TRIAGON “TR-100” laser and from 0.2 to 4.4 kW when using the ROFIN-SINAR “DY044” laser; the diameter of the spot (d_n) of laser radiation on the surface of the sample varying between 1 and 5 mm; the linear speed of the alloying process was varied from 3 to 50 mm/s; implanting powder mixture consumption speed (Q_n) was changed discretely in steps of Q_n=0.1; 0.15; 0.2; 0.25; 0.3; 0.35; 0.4; 0.45; 0.5 g/s; the alloying track overlap coefficient (K_p) varying between 20-70%. In some cases, immediately before alloying, the sample was preheated by laser radiation. The depth of the alloyed layers varied from 0.2 mm to 2.5 mm.

Over the course of the experiments, the planting material entered the heat-affected zone using one of the following methods:

1. using additional slip coating, when a mixture of powder materials was applied in an even layer and fixed with the help of "Tsapon" varnish on the surface of flat samples of different thickness from the above-mentioned steels. The thickness of the applied layer of the powder material was controlled by comparison with the "control sample" and using a weight method (that is, by weighing the samples before and after applying the filler materials). Experiments were carried out both when using argon as a shielding gas, and without gas shielding of the melt bath;
2. using a transporting gas jet when using the technological alloying head, developed and described in the third section.
3. with the help of preliminary application by gas-thermal methods.

Experiments on alloying were conducted for both individual and "overlapping" tracks with a 2...4 mmlaser beam moving step. When using the ROFIN-SINAR “DY044” laser to prevent laser radiation, reflected from the surface of the bath of liquid metal, from hitting back into the optical path, the laser head was fixed on the carriage of the three-coordinate manipulator at an angle of 10° to the vertical axis (in the direction of movement of the carriage).

III. RESULTS AND DISCUSSION

Conducting experiments on steel samples showed that in the laser radiation power range of 1.0-5.0 kW (using a CO_2 laser) and 0.8- 4.4 kW (using a Nd:YAG laser) the optimal (from the point of view of minimizing the thermal impact on the alloyed product) the diameter of the radiation spot on the alloyed surface is directly proportional to the power and is 1 mm per 1 kW for 5...20 mm/s processing speeds and implanting powder mixture consumption speed of Q_n=0.1...0.3 g/s. The corresponding range of radiation power density is $W_p=(0,5...5,0)\times10^5 W/cm^2$. The time of existence of the melt bath can vary from 0.01 to 0.5 s. The specified dependence in this range allows us to obtain high-quality alloyed layers with a 0.2-2.0 mm thickness in one pass on steel products when using filler alloys on based on iron, chromium and nickel.

Increasing the radiation power (when obtaining high-quality alloyed layers with minimal thermal influence on the product) beyond the specified limits showed us, that the dependence of the focusing spot on the power becomes nonlinear. Thus, at P=5.5 kW for CO_2 lasers, the recommended diameter of the focusing spot (d_n) is 5.0 mm. This is explained by following: high temperatures in the heat-affected zone of laser radiation lead to formation of a plasma torch above this area, which partially absorbs the radiation. In addition, part of the energy supplied to the melting zone is lost with the emission of drops of molten implanting material, which occurs when they are dropped from the plasma zone. To overcome the plasma-droplet torch, it is necessary to increase the supplied laser energy and (or) decrease the speed of the alloying process. The latter increases heat dissipation into the depth of the alloyed product, which also requires an additional increase in radiation energy. A similar effect occurs at the recommended power values, however, in this range, if the above parameters are observed, in particular, the direct proportion of P and d_n, this effect is more weakened.

A decrease in radiation power to values of less than 1 kW also leads to a non-linearity of the relationship between P and d_n, because a decrease of d_n to the values of<1 mm can lead to undesirable processing in the focus of the laser emission, characterized by an increased burnout of some elements of the implant material (for example, boron and carbon) and formation of the pores.

As a result of the research, it was established that the influence of the wavelength of laser radiation on the parameters of the alloying process of steel samples is linear. Thanks to the use of laser radiation from the Nd:YAG laser "DY044" under the same initial conditions (P, ΔF, consumption and type of implant material, etc.), it was possible to increase the processing speed by 30-70% (while maintaining a similar alloying depth, such as one shown when using CO_2 lasers).

IV. CONCLUSION

During laser alloying of thin-walled and small samples, the lower limit of the indicated P-d_n range should be observed. On the contrary, when alloying thick-walled (with a wall thickness of more than 10 mm) flat and rotational parts or solid cylindrical samples with a diameter of more than 40 mm, it is advisable to observe the upper limit of the P-d_n range, and in some cases, use lasers capable of emitting laser radiation with radiation power values in excess of 4.5 kW.

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