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АВТОМАТТАНДЫРУ, ТЕЛЕМЕХАНИКА, БАЙЛАНЫС, ЭНЕРГЕТИКА, АҚПАРАТТЫҚ ЖҮЙЕЛЕР
АВТОМАТИЗАЦИЯ, ТЕЛЕМЕХАНИКА, СВЯЗЬ, ЭНЕРГЕТИКА, ИНФОРМАЦИОННЫЕ СИСТЕМЫ
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ANALYSIS OF TECHNOLOGICAL PROCESSES LASER SURFACING IN ADDITIVE MANUFACTURING

Abstract. The prospects for the development of the machine-building complex are largely associated with a reduction in the volume of production waste and the number of operations in the production chain. The realization of this task is possible thanks to the use of technologies that ensure that the workpiece is shaped close to the shape of the finished product in one technological operation. A landmark event in mechanical engineering was the development of additive manufacturing, combining technologies for manufacturing parts based on a three-dimensional CAD model without the use of forming elements and machining.

One of such technologies is three-dimensional shaping by laser surfacing. This method of physical and technical processing uses the energy of laser radiation to melt the surfacing material and the underlying layer in order to form a roller on it, metallurgically connected to the base. Laser surfacing is effective when applying coatings and repairing worn parts.

The article analyzes the technological processes of laser surfacing in additive manufacturing. Laser surfacing, limited in its technological capabilities, has so far been used for surface modification, restoration and production of medium- and large-sized products with low requirements for surface quality, dimensional and shape accuracy and significant allowances for machining.The creation of precision system technology for laser surfacing made it possible to expand the scope of its application into the submillimeter area and develop an independent direction - microlaser surfacing. In the conditions of growing demand for manufacturing technologies of small-sized products, including thin-walled ones, the development of the technological process of microlaser surfacing is an urgent scientific and technical task.

However, its capabilities in the manufacture of small-sized products are limited by the minimal size of the grown element, which, in turn, depends on the size of the impact zone (transverse dimensions of the melt bath and the deposited roller).

For this reason, laser surfacing is traditionally used in the production of medium- and large-sized parts with significant allowances for subsequent machining.

Scientific and technological progress in laser surfacing technology has created prerequisites for the miniaturization of the processing zone of less than 1 mm and the development on this basis of technological processes of laser surfacing in the submillimeter region (microlaser surfacing) to expand the capabilities of the method in the production of small-sized products, which is an urgent task in the conditions of growing demand for-manufacture of small-sized parts.

Keywords. Surfacing, laser, powder, wire, layer.

Introduction.

The prospects for the development of the machine-building complex are largely associated with a reduction in the volume of production waste and the number of operations in the production chain. The realization of this task is possible thanks to the use of technologies that ensure that the workpiece is shaped close to the shape of the finished product in one technological operation. A landmark event in mechanical engineering was the development of additive manufacturing, combining technologies for the manufacture of components based on a three-dimensional CAD model without the use of forming elements and mechanical processing. At the beginning of its development, additive technologies focused on the production of prototypes. Today, they combine a wide class of technological processes for manufacturing products, one of which is three-dimensional shaping by laser surfacing. This method of physical and technical processing uses the energy of laser radiation to melt the filler material entering the processing zone together with radiation and the underlying layer in order to form a surfacing roller on it, metallurgically connected to the base. The relative displacement of the laser beam and the working surface allows the material to be applied along the selected trajectory, and the layered overlay of contours allows the creation of three-dimensional objects [1].

Materials and methods.

The study was carried out using a regression analysis apparatus, by analyzing existing technological processes of laser surfacing in additive manufacturing.

Results.

The technological principle of laser surfacing (Figure 1) in additive manufacturing is commercialized under various trade names: Laser Engineered Net Shaping [2], Direct Metal Deposition [3], etc. The powder, preheated and partially melted during the passage of laser radiation, enters the melt bath formed on the working surface, where it finally melts. Upon crystallization of the resulting melt, a surfacing roller is formed.

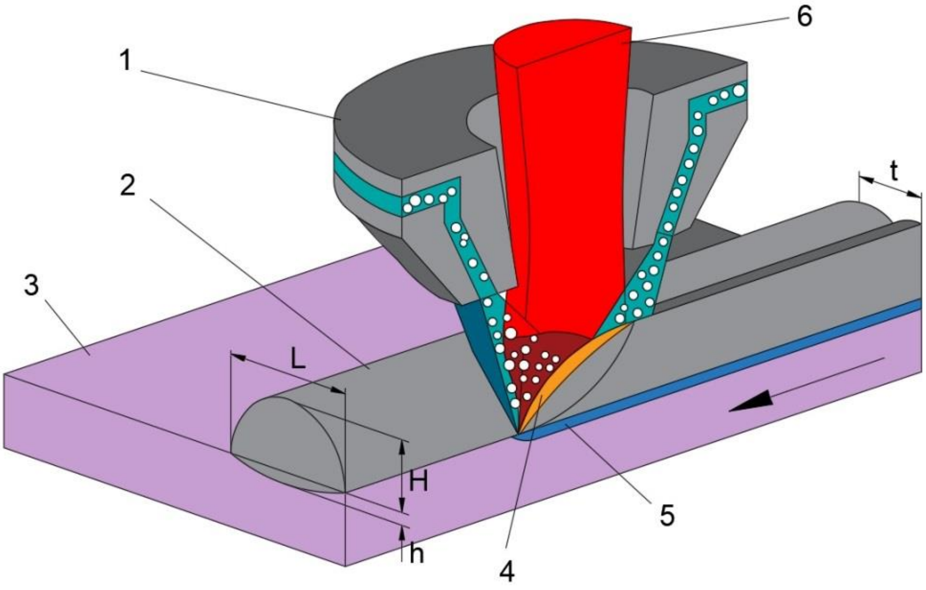

Figure 1 - Diagram of the laser surfacing process and the corresponding input and output values: 1 - coaxial nozzle, 2- surfaced roller, 3- substrate, 4 – melt bath, 5 - thermal influence zone, 6- laser radiation

The presence of a CAD model allows you to automate the process of laser surfacing. By means of special software (software), the part model is divided into a discrete number of layers, for which the trajectory of the tool is calculated and its conversion into a CNC-compatible format is performed. The final file is loaded onto a CNC machine adapted for laser surfacing processes. The growing of the part takes place by layer-by-layer surfacing of the contours.

The device of laser surfacing installations. The layout of the installation for laser surfacing is chosen in accordance with the technological task. The radiation from the source comes through an optical fiber to the lens system, where it is focused. The protective gas enters the treatment area together with laser radiation. The powder dosed by the feeder is transported by the carrier gas through the supply channels to the nozzle, which focuses the powder in the working area. The positioning system provides relative movements of the nozzle and the substrate.

The formation of laser radiation is based on the phenomenon of light amplification through forced emission in an active medium. The active medium, the method of its excitation and the type of resonator determine the spatial structure of the radiation (the configuration of the field in the cross section) and its spectral composition (light wavelength X). Ideally, the laser radiation is an electromagnetic wave of a high degree of monochromaticity, the intensity distribution I (x,y) in the cross section of which corresponds to the Gauss law (Gaussian beam):

$$I(x,y) = I_{max}\left(-\frac{4(x^2+y^2)}{d^2}\right), \tag{1}$$

where I_{max} is the maximum intensity in the beam,

x, *y* is coordinates in cross section, mm;

d is the diameter of the beam, mm.

When focusing the radiation (Figure 2) at a distance equal to the focal distance of the lens *f* *Fok*, a zone of constriction with a focusing diameter d_F is formed, at a distance from which, in the direction of beam propagation *z*, its diameter *d(z)* increases in accordance with the expression [5]:

$$d^2(z) = d_F^2 + \theta^2(z - z_0)^2, \tag{2}$$

where θ is the total divergence angle of the laser radiation, rad;

z_0 is the position of the tie, mm.

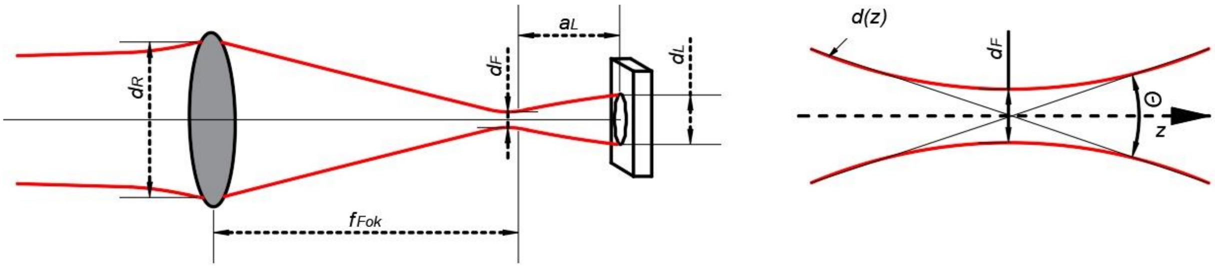

Figure 2 - Radiation focusing scheme

The product of the divergence and the diameter of the constriction remains constant during the propagation of radiation through the optical system and serves as its characteristic, which is called the beam quality parameter VRP [5]. For a Gaussian beam (single-mode radiation) it is valid:

$$BPP = \frac{d_F * \theta}{} = \frac{\lambda}{}. \tag{3}$$

In practice, the transverse spatial structure of the radiation is formed by the superposition of transverse modes of a higher order than the main mode of the Gaussian beam. The divergence and the diameter of the tie increases by a factor of M, and the beam quality parameter is:

$$BPP = \frac{d_F * \theta}{} = M^2 \frac{\lambda}{}. \tag{4}$$

where M^2 - the parameter shows the multiplicity of the increase in the diameter of the real beam with respect to the Gaussian beam at one divergence, and serves to assess the focusability of laser radiation. Taking into account the expression (4), the change in the beam diameter along the propagation axis takes the form:

$$d^2(z) = d_F^2 + \left(\frac{M^2 \lambda z}{}\right)^2. \tag{5}$$

The surfacing process provides for the value of the working margin a_L (Figure 2). The diameter of the focal spot in the working plane d_L can be calculated using the value of the working offset a_L with the known function *d(z)*.

The characteristics of industrial lasers used for laser surfacing processes are presented in Table 1.

Powder or wire is used as a surfacing material. Wire surfacing provides a higher material utilization rate, however, the choice of wire material and its minimum size are limited. Therefore, powder surfacing is more common, for which powders of various fractions (20-150 microns), shape and chemical composition are used.

From the tank, the powder enters the distribution drum, where it is captured and fluidized by the carrier gas.

Table 1 - Characteristics of lasers used for laser surfacing

Name	Type of laser		
	diode	rod	fiber, disk
Power, kW	up to 10	up to 5	up to 16
Wavelength, microns	0,9-1,03	0,355-1,064	1,064
Parameter M^2	>20	min. 1,2	min. 1,05
Spatial beam profile	multimode ("Top-Hat")	multimode	multimode/single-mode (Gaussian)

Fluidization of the powder, depending on the density and particle size, is estimated using the Geldart diagram (Figure 3). The gas-powder mixture enters the feed channel 6 through the exhaust port 5. The pneumatic transportation of powder through the feed channels is based on the phenomenon of the formation of an aerodynamic field, the characteristics of which are determined by the properties of the powder, its flow rate, flow rate and characteristics of the channel [6].

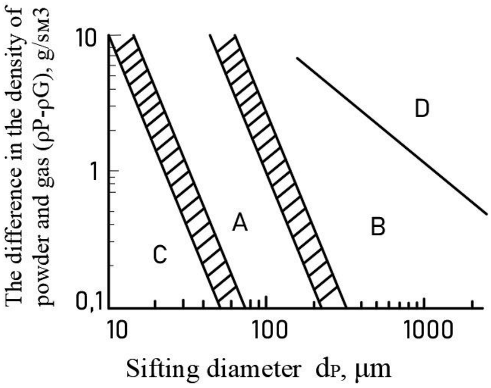

Figure 3 - Geldart diagram:
A- dispersed powder, fluidization with the formation of a uniform flow; B- larger, denser particles than in zone "A", fluidization with the formation of a non-homogeneous flow; C- fine powder, difficulties in fluidization, D-the largest dense particles, uneven fluidization with a fountain

A mixture of gas and powder enters the nozzle through the supply channels, where it is coaxially or laterally fed to the radiation into the treatment area. Coaxial nozzles are made with a conical slit or jet injection. The nozzle design (Figure 4) in combination with the processing parameters affects the interaction of radiation, powder and melt.

The following indicators are used to characterize the nozzle:

- working offset a_n (distance between the lower edge of the nozzle and the substrate surface);
- the minimum size of the focal spot of the powder is d_{FD};
- width of the conical slit b_{RS};
- cross section of the powder nozzle outlet;
- cross section of the protective gas outlet;
- powder nozzle angle θ_{Dn};
- guide base l_{RS}.

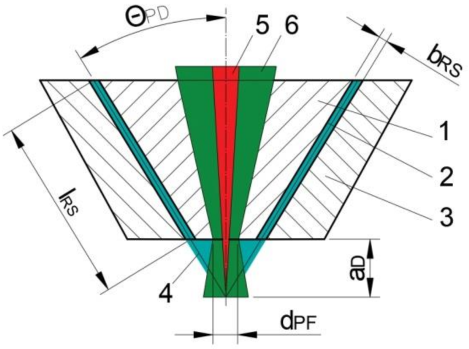

Figure 4 - The structure of a coaxial nozzle with a conical slit:
1- inner cone, 2-conical slit, 3- outer cone, 4 – gas-powder mixture flow, 5-laser radiation, 6 – protective gas

The relative movement of the nozzle and the substrate necessary for growing products is carried out by a positioning system, which is usually used as 5-coordinate CNC milling machines

For a rational choice of modes, the technological process of laser surfacing is presented as a complex system linking the input independent quantities *x1*, *x2*,..., *xk* (factors) and the output quantities *Yj* (response functions) by means of a mathematical model (Figure 5).

Individual phenomena observed during laser surfacing are described by constructing appropriate models and verified. However, a full description of the process has not yet been developed.

The application of single rollers is the first stage of the development of the technological process of laser surfacing. The formation of the layer during the cultivation of two- and three-dimensional objects is carried out by applying separate rollers. There are a number of models of coating shaping based on the geometry of the roller [6,7]. The additive model [6], based on a simple summation of the sections in the overlap zone, predicts an abnormal undulation of the surface, not observed in a real experiment. The authors of the work complete the profile of the layer in the zone between adjacent rollers with a rounded curve describing a cross-section with an area equal to the area of a single roller, which also contradicts the experiment. The most adequate recursive model of step-by-step profile calculation [7] is based on three physical assumptions (Figure 6):

- the width of the roller is determined by the processing parameters and does not change its value from pass to pass;

- the shape of the roller is determined by the physical properties of the melt and does not change during overlap;

- the surfacing speed is constant with constant surfacing parameters.

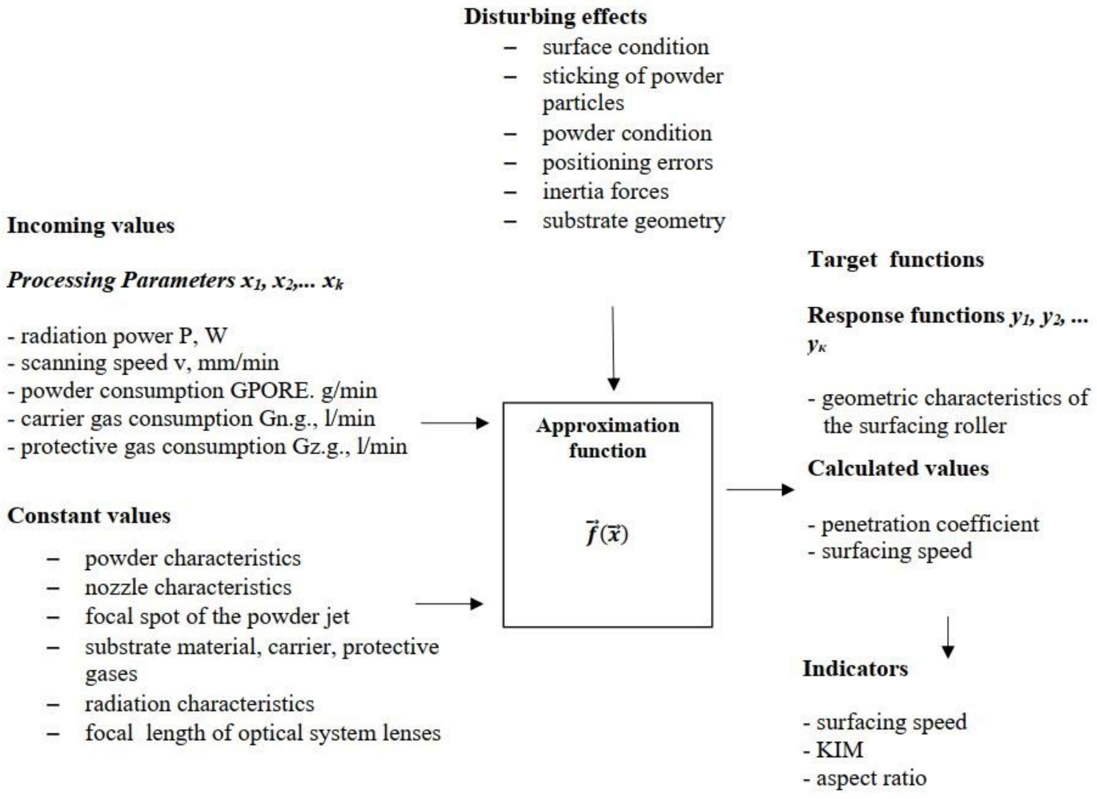

Figure 5 - Formalized representation of laser surfacing as a system of input and output variables

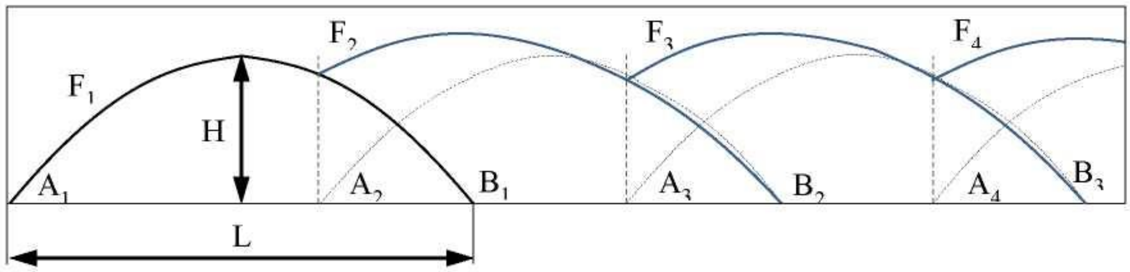

Figure 6 - Schematic representation of a recursive model for calculating the coverage profile: Ai, Bi - the leftmost and rightmost point of the profile of the i-th roller

Process indicators allow you to compare laser surfacing modes in terms of efficiency and facilitate their selection.

The surfacing rate M reflects the productivity of the process and is defined as the mass of the deposited material per unit of time.

The material utilization factor (CMM) is the ratio of the deposited mass to the consumption of the powder $F_{пор}$:

$$K_{им} = \frac{М}{\_}. \tag{9}$$

Due to the complex mechanism of interaction of radiation, powder and substrate, the energy in the system is distributed unevenly, which leads to fluctuations in the temperature of the particles (Figure 7). Insufficiently heated particles are reflected from the surface, which reduces K_im. The adhesion of heated particles to the hardening melt and fused particles to the substrate increases the roughness of the surface *Ra*.

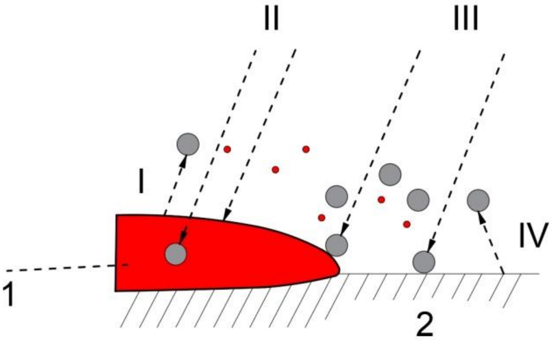

Figure 7 - Diagram of interaction of powder particles with melt and substrate: 1- melt bath, 2-substrate, I-reflection of cold powder particles in the melt bath, II – absorption of molten and partially molten powder particles in the melt bath, III - sticking of heated and partially molten powder particles to the surface of the roller/substrate, IV – reflection of cold powder particles by the substrate

Discussion.

The spread of the values of the input and output values of the laser surfacing process is large (Table 1, 2). In its traditional application, where productivity is of primary importance, high-power diode, fiber and disk lasers are used. The focal spot of the radiation of such lasers is more than 1 mm, and the power is several kW. The size of the melt bath reaches 20 mm, and the surfacing speed is 250 g/min, and the CMM can reach 95% [9]. When precision processing is required - local surface protection or shaping in the submillimeter region - the possibilities of laser surfacing are limited by the minimum size of the melt bath formed when exposed to radiation, and after its crystallization - a single roller [10].

Table 2 - Range of values of parameters of traditional laser surfacing [8]

Name	Designation	Meaning
Power, W	P	200-4000
Beam diameter, mm	d	0,6-8
Scanning speed, mm/min	V	200-20000
Powder consumption, g/min	$F_{\text{ПОР}}$	0,5-300
Carrier gas consumption, l/min	$F_{\text{Н,Г,}}$	2-15
Protective gas consumption, l/min	$F_{\text{З,Г,}}$	2-15

In view of the described technological features, the possibilities of laser surfacing in terms of surface quality, accuracy of dimensions and shape of products are limited by the minimum size of the impact zone and the resulting roller, which is usually several millimeters. As a result, laser surfacing is widely used for the repair of worn parts, surface modification and manufacture of medium- and large-sized products with low requirements for surface quality, dimensional accuracy and significant allowances for machining. According to research data, the consumption of the main share of laser additive manufacturing products falls on knowledge-intensive industries: 17% - automobile construction, 14% - medicine and 10% - aviation. At the same time, 38% of industrial equipment is operated in the USA, 9.7% - in Japan, 9.4% - in Germany. The introduction of additive technologies in domestic mechanical engineering is of a single nature.

Conclusion.

Laser additive technologies combine a wide class of technological processes for the manufacture of products, the most common of which is laser surfacing. Laser surfacing, limited in its technological capabilities, has so far been used for surface modification, restoration and production of medium- and large-sized products with low requirements for surface quality, dimensional and shape accuracy and significant allowances for machining.The creation of precision system technology for laser surfacing made it possible to expand the scope of its application into the submillimeter area and develop an independent direction - microlaser surfacing. In the conditions of growing demand for manufacturing technologies of small-sized products, including thin-walled ones, the development of the technological process of microlaser surfacing is an urgent scientific and technical task.

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ТЕХНОЛОГИЯЛЫҚ ПРОЦЕСТЕРДІ ТАЛДАУ АДДИТИВТІ ӨНДІРІСТЕ ЛАЗЕРЛІК БАЛҚЫТУ

Аңдатпа. Машина жасау кешенін дамыту перспективалары өндіріс қалдықтары көлемінің және өндірістік тізбектегі операциялар санының азаюымен айтарлықтай байланысты. Бұл тапсырманы бір технологиялық операцияда дайын өнімнің пішініне жақын дайындаманы беруді қамтамасыз ететін технологияларды қолдану арқылы жүзеге асыруға болады. Машина жасаудағы маңызды оқиға форма түзуші элементтер мен механикалық өңдеуді қолданбай үш өлшемді CAD моделі негізінде бөлшектерді өндіру технологияларын біріктіретін аддитивті өндірістің дамуы болды.

Осындай технологиялардың бірі-лазерлік балқымамен үш өлшемді қалыптау. Физика-техникалық өңдеудің бұл әдісі негізге металлургиялық байланысты ролікті қалыптастыру мақсатында беткі материалды және оның астындағы қабатты балқыту үшін лазерлік сәулелену энергиясын пайдаланады. Лазерлік қаптау тозған бөлшектерді жабу және жөндеу кезінде тиімді.

Мақалада аддитивтік өндірістегі лазерлік балқытудың технологиялық процестеріне талдау жасалды. Технологиялық мүмкіндіктерімен шектелген лазерлік беткі қабат осы уақытқа дейін бетінің сапасына, өлшемдері мен пішінінің дәлдігіне және айтарлықтай өңдеу жәрдемақыларына төмен талаптары бар орташа және үлкен өлшемді бұйымдардың бетін өзгерту, қалпына келтіру және өндіру үшін қолданылған. Лазерлік балқытуға арналған дәл жүйелік техниканы құру оның қолдану аясын субмиллиметрлік аймаққа кеңейтуге және тәуелсіз бағытты - микролазерлік балқытуды дамытуға мүмкіндік берді. Шағын өлшемді бұйымдарды, соның ішінде жұқа қабырғалы бұйымдарды өндіру технологияларына сұраныстың артуы жағдайында микролазерлі балқытудың технологиялық процесін әзірлеу өзекті ғылыми-техникалық міндет болып табылады.

Алайда, оның кішігірім өнімдерді өндірудегі мүмкіндіктері өсірілетін элементтің минималды мөлшерімен шектеледі, бұл өз кезегінде әсер ету аймағының мөлшеріне байланысты (балқытылған ванна мен балқытылған роликтің көлденең өлшемдері).

Осы себепті лазерлік балқыту дәстүрлі түрде кейінгі механикалық өңдеуге айтарлықтай жәрдемақысы бар орташа және үлкен өлшемді бөлшектерді өндіруде қолданылады.

Лазерлік балқыту техникасындағы ғылыми-техникалық прогресс өңдеу аймағын 1 мм-ден аз миниатюризациялау үшін алдын ала сілтемелер жасады және осы негізде шағын көлемді бұйымдар өндірісінде әдістің мүмкіндіктерін кеңейту үшін субмиллиметрлік аймақта лазерлік балқытудың технологиялық процестерін (микролазерлік балқыту) әзірледі, бұл өндірістегі технологияларға сұраныстың артуы жағдайында өзекті міндет болып табылады. Шағын өлшемді бөлшектерді өндіру.

Түйінді сөздер. Беткі қабат, лазер, ұнтақ, сым, қабат.

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АНАЛИЗ ТЕХНОЛОГИЧЕСКИХ ПРОЦЕССОВ ЛАЗЕРНОЙ НАПЛАВКИ В АДДИТИВНОМ ПРОИЗВОДСТВЕ

Аннотация. Перспективы развития машиностроительного комплекса в значительной мере связаны с сокращением объема отходов производства и числа операций в производственной цепи. Реализация этой задачи возможна благодаря применению технологий, обеспечивающих придание заготовке формы, близкой к форме готового изделия, за одну технологическую операцию. Знаковым событием в машиностроении стало развитие аддитивного производства, объединяющего технологии изготовления деталей на основе трехмерной *CAD*-модели без использования формообразующих элементов и механической обработки.

Одной из таких технологий является трехмерное формообразование лазерной наплавкой. Данный метод физико-технической обработки использует энергию лазерного излучения для оплавления наплавочного материала и нижележащего слоя с целью формирования на нем валика, металлургический связанного с основой. Лазерная наплавка эффективна при нанесении покрытий и ремонте изношенных деталей.

В статье проведен анализ технологических процессов лазерной наплавки в аддитивном производстве. Лазерная наплавка, ограниченная в своих технологических возможностях, до сих пор применялась для модификации поверхности, восстановления и производства средне- и крупногабаритных изделий с невысокими требованиями к качеству поверхности, точности размеров и формы и значительными припусками на механическую обработку.Создание прецизионной системной техники для лазерной наплавки позволило расширить область ее применения в субмиллиметровую область и развить независимое направление - микролазерную наплавку. В условиях растущего спроса на технологии изготовления малоразмерных изделий, в том числе тонкостенных, разработка технологического процесса микролазерной наплавки является актуальной научно-технической задачей.

Однако, ее возможности в изготовлении малоразмерных изделий ограничены минимальным размером выращиваемого элемента, который, в свою очередь, зависит от размера зоны воздействия (поперечные размеры ванны расплава и наплавленного валика).

По этой причине лазерную наплавку традиционно применяют при производстве средне- и крупногабаритных деталей со значительными припусками на последующую механообработку.

Научно-технический прогресс в технике для лазерной наплавки создал предпосылки для миниатюризации зоны обработки менее 1 мм и разработки на этой основе технологических процессов лазерной наплавки в субмиллиметровой области (микролазерная наплавка) для расширения возможностей метода при производстве малоразмерных изделий, что является актуальной задачей в условиях растущего спроса на технологии изготовления малогабаритных деталей.

Ключевые слова. Наплавка, лазер, порошок, проволока, слой.

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