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INTERDISCIPLINARY PROBLEMS IN ADDITIVE TECHNOLOGIES

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М43 **Междисциплинарные проблемы аддитивных технологий: сборник тезисов IV Всероссийского научного семинара с международным участием, 29-31 октября 2018, Томск**. [Электрон. текстовые дан.]. – Томск - 2018. – 65 с.

Этот сборник включает тезисы устных и стендовых докладов IV Всероссийского научного семинара с международным участием «Междисциплинарные проблемы аддитивных технологий». Семинар организован для содействия обмену результатами и опытом в области научных исследований, связанных с аддитивными технологиями, в целях развития и усиления интеграции упомянутых ранее исследований. Программа семинара в 2018 году охватывает проблемы материаловедения в аддитивных технологиях.

This book comprises the abstracts of the reports on the oral and poster sessions of the International Seminar on Interdisciplinary Problems in Additive Technologies. The Seminar is organized to promote the exchange of results and experiences in the field of scientific research relevant to additive technologies in order to develop and strengthen the integration of the research mentioned earlier. The program of the Seminar in 2018 covers the problems of materials science in additive technologies.

Доклады издаются в авторской редакции.

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DETERMINATION OF OPTIMAL PARAMETERS FOR SLM USING MATHEMATICAL MODELING METHODS

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For manufacturing new high-tech products using new design solutions and materials that have new properties, it is necessary to use new production technologies, in particular additive technologies [1, 2]. By means of additive production technologies, it is possible to create parts that can't be made in other ways. Selective Laser Sintering technology - SLS (Selective Laser Melting) is one of the most important directions of additive technologies. Here structural materials are loose, powdery materials, and the laser is a source of heat, through which the powder particles are melted [3].

Titanium alloys are widely used for manufacture of parts in the aerospace, medical, automotive, chemical and other industries [4-6]. The main advantages of titanium alloys in comparison with other materials are high specific strength with respect to the density of the material, good corrosion resistance and high mechanical properties when exposed to high temperatures. An important role in the development of technological processes for manufacture of parts by technology of selective laser melting is played by the stage of determining the optimal parameters of melting. The mechanical and strength properties of the products obtained depend on the correct choice of laser processing parameters. The use of optimal parameters of laser processing makes it possible to manufacture parts with specified mechanical and increased strength properties.

The main technological parameters of selective laser melting process, which determine the quality of melted material, are the granulometric and chemical composition of the raw materials, as well as the parameters of laser melting processing (laser emission power, scanning speed, laser spot diameter, etc.).

Today, the determination of optimal processing parameters is carried out experimentally, by making special samples, by performing mechanical tests and by studying the structure of the material obtained.

Carrying out experimental studies in the field of selective laser melting requires large material and time costs, so mathematical modeling is great importance for solving the problems of selecting and assigning the necessary parameters of laser processing.

In this connection, the actual task is to develop a method for selecting and assigning parameters of selective laser fusion technology based on mathematical modeling of physical processes occurring in the laser-affected zone.

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EVALUATION OF EFFECTIVE PROPERTIES OF METAL MATRIX COMPOSITE WITH INCLUSIONS SURROUNDED BY INHOMOGENEOUS TRANSIENT LAYER

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Synthesis in the thermal explosion mode or in the combustion mode is used to produce composites of different composition, including the Ti-C system. In equilibrium conditions, a composite consisting of a titanium matrix with carbide inclusions TiC is expected [1, 2]. However, due to nonequilibrium conditions realized in these technologies, nonequilibrium Ti_xC_y phases can form [3], the number of which varies depending on the synthesis conditions.

According to literature data, the following phases can be expected: TiC_2, Ti_3C_2, Ti_2C. [4, 5]

In this work, the effective properties of the composite based on titanium (perhaps with partially dissolved carbon therein) containing multiphase particles are estimate. The transition layer may consist of several successively formed phases (fig.1).

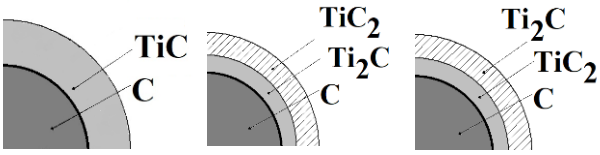

Figure 1. Scheme of spherical particle with the multiphase transition layer

The problem of particle inhomogeneity is solved using the method of replacing a non-uniform inclusion with an equivalent homogeneous one. The effect of the composition and size of the carbide phases on the effective properties (thermal conductivity and thermal expansion coefficient) of a composite material is studied.

The results of the study show the influence of the width, composition of the formed transition layer, and the order of the phases on the properties of inclusions formed during the synthesis of a composite material in the Ti-C system. The effect of concentration and size of particle on the effective properties of the composite was studied.

This work is supported by Russian Science Foundation (RSF), grant 17-19-01425.

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THE EFFECT OF ION PLASMA TREATMENT ON PHYSICAL AND MECHANICAL PROPERTIES OF SURFACE LAYERS IN AUSTENITIC STEEL

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The phase composition, fracture mechanism and elemental composition of surface layers of AISI 316-type austenitic stainless steel with a different grain-subgrain structure were studied after ion plasma treatment (IPT). Two portions of steel samples were subjected to cold rolling at room temperature to an upset degree of 80%. First portion of specimens remained in the rolled condition (Regime 1 – R1). The second portion of the rolled specimens was annealed at 600° C for 2 hours (Regime 2 – R2). R1 and R2 specimens were subjected to IPT for 12 hours at 540° C with a gas pressure P=300 Pa in the working atmosphere of Ar 70%, N_2 25% and C_2H_2 5%. Further, the tensile tests were conducted at an initial strain rate of 4.6×10^{-4} s^{-1}. Scanning and transmission electron microscopy (SEM, TEM), X-ray analysis, tensile tests, Auger electron spectroscopy (AES) and nanoindentation were used to study steel specimens after IPT.

Cold rolling of R1 specimens leads to the formation of a misoriented grain-subgrain structure with a high density of deformation defects (dislocations, subboundaries, twins, etc.). The analysis of TEM selected area diffraction patterns (SADP) shown a strong blurrings of austenitic reflections in the azimuthal and radial directions, which indicate a high internal stresses and low-angle misorientations in the structure. Annealing of the rolled specimens (R2) leads to a partial relaxation of the internal stresses, redistribution of dislocations. In specimens by R2, misoriented grain-subgrain structure forms with a slightly increased average size of elements as compared to R1-specimens. In addition to grains and subgrains, the recrystallized grains were observed. SADPs for R2-specimens have a quasi-ring, mainly point character, which indicates the prevalence of high-angle misorientations. But low-angle misorientations are also present in the structure. According to X-ray analysis, R1 and R2 specimens contain austenitic phase only.

IPT promotes a formation of the surface hardened layer about 18 μm in thick for both R1 and R2 specimens. Fracture surfaces of R1 and R2 specimens reveal that hardened surface layers fracture in quasi-cleavage micromechanism, but central parts of the specimens have ductile rapture (dimple one). A transition diffusion zones with a mainly ductile fracture, which have the traces of plastic deformation, are observed between brittle surface layers and ductile matrices both for R1 and R2 specimens.

The depth-distribution profiles of the elemental composition and nanohardness showed different flows for the specimens with a highly defective (R1) and annealed grain-subgrain structure (R2). For R1-regime, these distributions can be divided in two parts – fast decrease in concentrations of N and C and nahohardness in surface 5 μm-layer and, then, slow decrease down to 18 μm-depth. For R2-regime, the distribution of interstitial atoms and nanohardness smoothly decrease up to a depth of 18 μm. According to AES-data, the surface layer of 5 μm in thickness for R1 specimens is intensively saturated with carbon and nitrogen compared to R2-specimens. This provides different values of the nanohardness near the surface of the specimens: 24 GPa for R1-regime and 16 GPa for R2-regime. The increase in nanohardness and the quasi-brittle fracture of surface layers are due to several factors: (1) dispersion hardening in a surface layers up to 18 μm thick (formation of fine nitrides and carbonitrides Fe_4N, Fe_4 (N, C) or $Me_{(2,3)}$ N, $Me_{(2,3)}$ (N, C) in high-nitrogen austenite); (2) solid-solution strengthening of austenite and ferrite by interstitial atoms.

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MATHEMATICAL MODELING OF THE COMBUSTION WAVE IN THE SHS

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Currently, uranium dioxide is used as fuel for nuclear reactors. This compound has a low coefficient of thermal conductivity, which negatively affects its strength.

One of the ways to solve this problem is the use of dispersive nuclear fuel. Typically, dispersion fuels are manufactured using traditional powder metallurgy methods, but they have several disadvantages. These deficiencies deprived of the SHS method.

In the process of SHS, there are complex dependencies of phase formation on the temperature of the reaction, therefore, in order to predict the properties of the synthesized materials, it is necessary to build a mathematical model of the course of SHS.

Since SHS processes are associated with heat conduction, then the heat conduction equation can be used to describe the system.

The burning wave will propagate from the top of the sample to its bottom. It is seen from the experiments that the propagation of the combustion wave occurs at almost constant speed, therefore, to simplify the function of thermal sources, we take the velocity of its propagation constant. We also assume that chemical reactions occur instantaneously, this gives us the right to talk about the heat source as a point source of heat moving at a constant speed.

Let us assume that SHS occurs in vacuum, therefore heat transfer from the sample borders is possible only with the help of radiation, and the lower end of the sample is thermally insulated. Assume that the sample is uniformly heated at the initial time.

The heat equation with boundary and initial conditions will take the form:

$$\frac{\partial u}{\partial t}-\alpha^2\cdot\frac{\partial^2 u}{\partial z^2}=\frac{\delta(z)}{c};\ \lambda\cdot\left.\frac{\partial u}{\partial z}\right|_{z=H/2}=\varepsilon\cdot\sigma_B\cdot\left(u^4-u_c^4\right);\ \lambda\cdot\left.\frac{\partial u}{\partial z}\right|_{z=-H/2}=0;$$

$$\left.u\right|_{t=0}=u_0;\ \delta(z)=\begin{cases}Q, & z=H/2-v\cdot t;\\ 0, & z\neq H/2-v\cdot t;\end{cases} z\in\left[-H/2;H/2\right],$$

where λ is the coefficient of thermal conductivity;

u_c is the ambient temperature;

ε is the degree of blackness of the body;

σ_B – Stefan-Boltzmann constant;

$u = u(z,t)$ – function of temperature;

u_0 – initial body temperature;

α – thermal diffusivity;

H – height of the sample;

v – velocity of propagation of the combustion wave;

Q – heat source.

HARDNESS AND WEAR RESISTANCE OF SHS TIC+HSS COMPOSITE COATINGS, OBTAINED BY ELECTRON BEAM SURFACING

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High-speed steel (HSS) is widely used for the manufacture of metal cutting tools. Due to high heat resistance, this steel is also of interest as a material of wear-resistant coatings operating at high temperatures. The important advantage of the HSS for plasma or electron beam surfacing originates from well-known self-hardening effect during cooling of the cladded coating [1].

An additional properties improvement of the coatings cladded with high speed steel powder can be obtained by adding refractory compounds into the powder. Metal carbides are used as the additives most often [2-5]. The TiC carbide appears to be the most effective additive due to the highest hardness, compared to other metal carbides.

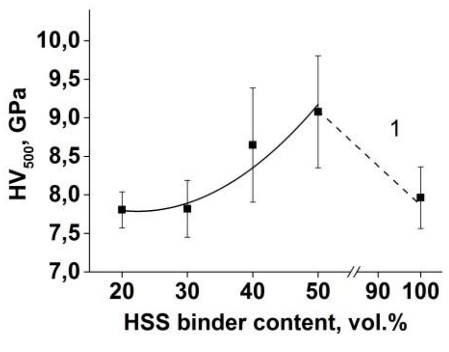
The powder mixtures are often used in coating technologies. Components segregation in the powder mixture and during delivery into melted bath can occur. That will result in inhomogeneity of elemental composition of the coating [6-9]. In this case, it is particularly necessary to use granulated composite powders, already composed of carbide particles embedded into metal binder.

Self-propagating high-temperature synthesis (SHS) in powder reaction mixtures of carbon, a carbide forming metal, and matrix metal should be recognized as the most technologically and highly productive way of obtaining composite powders "dispersed carbide-metal binder" [10].

SHS composite powders "titanium carbide – HSS binder" were obtained and investigated earlier [11]. In the present work, these powders were used for electron beam surfacing of coatings. The aim of the work was to investigate the influence of the structure of the deposited coatings on their hardness and wear resistance.

Coatings cladded by multipass electron-beam surfacing, have 2-5 mm thick (depending on the number of passes). A middle part of the coatings (outside of coating-substrate transition zone) has a specific structure including the grains of the composite powder and individual carbide inclusions embedded into the steel matrix.

It can be assumed that with the same integral content of the steel binder in the cladded coatings (80 vol. %) hardness and wear resistance can be affected by structural characteristics such as the volume content and average size of the non-dissolved granules, as well as the volume content and average size of the individual carbide inclusions in the steel binder. We cladded two kinds of coatings, using powder mixtures containing composite powder granules of different size.



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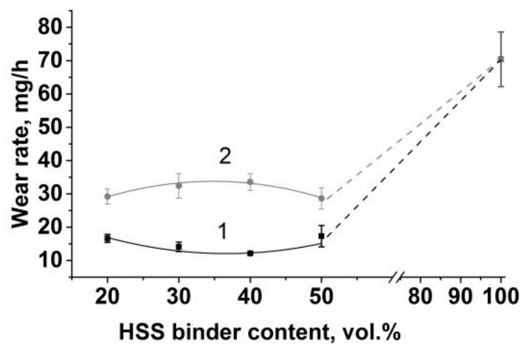

b)

Figure 1. Dependence of hardness (a) and wear rate (b) of coatings from HSS powder and powder mixtures with different content of steel binder in SHS compositie powders. The integral content of HSS in the powder mixtures is 80 vol. %. 1: - cladding with powders of 200-315 μm; 2: - cladding with powders of 125 - 200 μm.

The average hardness of coatings cladded with small-scale composite powders granules increases with increasing binder content (Figure 1a). A scatter in the coatings hardness values cladded with a large-scale powder is wider, than in coatings cladded with small-scale powder. It is interesting, that the hardness of the coating, deposited by the steel powder is approximately in the middle of the interval, in which the hardness of coatings cladded with composite powders varies. So it could be stated, that, due to the effect of self-hardening of HSS steel, the titanium carbide additive into HSS binder has little effect on the composite coatings hardness in contrast to its effect on abrasive wear resistance (Figure 1b). The wear resistance of coatings cladded by a small-scale composite powders is 2.3 times higher than the wear resistance of HSS coatings, and approximately 4.7 times higher for coatings cladded with large-scale powders.

The parallel grooves on the worn surface of the HSS surface (Figure 2a) points on the microcutting wear mechanism of the steel by sharp corundum particles with about 20 GPa hardness. Composite coatings wear mechanism is influenced by the rest granules in the composite coatings structure.

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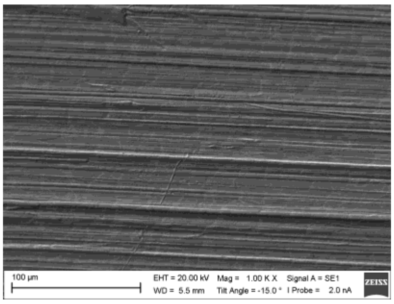

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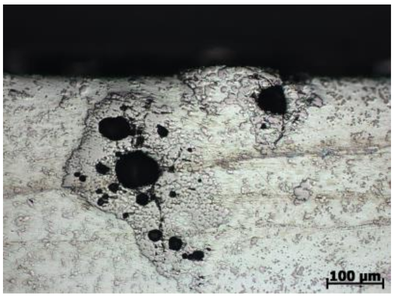

b)

Figure 2. Pictures of worn coating surfaces from HSS powder (a) and from composite powder TiC +20%HSS (b - side view).

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THE ADJOINT PROBLEM OF THERMAL CONDUCTIVITY OF HEATING A COMPOSITE MATERIAL FROM POWDER MIXTURES IN A CYLINDRICAL MOLD BY VARIOUS HEATING METHODS

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The Ni3Al intermetallic compound has a wide range of applications. Due to the properties of Ni3Al, such as high melting point, low density, high corrosion resistance and good high-temperature strength is the basis of modern high-temperature alloys [1]. Nickel aluminide also has good oxidation resistance. However, the use of Ni3Al is limited due to its low plasticity, the large difference between the melting points of Ni and Al, and the exothermic nature of the formation of this phase, which makes the synthesis process poorly controlled. Increasing the strength of an intermetallic compound is possible in several ways [2, 3]: for example, due to its doping with boron; plastic deformation; mechanical alloying with subsequent heat treatment, etc.

The most promising method for producing intermetallic compounds is the method of self-propagating high-temperature synthesis (SHS) [4, 5]. The basis of this method is heating the mixture of powders to a certain temperature, upon reaching which a spontaneous reaction occurs in the mode of combustion or thermal explosion. As the energy that promotes the initiation of the reaction, various types of heat sources are used [6, 7].

The paper proposed a conjugate problem of thermal conductivity for heating a composite material from powder mixtures in a cylindrical mold, depending on different types of heat sources. The problem of heating a steel cylindrical mold includes the heat equation for various materials (reactive mixture and walls of the mold). The model takes into account the heating of the reactor walls by various heat sources. Such sources are heating from the pistons, induction, volumetric (Joule), high-frequency heating, etc.

The results of a numerical study give an idea of the dynamics of heating the powder mixture in a cylindrical mold. It is shown that inhomogeneous temperature distribution in the compact is an important factor determining the dynamics of the process and the completeness of the transformation.

This work has been performed under the program of fundamental research project 23.2.2.

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PERSONALIZED APPROACH TO VISCERAL SKULL REGION CERAMICS OSTEOIMPLANTS MANUFACTURING

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The increase in the life duration and quality, the transition to the provision of reconstructive personalized medical care is one of the main directions of the Russian Federation scientific and technological development.

Oncological diseases are on the second place among of death and disability causes in the Russian Federation [1]. In most cases, timely-rendered medical care implies surgical intervention with a one-timereconstructive stage. In the case of bone tissue tumor lesion, the use of standard and serially produced osteosubstitution implants cannot always satisfy modern principles of reconstructive and plastic surgery, and sometimes involves a high risk of postoperative complications.

When the bones of the skull visceral region are affected, the aesthetic aspect of the prosthesis plays an important role: the anatomical geometry violation of the face leads to social and psychological disadaptation of patients. The solution in this case can be a personalized approach to the design of an osteoimplant based on the construction of a three-dimensional model of a bone tissue region planned for resection and its reproduction in a biologically compatible material by the additive production methods.

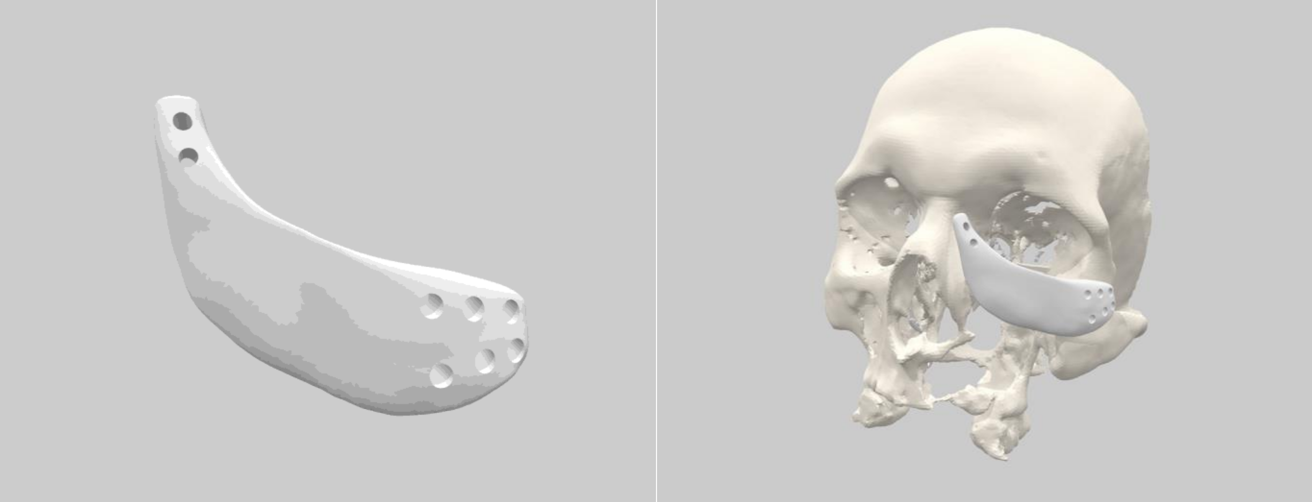
The successful osteosubstitution is determined not only by biochemical, but biomechanical compatibility of the prosthesis material with the bone tissue also. It is consisting in accordance strength parameters and structural identity. From the literature it is well known that for the providing of osteointegration processes the most preferable is the connected polymodal pore structure of the osteoimplant. The macropores play the role of niches for the pre-osteoblasts cell clusters proliferation, and the micropores - channels for the vascular system development [2,3]. At the same time, in the area of absence of contact in the implant-bone system, it is necessary to avoid the developed surface structure to prevent excessive development of soft tissue integration processes, which can negatively affect the muscular activity and mimicry.

At present, metal materials are widely used in osteo-prosthetics, but the high risk of metallosis and inflammatory reaction leaves the need for new solutions.

From the point of view of biochemical compatibility with body tissues, the most preferred material is oxide ceramics based on ZrO_2 and Al_2O_3 [4]. They have a similar to inorganic bone matrix type of chemical bonds and do not provide the electrochemical interaction with the body. However, the sintered ceramic material mechanical treatment is a high-tech task, which makes it impossible to fine-tune the serial ceramic osteo-implant for the needs of a particular patient in the clinic conditions.

Thus, the aim of this work is to develop an approach to the personalized osteoimplants based on oxide ceramics production. The personalized approach to the manufacture of osteoimplants allows to take into account the peculiarities of the individual structural state of the patient's prosthetic bone tissue and to minimize the resection area, which satisfies the principle of organ preservation.

The basis for creating a model of osteoimplant is a high resolution three-dimensional computer tomogram. The computer model of the endoprosthesis is constructed using modern CAD / CAM design systems. The main difficulty at this stage is to determine the bone matrix on the tomogram, excluding soft, fatty and cartilaginous tissues, Figure 1.



(a) (b)

Figure 1. Osteoimplant model (a). Comparison of the osteoimplant model with a three-dimensional computer tomogram of the skull visceral region (b).

The application of additive production technologies for the ceramic, in contrast to the traditional methods of compacting or injection molding, consists of layer-by-layer prototyping, which makes it possible to vary the structural parameters of the implant being created. Reproduction of the osteoimplant model in ceramic material using 3D prototyping technology allows specifying the ceramics pore space volume up to 70%, creating a bimodal pore structure with an average micropores size of 10 μm and a macropores of 100 μm.

By varying the technological parameters, it is possible to control the mechanical characteristics. The compressive strength can be from 20 to 200 MPa, depending on the structure of the prosthetic bone tissue. It will prevent the potential probability of the osteoimplant or bone tissue destruction in the contact area.

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SMALL-ANGLE ULTRASONIC TOMOGRAPHY WITH MILLS CROSS ARRAY FOR NDT: A SIMULATION STUDY

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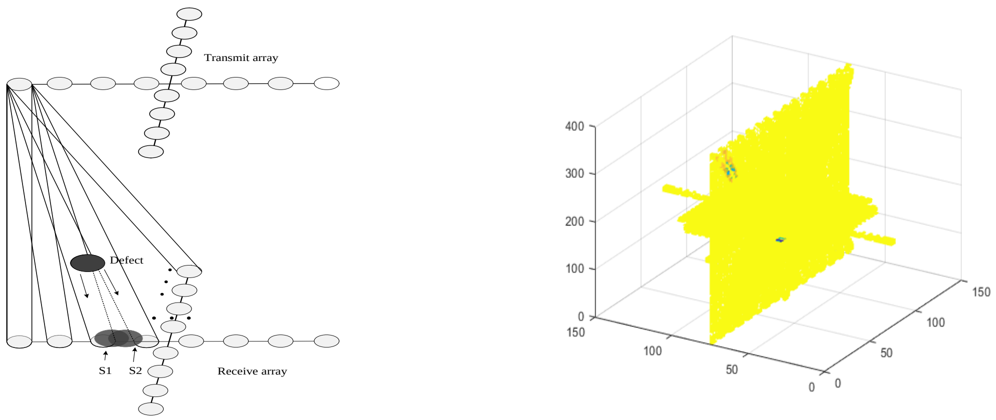
High attenuation and complex structures of some materials limit pulse-echo method inspecting engineered structures. Through-transition transmission method is particularly effective in the testing of highly attenuating and complex structured materials such as multi-layer composites, because it has a higher sensitivity noise immunity, deeper penetration depth and no dead area, in comparison with the pulse-echo reflection method. Traditional transmission method use one fixed transmitting and receiving transducer pair measurements, which make it impossible to determine the depth and shape of defects. Projections from different angles used to solve this problem, and anisotropy of acoustic impedance and shape of material limit large-angle tomography inspecting engineered structures. There are two methods of small-angle tomography are used to build two-dimensional model: mechanical scanning with two unfixed sensors and electronic scanning of with two linear arrays [1]. In order to build three-dimensional model quickly and efficiently, a new method, which use two Mills cross arrays is studied. Mills cross arrays consists of two vertical linear arrays. This method can worked in two modes: In two-dimensional scan, results that are more accurate obtained, in comparison with other methods; in three-dimensional scanning possibility to have a high-speed scanning. The disadvantages of this method - only can be used for the detection of materials with a fixed geometrical structure, complicacy control circuit, high cost of arrays, limited detection range and not necessarily more accurate test results in three-dimensional scanning.

On the basic of the Kirchhoff diffraction theory and the assumption of the existence of absolutely waves in a given acoustic path, it asserted that the diffraction integral in the shadow region very rapidly tends to zero. Thus, this digital model of the acoustic path is valid for the high-frequency case of the transmitting of the wavelength and the perimeter of the defect model [2]. In addition, it should be emphasized that the distance between the transmitter and the receiver is assumed sufficiently large. Consequently, the piezoelectric transducers composing antenna arrays are located in the Fraunhofer diffraction zone, and their working surface is much smaller than the first Fresnel zone. This makes it possible to consider the distribution of ultrasonic pressure on the elementary receiving element to be uniform, and the amplitude of the received signal of a directly proportional “sounded” surface. In addition, the size of elements is bigger than the wavelength of the sounds. Therefore, the shape and dimensions of each pair of transmitter-receiver acoustic path determine by the elements of the antenna arrays and the distance between the receiver and the transmitter.

A three-dimensional model of the acoustic path with the emitting and receiving arrays is shown in Fig1,a.



a) b)

Figure 1. (a) the acoustic paths of transmission method with Mills cross arrays; (b) result of simulation.

In this work, ignore diffraction, scattering and upper surface reflection. Each linear array consist of N same size round sensors with area S. The transmitters sequentially transmit the ultrasonic waves, and receivers receive signals in parallel. The projected area along the direction of the acoustic paths on the second receive transducer is S1 and on the third transducer is S2. The coefficients for image reconstruction are calculate in accordance with the formula:

$$k=A/A0 \quad (1)$$

Where A amplitude of received signal when there is defect in defected object, A0 signal amplitude received by the same sensor when there is not defect in defected object.

A defect in the model is simulated by a disc that is parallel to the x axis, and it is located in the testing zone with the coordinates X1, X2, Y. The defect supposed to be opaque. The defect attenuation depends on the overlap of radiation tape (Figure 2). Therefore, the transmission ratios are calculate in accordance with formula:

$$k = 1- Sm/S \quad (2)$$

Where Sm – the shadow area along the direction of the acoustic paths on the receive sensor, S – the sensor area. Due to the superposition effect, we can calculate and obtain the reconstruction of defect by back projecting data.

The shadow area along the direction of the pair of sensor path on its receiver Sm, then calculated coefficient k and assign the area covered by this acoustic path a value of k. Then sum all the path coverage areas to get the reconstructed image. Tomography reconstruction of defect showed on fig 1,b.

The paper describes a method of three-dimensional small-angle tomography for highly attenuation materials with Mills cross array. Due to the superposition effect, obtained the reconstruction of object by back projecting data, optimized simulation results by weight coefficient. Simulation results prove the theoretical feasibility of this method. However, the detection area is limited and the results are not accurate enough.

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NUMERICAL MODELING OF HEAT PROCESSES IN BIOLOGICAL TISSUE HEATED BY NANOPARTICLE

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One of the directions in modern medical physics is the development of minimally invasive methods of microsurgery. These methods imply minimal surgical intervention in the human body and allow reducing the degree of tissue trauma. In connection with the using of such methods the problem of the thermal and chemical processes arises. The solution of such problems is possible applying the interdisciplinary approaches. In particular, in [1] the problem of the action of a nanoparticle on biological tissue was solved. The paper presents the results of the research by a team of authors consisting of biologists, physicists and specialists in the field of computational mathematics. The results obtained in this work are devoted to the effect of gold nanoparticles and laser radiation on cancer cell cells.

We have solved the problem on the thermal interaction between a metal two-layer nanoparticle and a biological tissue. The aim of the research is to determine the heating characteristics of the tissue interacting with the bilayer nanoparticle heated by periodic laser radiation.

The particle is made of quartz and covered with a gold layer. The particle is in a biological tissue and is exposed to periodic laser radiation. The laser pulse heats the particle shell and the particle itself. The tissue medium is heated by heat exchange on the border of the biotissue-particle shell. The statement of the problem is based on [2], taking into account a two-layer particle structure and it is assumed that all the radiation from the laser is absorbed by the particle shell and the particle itself.

The mathematical model includes the heat equation in spherical coordinates for the quartz particle, the particle gold shell and the biotissue surrounding the particle. At the initial time, the temperature throughout the calculation area was constant and equal to the normal human temperature, T = 36.6 ° C.

The solution of the problem was carried out numerically with an implicit difference scheme using the sweep method. The movement of the isotherm $T = 44\,^oC$ along the biotissue was determined. It is believed that $T = 44\,^oC$ corresponds to the "thermal death" of the biotissue. The laser action period was set as the sum of laser action time and stopping time. The value of action time and the action-stopping time ratio ware varied in the calculation.

An analysis of the tissue heating rate which depends on the laser characteristics has showed that with an increase in the action time and in the laser pause, at the same ratio between the times, the medium warming up proceeds uniformly and it heats the faster the greater the increase. With an increase in the pause time and a fixed operating time of the laser, it is observed the heating with an oscillatory displacement of the isotherm $T = 44\,^oC$. The period of the oscillations is the greater the longer the time of laser pause.

The research was carried out by financial support the Russian Science Foundation (project No. 17-79-20011).

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ULTRASOUND DIAGNOSTICS OF DAMAGE OF THE METAL PRODUCTS OF ADDITIVE TECHNOLOGIES

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Introduction. To determine the resource properties of metal materials of additive production, it is necessary to analyze the sub -, micro - and macroscopic mechanisms of development of mechanisms of damage caused by external influences of different physical nature. Highly sensitive parameters of the evolution of the damage of materials are the characteristics of its elasticity (dynamic modulus of elasticity – DME) and inelasticity (internal friction – IF and damping capacity – DC). This allows them to be used as criteria or characteristics of damage.

The aim of the work is to improve the developed by the authors [1,2] methods of ultrasonic diagnostics (UD) of damage of cast and powder steels and alloys using hardware and software complex (HSC) by means of complex measurement in self – oscillating mode DME, DC and IF by means of engineering software (ES) in the ultrasonic frequency range. The based HSC - ultrasonic unit, and the mechanical oscillatory system with concentrator, resonator, piezoelectric sensors, and rigidly United with them sample.

Results. The authors have improved the complex of equipment and engineering software (ES) for the automated software complex (HSC) for testing and assessing the damage of materials of additive production in a wide range of loading cycles, by complex measurement in the self-oscillating mode of the characteristics of elasticity and inelasticity in the elastic-plastic region in the kHz frequency range [3-5]. The complex for fatigue testing and damage assessment of materials in a wide range of loading cycles consists of: resonant ultrasonic installation and hardware software. Computer control allows you to convert an electric (analog) signal to digital, and vice versa.

Methods. Purpose of HSC: a) setting and automatic control of electrical parameters of ultrasonic installation; b) collection, processing and display of measurement results of voltages, currents, frequencies on the elements of ultrasonic installation; C) calculation, display and registration in the archive log files of target characteristics (DC, IF, DME); d) automation of dynamic testing of samples at different frequencies and amplitudes of oscillations. Working conditions HSC. Hardware: a) computer (Pentium II 233 MHz; RAM 64 MB; the system bus PCI; the floppy disk and CD ROM; 4 GB HDD; I/o Board of discrete signals PCI-1753 of Advantech company); b) IPO includes: Windows 98 SE/XP; software development tool GeniDAQ V 4.11.001 of Advantech company with driver of input / output Board of discrete signals of Advantech PCI-1753; text editor for viewing log files; spreadsheets for processing of results of experiments.

Software environment HSC: APCS GeniDAQ V 4.11.001 company Advantech, consisting of modules: GeniDAQ Builder and GeniDAQ Runtime. Agribusiness is a well-established strategy. Structure of HSC: auto-generated main control script; the three tasks in the environment of the Task Designer; seven display forms in the Display environment Designe. ES HSC implements algorithms: secure the AFC; automatic search of the resonance frequency; measuring the amplitude dependencies; of the fatigue tests; automatic tracking of the resonance frequency shift; communication HSC with other programs.

Summary. The development and use of equipment and ES in HSC for operation in self-oscillating mode (measurement and registration of parameters proportional to the input and scattered power), allowed to turn the ultrasonic device into a fully automated device controlled by a computer. This made it possible to study the processes that control damage in structural materials by complex measurement on a single sample in a wide range of deformation amplitudes of the true value of internal friction, damping capacity, dynamic modulus of elasticity. The development and use of ES for ultrasonic testing has significantly improved the accuracy and informativeness of the measurement results by significantly reducing the time step of the experiment. It allows to use the whole complex for measurements of standard reference data of measured parameters of Rosstandart. The inclusion in the HSC of additional modern equipment makes it possible to conduct impact tests, which significantly increases the amount of information about the material of the tested samples.

Gratitudes. The work was carried out within the framework of the Federal program «Research and development in priority areas of development of the scientific and technological complex of Russia for 2014-2020" on the theme "development of a prototype of ES based on high-performance computing to assess the mechanical characteristics of products produced using additive technologies (selective laser sintering) based on the manufacturing strategy» (unique project identifier RFMEFI57717X0271).

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NUMERICAL INVESTIGATION OF THE INFLUENCE OF THE COMPOSITION OF A THREE-COMPONENT POWDER MIXTURE ON A SHS COMPOSITE MATERIAL

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Self-propagating high-temperature synthesis (SHS) is the simplest and low energy consumption method of materials production including triple composites based on titanium. However, this process is nonequilibrium one and the not always given stoichiometric composition of the powder mixture contribute to the production of the synthesized composite of the desired composition in the SHS process. Therefore, the purpose of this work is to develop and study a model for the synthesis of composite materials in a Ti-Al-C powder mixture by SHS mode.

The mathematical model of the process of initiation of the reaction in a powder mixture is considered. The sample is a cylinder of radius *R* consisting of two layers of pressing powders (figure). Let the temperature with respect to the diameter of the samples is uniform; the igniter and ignition mixture are gas-free. The layer 1 (igniter) is supposed to be a stoichiometric mixture of Ti and Si powders, the thickness of the fill is *l* (i.e., η_{01} (Ti) = 73.9 wt%, η_{02} (Si) = 26.1 wt% or Ti/Si = 5/3 in at%), which corresponds to the reaction

$$\text{I) } 5Ti + 3Si = Ti_5Si_3.$$

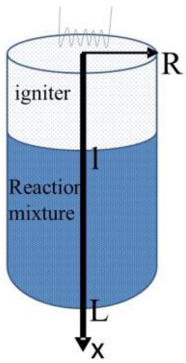

Figure 1. Scheme of process

The second layer (reaction mixture) has thickness *L* and it consists of the mixture of titanium, carbon and aluminum powders. From the analysis of the experimental works devoted to investigation of the phase composition of materials obtained by SHS in the Ti-Al-C ternary systems and in accordance with the phase diagram of the Ti-C, Ti-Al, Al-C, Ti-Al-C systems, a system of chemical reactions for second layer includes 8 reactions:

II) $Ti+C\rightarrow TiC$, III) $Ti+Al\rightarrow TiAl$, IV) $TiAl+TiC\rightarrow Ti_2AlC$, V) $2Ti+Al+C\rightarrow Ti_2AlC$,
VI) $Ti+3Al\rightarrow TiAl_3$, VII) $3Ti+Al\rightarrow Ti_3Al$, VIII) $Ti+TiC\rightarrow Ti_2C$, IX) $3Ti+Al+2C\rightarrow Ti_3AlC_2$.

In the energy equation, the heat losses to the environment due to convection and due to thermal radiation are assumed. The kinetic equation for concentration of phases corresponding to the reaction with strong retardation of layer reaction product is considered. The melting of the component (reactants) is taken into account by changing the effective heat capacity and density in the vicinity of the melting temperature.

Since the structure of the powder system is changing and unknown at any time, the rule of the mixture to calculate the effective properties of initial substance and synthesized composite is used. To evaluate the porosity change, the relation obtained in the sintering theory for the case of the action only capillary forces is used.

The suggested model made it possible to explain the phenomena observed in the experiment. The character of the influence of the composition of the initial regents and the initial heating of the reaction mixture on the phase formation during solid-phase synthesis was showed in work. The calculations shown that an increase in the initial temperature of the reaction mixture from 300 to 500 K leads to an increase in the concentration of the Ti_2AlC phase and a decrease in the mass fraction of the Ti_3AlC_2 and TiC phases, regardless of the composition of the initial powder mixture. A good agreement between the calculated and experimental data suggests that the model can provide useful recommendations for solid-phase synthesis of composites of a given composition from a three-component powder mixture.

The work is supported by Russian Science Foundation (RSF), grunt number 17-19-01425

INFLUENCE OF HYDROXYAPATITE FILLING DEGREE ON MECHANICAL PROPERTIES OF 3D-PRINTED POLY(L-LACTIC ACID)-BASED IMPLANTABLE MATERIAL[1]

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Synthesis of new biodegradable materials is one of the most promising area of reconstructive and regenerative orthopedy development. The implant made of biodegradable material serves as a temporary scaffold in the process of new tissues growth and fully dissolves during osteosynthesis [1]. Poly(L-lactic acid) (PLLA) is highly attractive polymer for biodegradable implants fabrication due to its ability to degrade to non-toxic lactic acid monomers [2]. However, poor mechanical and bioactive properties restrict applying of PLLA as a material for orthopedic implants [3]. In this research biological mineral hydroxyapatite (HAp) was used to obtain biodegradable PLLA-based composite with enhanced mechanical and bioactive properties.

Composites were produced from PLLA and biological HAp at different wt.% HAp content (12.5, 25, 50 wt.%). To produce PLLA-HAp filaments, PLLA pellets were dissolved in chloroform and mixed with HAp powder, then composite mixtures were granulated and extruded through 1.75 mm nozzle. In addition, 100% PLLA filament was prepared for printing control samples. Samples were obtained using FDM 3D-printing technology. Samples were divided into two groups, and then samples from one of the groups were annealed at 110˚C for 12 hours to increase PLLA matrix crystallinity degree.

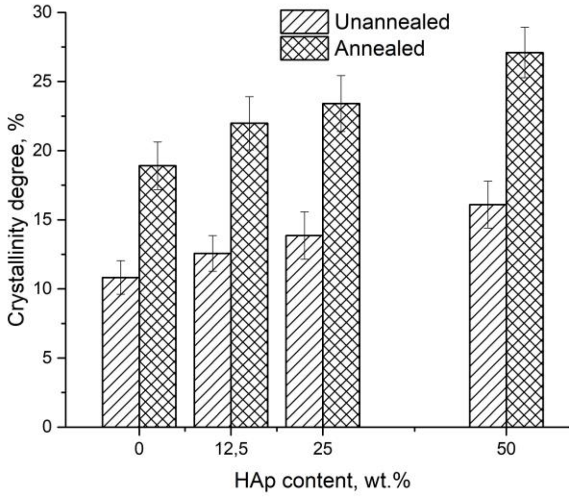

Figure 1. PLLA-matrix crystallinity

According to the XRD data, crystallinity degree was increasing from 10.83 ± 1.21% for pure PLLA to 16 ± 1.69% for composite with 50 wt.% of HAp (Fig.1). After annealing crystallinity increased by 9.51 ± 0.39% at the average for all materials.

Results of mechanical tests show the growth of Young's modulus of composites with an increasing of HAp content (Fig.2). The maximum elastic modulus value of 9.4 ± 0.71 GPa was reached for annealed composite with 50 wt.% content of HAp. Furthermore, the decrease in the samples deformation during the crystallization was observed with increasing of HAp amount. The deformation decreased from 8.3% to 1.86% with an increase of HAp amount in the polymer matrix from 12.5% to 50%.

[1] This work was financially supported by the Ministry of Education and Science of the Russian Federation, Federal Target Program (agreement # 14.575.21.0140, unique identifier RFMEF157517X0140).

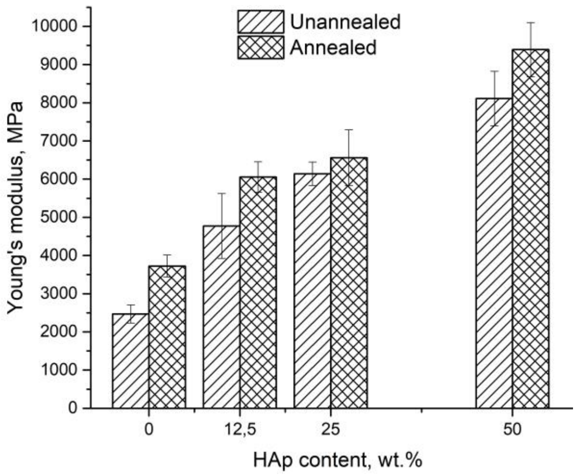

Figure 2. Young's modulus of obtained materials

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MODELING OF THE INKJET PRINTING AND PRINTING OF ORGANIC SEMICONDUCTOR MATERIALS

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Printing technologies provide great opportunities for rapid and low-cost technology of electronic devices. Ink-jet printing technology is especially useful for creation of individual devices. There are no requirements for shadow masks or stencil-plates as in the case of thermal vacuum evaporation, photolithography or screen printing. Solutions of organic polymeric semiconductor materials are the most interesting for printing because they may be used for creation of organic electronic devices. There are special requirements (viscosity, surface tension, particle size, pH) for inks used for inkjet printing. At the same time, inkjet printing process requires careful adoption of operating modes of the printer heads for different inks. Computer experiment allows facilitate this work, and helps to understand how different parameters affect the process of droplet formation. Therefore, the aim of this work is to simulate the process of inkjet printing of organic materials based on semiconducting polymers and choose operation modes.

Simulation was carried out in the specially designed program. Printing was performed on the inkjet DOD printer Dimatix DMP-2831 (Fujifilm), rheological characteristics were determined with rheometer DVT3T-LV+CP (Brookfield) and surface tension – with DSA 25E (Kruss).

Simulation of acoustic response of the inks driven by pulse in pump chamber of print head was carried out. It was shown the dependence of maximum printing frequency as function of viscosity, density and sound velocity in the medium. Low viscosity polymer solutions can also be used for inkjet printing, but with limitations on printing frequency and with a special driving pulse shape. In the modeling it is necessary to take into account the density, viscosity, surface tension and velocity of sound propagation in the medium. Organic inks based on semiconductor polymeric solutions satisfied for print-head requirements were created.

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USING SOIL CONCRETE IN 3D PRINTING

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Construction 3D printing (3DCP) is one of the developing branches of additive technology. Main differences from other 3D printing technologies are a large size of printed object, it's solidity, durability in different climate conditions, relatively low accuracy requirements.

Cement based soil concrete is known, but rarely used construction material for buildings. It has serious disadvantages that make it impracticable for classical building technologies, but also it has some useful properties that make it suitable for 3D printing process. The objective of the research is to show a possibility to print arches and domes with at least 45 degrees overhang (which is hardly achievable for Contour Crafting) using cement based soil concrete as material. To reach this goal several concrete composition was tested, then suitable 3D printer and printhead was made and printing process implemented.

The main useful property of a soil concrete is it's plasticity (rheological model of Bingham fluid can be used) during first several minutes it was mixed with a water. Fortunately the plasticity allows to implement DIW (direct ink writing) printing method and reach whole specter of a geometry could be printed with clay. Unfortunately it is impossible to use common DIW extruder types because of short lifetime of a fresh mixed printing media, so the special hardware have to be designed.

To implement a soil concrete 3D printing process there should be an extruder, that is a mixer also, so we could mix a dry component powder with a water (or another fluid) continuously, following right proportions, and extrude it as soon as possible before rheological properties of mixture gone unsatisfactory. The possibility to make relatively small and lightweight suitable hardware caused by the fact, that a mixing of fluid and powder in small volume is significantly affected by capillary suction, so there is no lengthy and intensive mechanical mixing needed.

The article contains several qualitative statements about using a soil concrete as a material for 3DCP and it's experimental approvement, also it contains some quantitative characteristics of print media that is suitable for 3D printing.

The result of research is a 3D printed dome with 45 degrees overhang, that means it's possible to use a cement based soil concrete to print such kind of geometry.

ON THE STRUCTURE OF INTERGRANULAR AND INTERPHASE LARGE-ANGLE BOUNDARIES AND THEIR CONTRIBUTION TO THE HIGH DEFORMATION ABILITY OF HIGH-ALLOY METAL HETEROPHASE SYSTEMS

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Introduction. At the present time, there are a number of hypotheses linking the structure of the large-angle boundaries with the processes occurring in their individual sections when interacting with intragranular defects and their clusters. Considering the importance of this issue in the processes of plastic form changing and non-stationary thermomechanical deformation of complex alloyed heterophase metal systems (pure metals, steels, non-ferrous alloys, etc.), let us consider these hypotheses in more detail. The hypothesis developed in the works is the most common. It assumes the structure of the large-angle boundary as the Mott boundary, consisting of alternating sections with a dislocation structure in places with a low disorientation of the lattices of neighboring grains and areas with an amorphous structure where the disorientation is large.

Methods. Method of high-resolution electron microscopy, method of X-ray analysis, method of electronic fractography.

Results and discussions. Amorphous regions easily provide annihilation of dislocations in the head of the aggregates serving as stoppers for grain boundary sliding (GBS), which occurs only when the grain boundary dislocations slip along relatively straight sections of the grain boundaries oriented in the direction of the vector of the maximum tangential strains. If the clusters abut the sections of the boundaries with a dislocation structure, there are two possible options for removing the stoppers either by climbing of the head dislocation into the neighboring extraplane or passing it to the boundary, depending on the misorientation angle, the excessive concentration of vacancies and the magnitude of the strain in the head of the cluster, or by forming clusters with an amorphous structure formed from clusters of partial dislocations with excess vacancies or vacancy loops that are excessively formed in superplastic deformation (SD). On sections with an amorphous structure, GBS occurs by the mechanism of viscous Newtonian flow. These processes develop especially intensively in places where the boundaries of adjacent grains converge and lead to a gradual rotation of grains in the direction favorable in orientation to the action vector of the maximum tangential strain and an increase in the number of such grains. This is the sequence of the general process of grains accommodation under SD. Another hypothesis assigns the main role in the accommodation of grains under SD to the development of micromigration processes of grain boundaries to the gradual rotation of grains and the propagation of GBS to the entire volume of the tensile sample.

Conclusions. It has been calculated that, for alloys with a crystal structure, the activation SD energy under structural superplasticity slightly exceeds the activation energy of self-diffusion of the base atoms over the large-angle boundaries, but it is considerably less than the activation energy of bulk self-diffusion, and in phase superplasticity it has even lower values and depends on the dispersion of structural and phase components, which indicates a significant contribution to GBS of boundaries between the phases. The SD activation energy in amorphous alloys corresponds to the activation energy values of the Newtonian viscous flow, and the larger the value of the glass transition temperature ratio to the alloys melting temperature, the higher it is. This determines the high resource of deformation ability of alloys.

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SYNTHESIS OF SURFACE ALLOY ON THE BASIS OF ALUMINUM IN COMBINED ELECTRON-ION PLASMA TECHNOLOGIES

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The purpose of the study is the development of a combined electron-ion-plasma method for the formation of a surface alloy based on aluminum in conditions of combined technologies.

As the basis material technically pure aluminum A7 grade was used. The formation of the surface alloy was carried out in a single vacuum cycle at the "COMPLEX" setup by deposition of 0.5 μm thick titanium film and subsequent irradiation with an intense pulsed electron beam in the aluminum melting mode. Number of deposition/irradiation cycles is 20. At the final stage, the nitriding of the formed surface alloy in a low-pressure gas discharge plasma was carried out. Investigations of the elemental and phase composition, the state of the defective substructure were carried out by scanning and electron diffraction microscopy, X-ray diffraction analysis. The material properties were characterized by hardness, wear resistance and coefficient of friction.

It is established that as a result of the performed multicyclic processing a modified layer with a thickness of up to 18 μm has a submicro-nanocrystalline multiphase multielement structure, the characteristic image of which is shown in Fig. 1.

It is shown that the modified layer is multiphase: α-Ti (5.24 mass. %), Al_3Ti (58.43 mass. %), AlN (36.33 mass. %).

It was found that the hardness of the formed layer exceeds the hardness of the initial material by more than 9 times, the wear resistance is more than 450 times, the friction coefficient is less than 3.5 times.

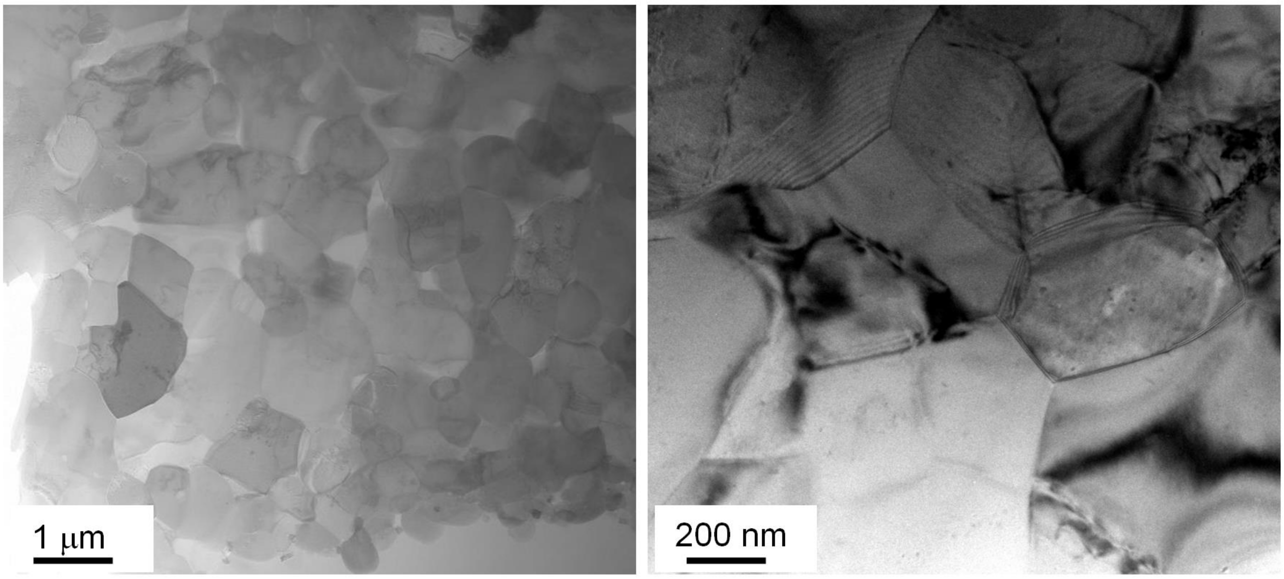

Figure 1. Electron microscopic image of the structure of the Al-Ti-N alloy formed by a combined electron-ion-plasma method in a single vacuum cycle

Conclusion. The method of electron-ion-plasma formation in a single vacuum cycle of a multiphase alloy of Al-Ti-N system, the mechanical and tribological properties of which repeatedly exceed the properties of the commercially pure aluminum of A7 grade, has been developed.

DEVELOPMENT OF EQUIPMENT COMPLEX FOR ADDITIVE PRODUCTION

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Improving the efficiency of production activities is the creation of complexes of technological, transport, energy and information machines based on new additive technologies, nanotechnology and improving the performance of the already used.

Currently, a new era of production is emerging - mass customization, characterized by the fact that the consumer acts as a designer and engineer. Now, at the request of the consumer, you can directly monitor and control, as well as change the production process.

As a result, in the system analysis of the growth of the efficiency of technological complexes, it is necessary to count not only the specific technological labor intensity (cost price) per product, but also the costs throughout the product life cycle, especially related to its customized marketing, design, operation, utilization and reduction of various logistic supplies.

Production and targeted delivery of a customized product, taking into account the external and internal logistics of the enterprise (including virtual), can be supplemented with the future stages with a forecast for the future, which is often associated with the new paradigm of intellectual production called «Industry 4.0». This term was proposed by German companies at the Hannover Technology Exhibition in 2011 to mark the beginning of the “era of the fourth industrial revolution” associated with the industrial Internet of things (IIoT - Industrial Internet of Things).

The development of technological complexes begins with an analysis of the concept of a mechatronic system having two control loops, through direct communication with the external environment and feedback on the results of diagnostics of the state of the control object.

The choice of energy flows and materials for the layer-by-layer synthesis of the product is carried out depending on the properties of the materials or their compositions, the geometric characteristics of the surfaces, and their accuracy. At the same time, special attention is paid to the focusing or distribution of flows in space and time.

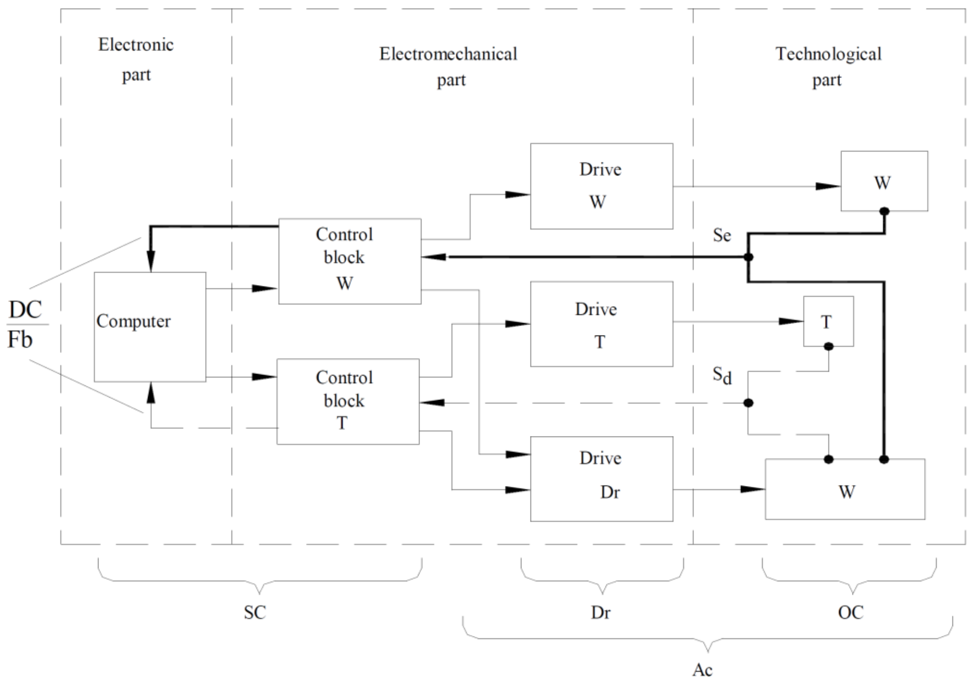
Mechatronic technological complex implements a direct connection in controlling the flow of energy or material synthesizing the product in layers, and feedback on the state of the formed layer or the surface of the formed product (Fig. 1).

The choice of sources for cutting equipment is determined by both the thickness and the material of the sheet blanks, and the processing accuracy. A graph of tuples of various types of processing of the designed technological equipment is considered and the imposed connections are analyzed: mechanical and electrical (drives and sources), electronic and software (controls and controls) in the mechatronic system. As a result, the source drive is implemented as a multi-axis manipulator, and the complex itself and its equipment are a mechatronic technological system (Fig. 2).

This technological complex allows both cutting and subsequent layer-by-layer sheet assembly of the finished product by welding along the contour with a plasma welding head of the Kjellberg company (Fig. 3).

Thus, the analysis of the current state and prospects for the development of additive technologies of computerized production allows us to speak about a new paradigm in its evolution – «Industry 4.0».

As a result, the concept of a “digital factory” is formed and detailed, in which additive and nanotechnologies are the decisive element of the system, including advanced subsystems: 3D design and production and consumption management, starting from modeling a product, its materials and components in accordance with new technological capabilities and ending with the receipt and operation of a functionally oriented customized product.



W – workpiece;
T – tool;
E – concentrated energy source;
Sd – displacement sensor;
Se – energy flow sensor;
SC – control system;
Dr – drives;
OC – control object;
Ac – actuators;
DC – direct connection;
Fb – feedback

Figure 1. Block diagram of the mechatronic system

Figure 2. Technological complex of plasma cutting material with a manipulator for cutting and cutting the edges of the workpieces at an angle

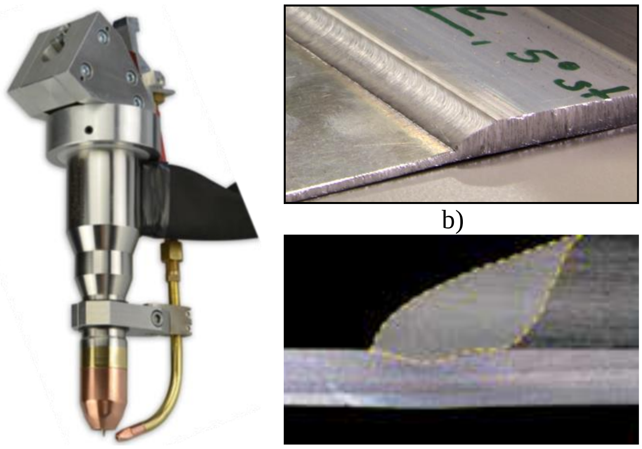


Figure 3. Equipment for plasma welding: a) Kjellberg welding head; b) layer-by-layer welding of the product; c) welding section (information from www.kjellberg.de)

THERMAL PHYSICAL MODEL OF COMPOSITE CREATION IN LOM TECHNOLOGY

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Modern additive manufacturing (AM) processes can be classified into seven categories: Powder Bed Fusion, Material Jetting, Directed Energy Deposition, Binder Jetting, Material Extrusion, Vat Photopolymerization and Shit Lamination. Laminated object manufacturing (LOM) and ultrasonic additive manufacturing (UAM) are the two main categories of the sheet lamination processes. In these, material sheets are either cut by using laser or combined by using ultrasound. In turn, LOM can be further classified based on the bonding mechanism between the sheets. Initially LOM-process was developed to produce the parts from paper at the low temperature and without explicit chemical reactions. Then the basic idea was disseminated to other green materials, when sheets can be joined by intermediate layers due to diffusion, filtration, and chemical reactions. Today LOM – process belongs to the quickly developing technique for metal and ceramic layered composite production. In this paper the model is suggested to investigate physical-chemical conversions in adhesive layer between conjugated layers with different properties during LOM-process. Adhesive bonding layer is used, for example, during one of way of ceramic formation from pre-ceramic paper sheets [1].

It was detected that reaction can starts in form of thermal explosion in spite of low energetic parameters and in the form of slow accumulation of the reaction product. This depends on contact area size of roll and synthesized composite, roll velocity and temperature.

Generally, ceramic paper formation consists of several separate stages [1,2], each of which is accompanied by physical-chemical conversions that affect the properties of final product. These are the stage of paper formation from green suspension containing fibers, fillers, retention aids and binder; the stage of conversion of pre-ceramic paper that could be organized by various ways depending on find of fillers and the desired composition of final products; the stages of sintering, infiltration, and certainly laser cutting. Using described above approach one can to predict the possible mode of structure and composition formation. Detailed chemistry could be taken into account similarly to [3]. Some results were published in [4].

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FEATURES OF THE BEHAVIOR OF TI-SI POWDER MATERIALS DURING SINTERING

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In the last decade, technologies associated with the formation of complex multilevel heterogeneous and heterophase structures in materials and structures have received intensive development. Studies show that such structures provide the most preferred functional properties. Multicomponent metal-matrix composites (MMC), which include refractory compounds such as carbides, silicides, borides, etc., cause the greatest interest. Their use provides high physico-mechanical, chemical and tribological properties. Using different methods of obtaining the MMC from the same elements, it is possible to form a structure of a composite material with different characteristics. As a rule, powder mixtures of titanium, silicon, boron, and carbon are used as precursors of the metal-matrix composite. This can be either a mixture of elemental (monocomponent) powders, or a mixture with powders of ready-made refractory compounds. Among the technological processes of powder metallurgy, the self-propagating high-temperature synthesis (SHS) of multicomponent powder mixtures has received the widest use. As a result of SHS, a metal matrix structure can be formed with refractory solid phases formed directly in the synthesis process. The main condition in this case is the concentration of components, which provides exothermic reactions for the formation of simple or complex compounds (carbides, borides, silicides, intermetallic compounds) depending on the selected elemental composition of the powder mixture.

Production of metal-matrix composites based on titanium-refractory element systems from among Si, C or B by traditional sintering from mixtures of elemental powders comes up against difficulties associated with large volume growth due to the formation of a rigid framework from their compounds accompanied by significant heat generation. In order to reduce volumetric growth and obtain an acceptable porosity of the sintered material, the powder of the second component can be replaced by the powder of its refractory compound Ti_mA_n, which will make it possible to go from uncontrolled liquid-phase sintering to solid-phase sintering.

Additional interest in the presented materials is caused by the prospect of using them in additive technologies. In this case, a number of questions arise related to the behavior of metal matrix compositions under conditions of additional thermal processes (various types of surfacing, sintering, etc.), including the question of the stability or degree of transformation of a heterogeneous structure under such external influence.

The use of hardening additives in mixtures of powders or the synthesis of metal matrix structure directly in the process of product formation face additional problems that can be associated with a number of physicochemical characteristics of materials (wettability, different melting points and coefficients of thermal expansion, etc.). The use of synthesized composite powders with an already formed structure instead of mechanical mixtures makes it possible to eliminate segregation (separation) of powder components. At the same time, the microstructure and phase composition of the composite powder upon thermal exposure during the fusion process may change significantly. From the point of view of the additive production of products and parts, the process of layer-by-layer melting or “sintering” of composite powder materials plays an important role. In connection with this, it is of interest to study the behavior of metal-matrix powder composites under vacuum sintering conditions for various combinations of components.

CALCULATION OF THE SPEED OF GASLESS COMBUSTION OF MULTILAYER BIMETALLIC NANOFILMS

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To apply a technology of gas-free combustion in various technical applications, it is important to know the regimes and propagation velocity of the gas-free combustion wave. Accounting for the heterogeneity of the structure and using the reaction cells models to simulate a nonstationary gas-free combustion allow predicting the combustion regime and the velocity of gas-free combustion depending on the size and shape of the heterogeneous structure of the samples. The multilayer metal nanofilms capable of chemical reaction are created to obtain a high propagation velocity of the gas-free combustion wave [1, 2]. The created bimetallic multilayer nanofilms under the action of high-temperature sources on the boundary are ignited and the SHS process proceeds in the combustion propagation mode along the film.

The aim of the research is to study nonstationary regimes of gas-free combustion using the model of reaction cells and without the kinetic functions. The research is based on the physico-mathematical formulation of the problem [3], written in non-stationary form. In the mathematical model for the combustion front propagation of the SHS composition, the chemical reaction rate at each point along the length of the SHS sample is determined by the solution of the diffusion and chemical reaction problem in the reaction cells, the diffusion of the reactants through the product layer and the temperature dependence of the diffusion coefficient are taken into account. In each element of the heterogeneous structure of the SHS composition, diffusion and reaction processes take place at its own cell temperature, which varies in time during the reaction. It is assumed that there is no spatial temperature distribution in the reaction cells.

The model of nonstationary gas-free combustion of multilayer bimetallic nanofilms is formulated taking into account the heterogeneity of the structure and the dependence of diffusion on temperature using an approach of planar reaction cells. We have carried out the numerical simulation of the combustion wave propagation along bimetallic multilayer nanofilms. The dependences of the burning rate on the characteristic size of the heterogeneous sample structure are obtained. The calculated theoretical values of the wave propagation velocity coincide with good accuracy with experimental data over a wide range of the heterogeneous structure sizes of the SHS composition.

The research was carried out by financial support the Russian Science Foundation (project No. 17-79-20011).

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INVESTIGATION OF ADDITIVE MANUFACTURING OF PARTS FROM MECHANICALLY ACTIVATED POWDER

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Composite materials with the structure consisted of disperse solid particles enclosed into a metal matrix (binder) are well-known to have a unique combination of hardness, strength, elasticity and wear resistance under abrasive wear and in tribological conjunctions [1, 2]. A specific example of such materials is tool hard alloys produced by sintering of disperse carbides and metal binder powder mixtures [3]. Moreover, the physical and mechanical properties and durability of composite materials are better-known to be primarily determined by the structure [3-5] (volume fraction, dispersion, and morphology of the strengthening phase).

Additive technologies allow you to create products of complex shape for a single technological cycle. The possibilities of additive technologies are much wider than those of classical technologies, but there is a very small list of materials on a metal base suitable for additive production. Technically, the technology of additive production of metal products is close to the technology of powder cladding or sputtering which are widely used [6-12].

In the present work, the structure of products obtained by Selective laser melting (SLM) and Electron beam melting (EBM) technologies using "TiC - Ti" composite powder has been studied. The composite powder was preliminarily mechanically activated in a high-energy ball mill of the planetary type in order to grind the structure of the powders. In addition, technological features of powder preparation and additive production processes are also described.

The MA process of powders was carried out in the planetary ball mill "Activator-2S". Composition of the initial composite powder "TiC + 50 vol. % Ti", additionally titanium was added to the charge to the total content of the titanium binder of 80 vol. %. The main task was not only to grind the carbide particles in the powder, but also the powder as a whole. The MA process was carried out at a drum rotation frequency of 960 rpm, a powder loading of 50 g, a "powder : ball" ratio was 1 : 1. The MA was carried out for various times in steps of 10 minutes up to 60 minutes, with a study of the fractional composition in each case.

It was found that after 30 minutes of MA the largest amount of fine powder is observed, in the future the powder adheres to powder particles exceeding the original size. A metallographic study of the composite powder was carried out after grinding for 30 minutes. After mechanical activation, it is possible to achieve an even distribution of carbide particles (light) in the titanium matrix (dark). In some particles of the powder, an increased amount of carbide particles is observed in the center and reduced in the periphery, but in general the distribution is uniform. Also, it is possible to effectively reduce the size of the carbide particles in the powder, but the powder particles themselves are not crushed. It should be noted that the shape of the powder after MA is close to spherical, which is important for the use of powder in additive technologies.

The obtained powder was used in laser and electron-beam melting technologies on the equipment of Tomsk Polytechnic University. Laser melting was carried out under the following operating conditions of 3D printer: radiation power is 200 W; scanning speed is 0.03 m/s; typical beam diameter at the sample surface is 200 μm; hatching is 150 μm; powder layer thickness is 100 μm; pressure of an inert gas (argon) in the chamber is 1.5 atm.; working area preheating temperature is 300 ° C. Electron beam melting operating conditions are the same with the exception of the pressure in the chamber and preheating - the EBM process was carried out in vacuum under pressure 5 · 10-3 Pa and preheating was performed using a defocused electron beam to a temperature of 700 - 800 ° C on each powder layer.

These operating conditions were selected in such a way as to ensure high homogeneity of the obtained samples in both technologies, while ensuring the equality of energy contributions to the surface of the powder. For this purpose, the area of high-energy beams, their speed of movement and effective power were the same.

Despite the proximity of energy inputs for the preparation of samples by different methods, the structure of the samples obtained differs. Carbide particles in the samples obtained by SLS have a shallower and disordered structure, whereas in EBM samples a dendritic structure up to the third order is formed in carbides. Presumably, this difference is associated with faster crystallization, which takes place in the process of selective laser melting, since to ensure sintering of the powder in EBM technology, it is assumed that the working region of the sample growth is continuously heated to a temperature of 700 - 800 ° C.

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TWO-SCALE SIMULATION OF PULSE SELECTIVE LASER MELTING

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Pulse selective laser melting of metals belongs to a complex phenomenon where melting, transport processes, and solidification proceed in a local volume over a very short period of time. Practically speaking, direct *in situ* experimental observation is limited by measurements of the pool temperature and shape. Phase analysis of the samples provides the additional information about microstructure and pore distribution. Therefore, study of correlation between processing parameters can be efficiently done only in combination of experimental and simulation tests.

A two-scale approach to simulation of transport phenomena in pulse selective laser melting of metals has been developed. It relays on the classical idea of splitting based on the characteristic time and spatial scales of transport phenomena. Although laser resolidification or ablation of the metal surface was analyzed in literature before, the novelty of this work is due to its application to the state-of-art technical problems in additive manufacturing. The developed two-scale method allows improving the accuracy of simulations to get better agreement with experimental data.

The following algorithm is suggested, Figure 1.

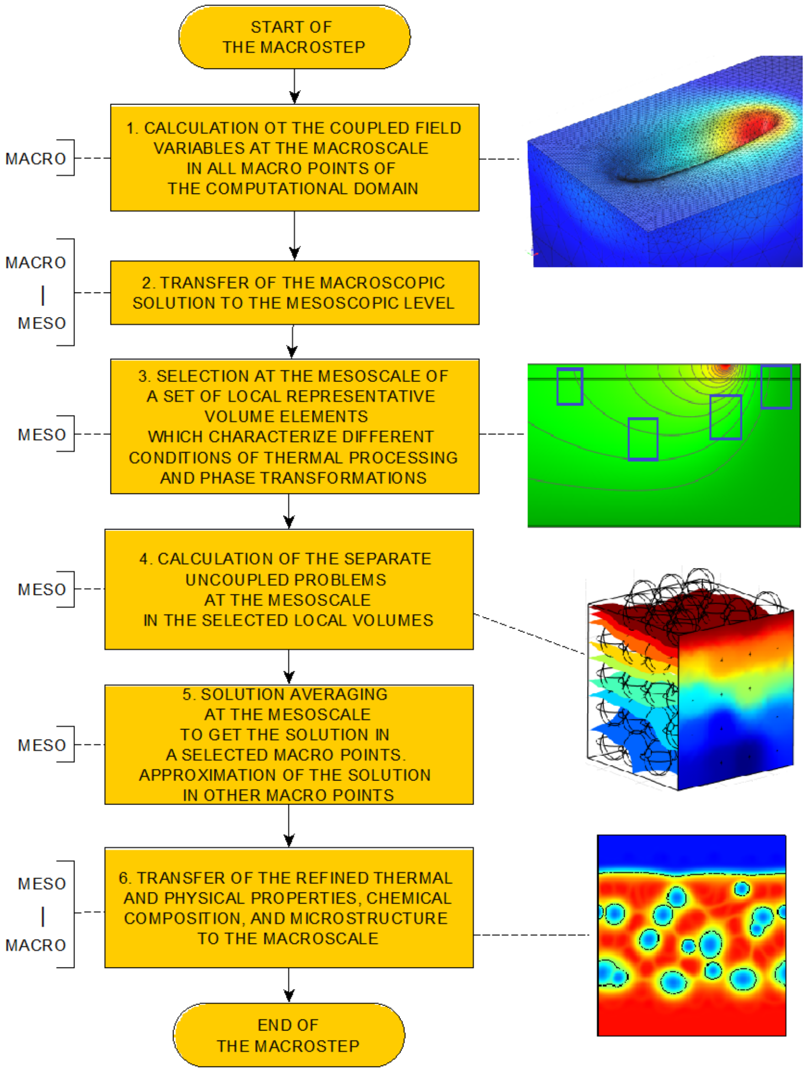

Figure 1. Algorithm of coupling between the macroscopic and mesoscopic levels used for integration of the solution in time.

At the macroscopic level, the coupled equations for temperature, enthalpy, porosity and coordinate of the layer surface are solved. Then these data are transferred to the mesoscale level. At the mesoscale level, study of local effects is performed. It includes determination of the effective thermophysical properties, powder consolidation, and solute redistribution. Since the mesoscopic processes are local and have a small correlation length at the macroscale, they can be solved as uncoupled problems. From the mesoscale to macroscale levels the constraint equations, kinetic and thermodynamic parameters are transferred back for more accurate definition of the macroscopic equations. There are the effective thermal conductivity, parameters of the consolidation model, and chemical segregation factor. Since the mesoscale problems are solved only in a limited set of volumes selected in different parts of the layer, it is required to conjugate and extrapolate the mesoscopic solutions at the macroscopic scale.

Main features of pulse selective melting have been studied in a series of computational and laboratory experiments. The comparison yields fair agreement in the porosity distribution. The differences are found in the shape and size of the solidified track. The obtained results and critically evaluated and explained.

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SIMULATION OF PHASE COMPOSITION EVOLUTION DURING ELECTRON-BEAM SYNTHESIS OF COMPOSITE COATING

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The creation of coatings and articles by laser technologies from metal powders forming intermetallic phases is described. For example, in [1-3]. Another way to produce intermetallic coatings can be initiation of chemical reactions in the layer preliminary deposited on a substrate using electron beam. The use of electron beam (EB) energy has proven itself in a wide range of technological applications [4,5]. Preliminary studies with the use of initial materials in the form of powder mixtures and composite wires from Ti-Ni, Ni-Al and Al-Ti [4] have shown that EB technologies enable a smooth transition of composition, chemical element distribution and mechanical characteristics from the deposited layer to the substrate.

Current work contains the mathematical model of coating composition formation under electron beam (EB) action with regard to staging of chemical conversion. The model was realized numerically for the Ni-Al, Ti-Ni , Ti-Al and Ti-Al-C systems (extensively studied in SLS and SLM and used for the development of new alloys). Model includes thermal conductivity equation, kinetical equations for components and porosity. The work has unveiled that the reaction always starts at some distance from the free surface; the process is appreciably nonstationary, and a non-uniform multiphase coating forms during electron beam scanning. It was shown that the chemical reactions do not complete during a single electron beam passage and continue during the next passage at a distance from the previous one and can start anew when the next layer is treated. The study has demonstrated that by varying the synthesis conditions (composition of initial powders, scanning regime, and electron beam power), different coating compositions can be obtained after treatment.

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CALCULATION OF STRESS FIELDS CLOSELY LOCATED CRACKS

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A set of software tools has been developed in the language of Matlab, for calculation of the stress field for a system of arbitrarily oriented non-intersecting rectilinear cracks in a loaded infinite elastic plane. The calculation is carried out numerically and reduces to solving a system of singular integral equations. The main feature of the complex is the possibility of calculation for closely spaced cracks. The ratio of the distance between the tips of the cracks to the length of the shortest crack can reach 10^{-45} at calculations.

The software package allows to calculate: stresses on the shores of the cracks, the values of the stress intensity factors (SIF), the stress field, the distribution of the discontinuity along the lines of cracks, and the values of the tensors of the compliance modulus.

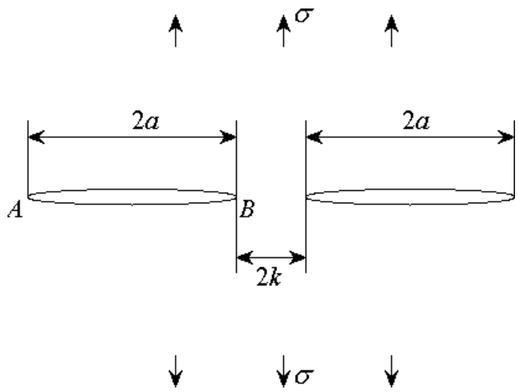

Figure 1. Infinite uniformly loaded plane with two collinear cracks

Table 1. Comparison of a straight crack with an equivalent chain of collinear cracks (see Fig.1) with a vertical tensile load ($\sigma = 1$)

	Two cracks: $2a + k = 1$		
$2k$	**SIF_{IA}**	**SIF_{IB}**	**$\delta_{\sqrt{\pi}}$, %**
10^{-5}	1.64205	5.8317	-7.36
10^{-10}	1.70185	$9.9845 \cdot 10^{3}$	-3.98
10^{-20}	1.73563	$5.2079 \cdot 10^{8}$	-2.08
10^{-30}	1.74754	$3.5227 \cdot 10^{13}$	-1.41
10^{-40}	1.75363	$2.6614 \cdot 10^{18}$	-1.06
10^{-50}	1.75733	$2.1386 \cdot 10^{23}$	-0.85
10^{-100}	1.76483	$1.0789 \cdot 10^{48}$	-0.43
10^{-150}	1.76735	$7.2140 \cdot 10^{72}$	-0.29
10^{-200}	1.76862	$5.4186 \cdot 10^{97}$	-0.22
10^{-250}	1.76939	$4.3388 \cdot 10^{122}$	-0.17

Along the fissure lines, node points are distributed and a system of linear equations (SLE) is formed on the base of the coefficients of mutual influence of node points on each other. The coefficients are calculated on the base of formulas for the stresses caused by a pair of point forces applied to the shores of the crack [1].

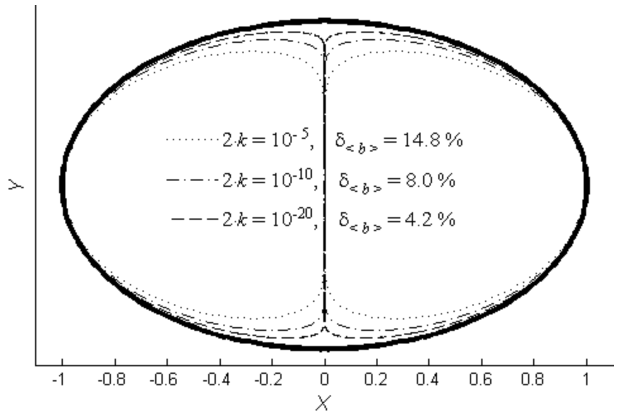

Figure 2. Crack opening displacement of a chain of two collinear cracks with a vertical tensile load

The values of the coefficients of the influence of a crack on the nodal points of other cracks are inversely proportional to the distance to these points. The stresses are also inversely proportional to the distance to neighboring cracks, which leads to the appearance of large stresses and SIF (see Table 1). All this at small distances between cracks makes it difficult to obtain an exact solution of a system of linear equations. In connection with this, in the formation of a system of linear equations, the Newton-Cotes method of the 45th order, and calculations were made using the Multiprecision Computing Toolbox [2] package with a bit capacity of up to 55 decimal digits.

For a loaded plane with chains of two collinear cracks of equal length (see Figure 1), there are exact analytical solutions for SIFs, which are given in the handbook [3]. These solutions were used to assess the accuracy of the software package. For two cracks with crack lengths $2a = 1$ and the distance between the tips of cracks $2k = 10^{-45}$, the relative error of the software complex did not exceed: δSIF_{IA} <0.003% and δSIF_{IB} <0.019%. Figure 2 compares the disclosure of one crack (a fat black line) and two cracks having the same length with a vertically applied tensile load. It can be seen from the figure that as the distance between the ends of cracks $2k$ decreases, the opening of the chain of cracks asymptotically approaches the opening of one crack, and the relative difference $\delta_{\langle b \rangle}$ of the average displacement discontinuity $\langle b \rangle$ of the chain of cracks and one crack is approximately proportional to $[\lg(2k)]^{-1}$. A similar dependence is observed for the stress intensity factor at the ends of the chain of collinear cracks (SIF) and one rectilinear crack (see Table 1).

Acknowlegment

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INCREASE OF ADHESION AND WAVEGUIDE PROPERTIES IN A THIN-FILM LASER-ACTIVE ELEMENT

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Nowadays lasers are widely used in such branches of science and technology as biology, medicine, photochemistry, laser isotope separation, etc. Organic lasers have a number of advantages: wide range of radiation, the possibility of wavelength tuning, low power consumption. Recently attention has been focused to the investigation of thin-film photoexcited lasers based on organic compounds, because of their simplicity of manufacture, compactness and the possibility of application in optoelectronics, optogenetics [1].

The spectral-luminescence and lasing properties of 1,4-distyrylbenzene in films were investigated. 1,4-distyrylbenzene has a high quantum yield of luminescence in solutions and films (φ = 0.9-1) [2, 3] and emits in the blue spectral range.

Spectroscopic measurements of thin-film structures were performed using Avantes fiber CCD spectrophotometer. Lasing properties were investigated by pumping the third harmonic (355 nm) of YAG-Nd^{3+} laser in a transverse excitation scheme (the power density varied from 0.5 to 50 MW/cm^2). In solutions resonator was formed by nontransmitting Al mirror and the cell wall, and in a 4-μm film the lasing was obtained as in a planar waveguide.

Polymethylmethacrylate (PMMA) was used as a polymer for 1,4-distyrylbenzene for films preparing. The concentration of PMMA was 100 mg/ml, the concentration of 1,4-distyrylbenzene was 2×10^{-3} M/l. Thin films were deposited by centrifugation from tetrahydrofuran solution to a pre-cleaned glass substrate with a spin rate of 3000 rpm.

As is known from [4], the adhesion of PMMA and quartz is not very good, and as a consequence, thin-film lasers on a quartz substrate have reduced operation-time. Effective way to increase the adhesion of the polymer to glass is to apply difunctional monomer onto a surface glass modified with silane derivatives, capable of reacting with both the polymer and molecules grafted to the glass surface. This technique was described in our patent "Thin film photoexcited organic laser based on polymethylmethacrylate" (a positive solution was obtained for the application № 2016150444/28(080918)).

Creating photoexcited thin-film lasers based on organic compounds, it is necessary to consider the relationship between the refractive indices of the substrate (n_{substr}) and the active layer (n_{med}). In order to realize the running wave mode in a thin-film structure, it is necessary to select materials with refractive indices satisfying the relations $n_{med} > n_{substr}$ and $n_{med} > n_{air}$.

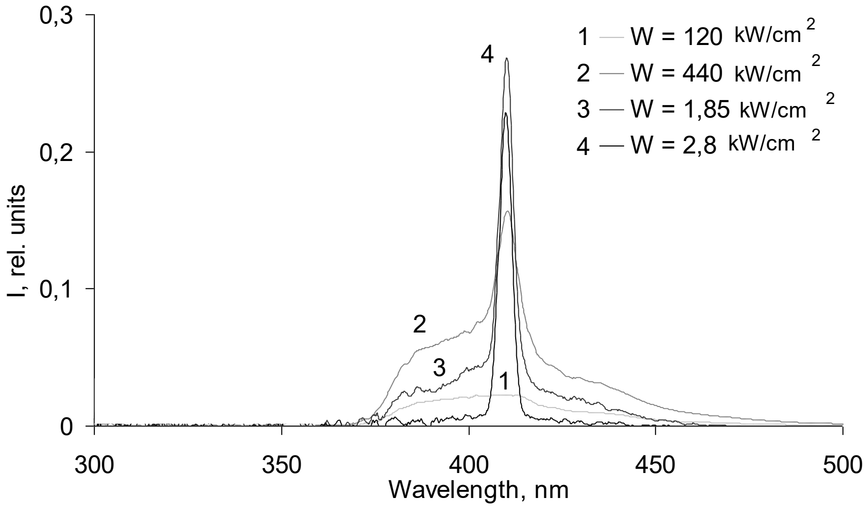
So the refractive index of PMMA is 1.49, and for glass it varies from 1.5 and more. It is known that for films based on amorphous SiO_2 the refractive index is ~ 1.44 [5]. Therefore, placing an intermediate layer of amorphous SiO_2 between PMMA and the glass substrate should lead to the appearance of total internal reflection. This in turn will decrease the lasing threshold and increase the conversion efficiency of such thin-film lasers.

To study the lasing characteristics of 1,4-distyrylbenzene in PMMA films, two types of thin-film photoexcited lasers with intermediate layer of amorphous SiO and without it were fabricated.

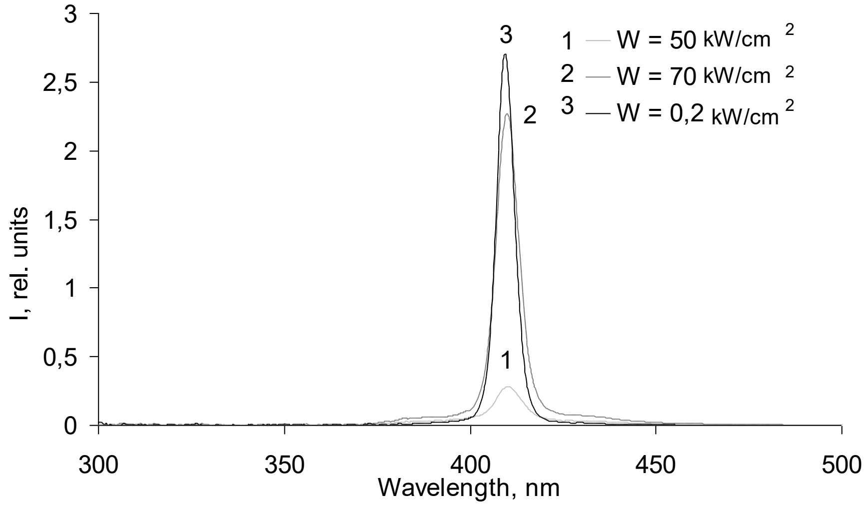
For the sample without intermediate layer, stimulated emission of 1,4-distyrylbenzene in a PMMA film on glass substrate with λ_{gen} = 410 nm and threshold pump power density W = 0.44 MW/cm^2 was recorded. For a thin-film structure without intermediate layer, the generation energy could not be measured due to the low radiation intensity.

Introducing an additional intermediate layer between the glass and the 1,4-distyrylbenzene film in PMMA, the lasing threshold was reduced to 50-70 kW/cm^2, with the conversion efficiency of 20%. The lasing properties of 1,4-distyrylbenzene are shown in detail in Fig. 1.

In summary we have shown that the introduction of an additional layer of amorphous SiO_2 between the glass and the 1,4-distyrylbenzene film in PMMA leads to the appearance of total internal reflection at the boundary of the active medium, reduces the lasing threshold, and increases the efficiency in thin-film photo-excited laser.



a)



b)

Figure 1. Luminescence and lasing spectra of samples: (a) without intermediate layer, (b) with intermediate layer

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ELECTRON BEAM SURFACE TREATMENT OF 3D-PRINTED TI-6AL-4V PARTS

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There is currently an increasing interest in automated intelligent post processing for metal additive manufacturing. The necessity for carrying out the thermomechanical post-treatment is related to heterogeneous structure of 3D–printed parts, the presence of metastable phases, the emergence of large amount of micropores and flaws induced by fast crystallization, directed solidification and phase transitions, with the latter resulting from repeating thermal cycles.

Continuous electron beam treatment can be successfully applied as post-processing techniques of 3D–printed components. During electron beam surface treatment simultaneous radiation, heat and impact treatment of the surface is accompanied by ultrahigh rates of heating (up to temperatures exceeding melting) and cooling ensure simultaneous roughness reduction, microstructure refinement in surface layers of 3D–printing parts as well as inducing the favorable residual compressive stresses, etc. The aim or this work is to study the effect of electron beam surface treatment on the surface morphology, microstructure and mechanical properties of Ti–6Al–4V parts manufactured by electron beam melting (EBM) process.

Ti–6Al–4V parts were built by EBM of titanium Grade 5 welding wire using an electron beam welding machine 6E400 (Teta, Russia). The electron beam welding machine was also used for the continuous scanning electron beam post-treatment of Ti–6Al–4V parts. A sawtooth signal with a frequency of 100-1000 Hz was used to turn the electron beam into a line of 27 mm length. The accelerating voltage and beam current were 30 kV and 10-60 mA, respectively. The focused electron beam with a spot of 0.5 mm in diameter treated the specimen surface line by line. The electron gun power and the specimen's movement speed were chosen to provide an energy density of 75-450 J/cm².

The effect of electron beam treatment on the surface morphology of 3D-printed Ti–6Al–4V parts was studied by a LEO EVO 50 scanning electron microscope and New View 6200 3D optical profiler. It is found that the melted surface layer of the EBM printed parts treated by continuous electron beams becomes more smoother in comparison with the as-build parts.

The phase identification and microstructural characterization of the samples in the plan-view and cross-section geometries were performed by a XRD-6000 diffractometer, a JEM-2100F transmission electron microscope and a LEO EVO 50 scanning electron microscope (SEM) equipped with EBSD and EDS detectors. The three-layer structure are formed in the surface layers of 3D-printed parts subjected to by continuous electron beam post-processing. The thicknesses of the outmost melted surface layer 1, underlying layer 2 and the heat-affected zone (the layer 3) are equal to 50, 60 and 400 μm, respectively. The equiaxial recrystallized grains of 15-20 μm size within layers 1 and 2 are observed. Inside the grains of layer 1, α-Ti and β-Ti fine plates collected in packets and oriented in the different directions. Within the recrystallized grains of layers 2 the bulk fraction of β-phase is lower, wherein the width of the α-Ti plates is higher. The $\alpha \rightarrow \beta \rightarrow \alpha$ phase transformation occurs within the α-grains of the heat-affected zone.

It is shown that the formation of 20 μm size prior β-grains with fine α- and β -lathes within the melted surface layer drastically increases in the surface microhardness of the 3D-printed Ti–6Al–4V parts from 3500 to 6800 MPa. Moreover, the surface hardening increases in tensile strength of the specimens.

COMPARISON OF STRUCTURE AND TRIBOTECHNICAL PROPERTIES OF EXTRUDABLE UHMWPE COMPOSITES FABRICATED BY ADDITIVE MANUFACTURING TECHNOLOGIES

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Ultra-high molecular weight polyethylene (UHMWPE) possessing strength characteristics acceptable for polymers as well as low coefficient of friction, high wear and chemical resistance in aggressive media is used for manufacturing friction units for machines and mechanisms. Besides, it has found wide application in medicine as components of orthopedic implants [1]. However, because of the long length of the polymer chains, UHMWPE has a near-zero melt flow index (MFI) [2] which significantly hinders the possibility of its processing by traditional methods (screw extrusion, injection molding, etc.). Therefore, the issues of improving the processability (in terms of extrudability) of UHMWPE and its composites are relevant.

The purpose of this work is to search for commercially available fillers (micropowders) as polymer fillers for adding into the UHMWPE matrix. This will make it possible to fabricate durable and wear-resistant complex shaped products for tribounits using 3D-production technologies.

The polymer-polymeric UHMWPE compositions filled with polypropylene powder grade 21030 were studied. Specimens were prepared by a) hot pressing of two-component powder mixtures and b) by 3D printing from pellets obtained by milling the extrudate after extrusion blending of the same polymer components. The task of the study was to evaluate the influence of the method and modes of superposition on the formation of permolecular structure, mechanical and tribotechnical properties of polymer-polymer composites.

Ultra-high molecular weight polyethylene (UHMWPE) by Ticona (GUR-4120) with a molecular weight of 5.0 million and particle size $d \approx 50$ μm and powder of polypropylene PP21030 with the particle size $d \approx 100 – 200$ μm were used. The granules of the grinded extrudate of the composite blend UHMWPE – PP after extrusion mixing had a size of 3 – 5 mm.

Bulk preforms of polymer composites were produced by: a) compression sintering at a pressure of 10 MPa and a temperature of 200°C with a subsequent cooling rate of 5°C/min; b) FDM method (Fused Deposition Modeling) plates with the size of 65 × 70 × 10 mm were printed from pellets of the same polymer components. Studies of tribotechnical properties of polymer-polymeric compositions of UHMWPE were carried out under different loads *P* and sliding velocities *V* (60 N × 0.3 m/s, 60 N × 0.5 m/s, 140 N × 0.3 m/s, 140 H × 0.5 m/s).

It is shown that the wear characteristics (Fig. 1) of the investigated UHMWPE composites fabricated by hot pressing at moderate sliding velocities (V = 0.3 m/s) and loads (P = 60 N) remain at the level of neat UHMWPE (I_V = 0.08 mm^3/h). At the same time, for composites obtained by 3D-printing wear resistance decreases (I_V = 0.12 mm^3/h).

Under severe testing conditions (V = 0.5 m/s, P = 140 N), there is a multiple increase in wear as UHMWPE (I_V = 0.71 mm^3/h) and its composites (by 5 – 10 times) regardless of the manufacturing method. In this case, the wear resistance of polymer-polymeric composites of UHMWPE obtained by extrusion mixing with subsequent 3D-printing at a load of P = 140 N and a sliding velocity V = 0.5 m/s are close to those for composites obtained by hot pressing of powder mixtures (I_V = 0.58 mm^3/h and I_V = 0.61 mm^3/h, respectively). Thus, when the content in the UHMWPE matrix is >20 wt. % PP abrasion resistance under severe test conditions (V = 0.5 m/s, P = 140 N) is 15 % higher than for unfilled UHMWPE.

The elastic recovery [3] of composites is slightly less than that of pure UHMWPE (decreases from 46.5 % to 19.6 % at a velocity of 0.3 m/s and a load of 60 N).

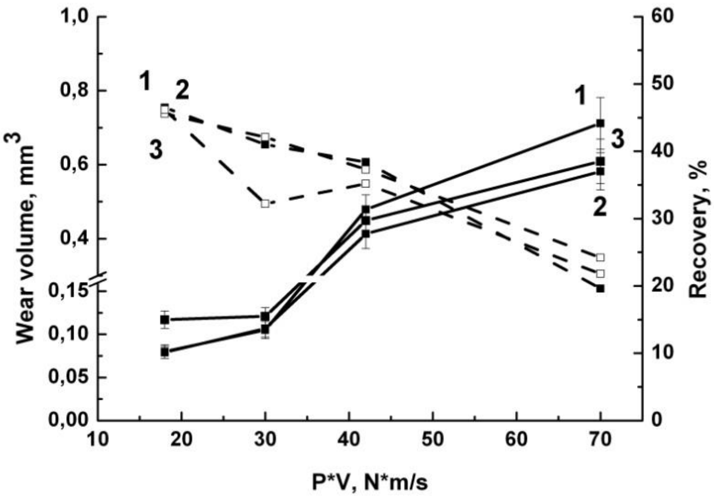

Figure 1. The volume wear (mm^3) and elastic recovery (%) for pure UHMWPE (1) and composites UHMWPE + 20 wt. % PP (powder technology) (2), UHMWPE + 20 wt. % PP (FDM method) (3) under conditions of dry sliding friction at velocities of 0.3 and 0.5 m/s with loads of 60 and 140 N at the steady-state stage of wear

The temperature of the counterbody under triboloading velocity of 0.3 m/s in the composite with polymer filler practically does not exceed T = 28 ± 2°C. When the velocity is increased up to 0.5 m/s there are beads and folds on the wear track surface of the neat UHMWPE. With an increase in the load up to 140 N the temperature for all composites increases to 51 ± 2°C.

The acceptable conditions of triboloading (velocity, load) for materials from extrudable polymer-polymer mixtures based on ultrahigh-molecular weight polyethylene for mechanical engineering and medicine have been determined.

Acknowledgments. The work was performed within the framework of the Program "Research and development on priority directions of development of the scientific and technological complex of Russia for 2014-2020" of the Ministry of Education and Science of the Russian Federation; Agreement No. 14.604.21.0154, project identifier RFMEFI60417X0154.

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USE OF CERAMIC CATHODE BASED ON LANTHANUM AND TITANIUM BORIDES FOR GENERATION OF ELECTRON BEAMS OF LARGE CROSS-SECTION

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Recently, among the various applications of high-power electron beams, applications related to electron irradiation of large surfaces and large gas volumes have taken an important place. This irradiation with electron beams is used for the heat treatment of materials, applying coatings, and realization of plasma-chemical processes, curing of polymer coatings, sterilization of food products, etc. Common to all these applications – the use of electron beams of large cross section.

The production of such electron beams is associated with the creation of a previously unused set of conditions in electrophysical installations, namely, a combination of electrodes of large sizes, high voltage of long duration and compliance with the requirements for the uniformity of the current density distribution over the flow section. Typically, the instability properties of radiation during the generation of beams of large cross-section associated with the heterogeneity of forms microstrip and irregularity of their location on the surface of the cathode. To realize the cathode operation in the mode of explosive emission, the same micro-tip shape with high surface density and uniform distribution over the cathode surface is required.

This paper presents the results of experiments on the creation of a multisection cathode for the generation of large-section beams by sections based on lanthanum and titanium borides treated by self-propagating high-temperature synthesis. The cathode is assembled on a brass matrix with 52 holes evenly distributed over its surface, into which sections are attached, which are tablets based on the LaB6-TiB2 compound. Microscopy of the surface of the section of the cathode showed that the height microstrip is from 9 to 13 microns, the base diameter 8-13 μm, the surface density of microstrip > $2 \cdot 10^6$ cm^{-2}. The manufactured multi-section cathode was tested at the omega-350 accelerator, which has the following parameters: the pulse amplitude of the accelerating voltage up to 350 kV, pulse duration up to 1.5 μs, the maximum beam current density up to 10 kA/cm^2.

For comparison of emission characteristics of the accelerator was also tested multi-sectional cathode is made of steel cylindrical sections repeating cermet on the surface of which had a flange height of 1 mm and a thickness of 0.5 mm. In the experiments we compared the amplitude and temporal parameters of the pulses of voltage and current at the cathodes. When using a metal-ceramic cathode, the impedance matching of the voltage pulse is better, and consequently, the pulse front increases steeper. Also, a multi-section cathode based on metal ceramics allows to obtain a large amplitude of the current pulse (up to 2.5 kA) at its longer duration (up to 3 μs).

CALCULATION OF THE EFFECTIVE CHARACTERISTICS OF PRODUCTS OF ADDITIVE TECHNOLOGIES USING PARALLEL COMPUTATIONS

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In Tula State Lev Tolstoy Pedagogical University carried out applied research work on the topic "Development of a software engineering prototype on the basis of high-performance computing to evaluate the mechanical characteristics of a product manufactured using additive technologies (selective laser sintering method) taking into account the product manufacturing strategy", within which a special software.

The main problem of the software is to calculate the strength characteristics of the manufactured metal parts at the stage of their design. The calculation is based on modern mathematical calculation methods that use parallel calculations to significantly increase the speed and accuracy of the calculation, which will be a unique competitive advantage compared to competitive counterparts. The parallelization method for solving problems using the finite element method is MPI technology. In the case of MPI technology, it is necessary to develop an algorithm for parallelizing computational processes for programming the finite element method in such a way as to represent the solution of the problem in the form of a joint action of several independent processes with independent data.

When organizing the computational process in such structures, developers are faced with the problem of non-optimal use of parallel hardware, which is associated with a low CPU utilization rate, conflicts in accessing shared resources, and so on [1]. Solving the problem of resolving conflicts and increasing the load factor leads to the need for such organization of software data processing, which would reduce the computational complexity to some minimum level. It can be intuitively assumed that the time of solving a problem in a parallel computing system can vary from the value obtained in the case when all the operators of the algorithm are sequentially interpreted by one processor (the upper limit) to the value obtained if all components begin and finish interpreting their parts of the algorithm simultaneously , and when solving the problem, cases of their idle time (the lower limit) are excluded. The necessity of the optimal partitioning of the algorithm into concurrently executing fragments makes the problem of estimating the computational complexity of fragments of algorithms realized in computational system components and the computational complexity of the algorithm realized in a parallel computing system as a whole actual.

In [2], based on a study of the process of executing a command by a von Neumann computer, it was shown that for an external observer, the number of machine clock cycles spent by the processor for its execution is a random variable, the distribution of which depends both on the hardware features and the distribution of the processed data command. In addition, in [2], the nature of the transitions between the operators of the algorithm for an external observer was studied, and its quasi-stochasticity is shown. Therefore, in estimating the time complexity, it is required to involve the theory of random processes, in particular Markovian (and more generally, semi-Marian) processes.

The methodology of modeling the parallel processes proper is laid down in the works of K. Petri, V. Reisig, J. Peterson, V.E. Kotova [3-4], where the apparatus of Petri nets was used to study parallelism. The situational (causal) nature of the links between positions and transitions of Petri nets is a prerequisite for modeling, firstly, the structures of algorithms, and secondly - the logics of events occurring in parallel systems. However, being asynchronous by definition, the models of this type allow only answering questions about the principle of attainable states of the system corresponding to the specified requirements, but it is impossible to predict the moments of the onset of certain states in physical time with the help of Petri nets in their classical interpretation.

Another extension of the classical theory of Petri nets, the temporary Petri nets, was widely used. In this model, counters are introduced to control local or global time. It also determines the time characteristics of the chips staying in positions, the generation / dying of chips after a predetermined time, and so on. The most popular models are those in which time characteristics are associated with transitions.

However, even in a modified version, the temporary Petri nets do not allow to take into account the whole variety of interactions in systems, which is connected, in particular, with the limited logical conditions for continuation of processes by an elementary conjuncture.

In general, the methodology for the formation of models oriented to assess the computational complexity of algorithms implemented in parallel computing systems should take into account the following features:

- a specific and specific for each parallel system strategy for using resources for information processing;
- the dynamic nature of the release / utilization of computing resources in the process of solving specific problems.

The most complete consideration of the above features can be realized in models, hereinafter referred to as Petri-Markov networks (SPM), in which the aspects relevant to random processes in modules of a parallel computing system are combined and aspects describing the logic of their interaction. In the models of the type under investigation, structures that take into account parallelism are superimposed on the stochastic-temporal parameters of the semi-Markov processes in separate computational modules and the logical conditions of interaction.

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MODELING OF SPECIAL CONDITIONS OF DIFFICULTALLY DEFORMABLE HETERO-PHASE METAL SYSTEMS

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Development and introduction in the industry of progressive low-conversion technological processes with the aim of increasing the efficiency of production, labor productivity and product quality, reducing the cost of materials and labor intensity of manufacture is an urgent task. The need to reduce the share of waste in metalworking, the development of low-waste and resource-saving technologies and the faster introduction of precision blanks from various metal steels and alloys into production plays a very important role [1].

The solution of the set tasks is possible due to the use of the superplasticity effect in various branches of production and advanced modern technologies for the production of blanks and articles obtained by various methods using additive technologies. The scientific interest and practical importance of this phenomenon led to its wide experimental and theoretical research in many industrialized countries of the world, since the effect of the joint venture makes it possible to obtain products from metallic materials under the conditions of their appearance of anomalously high plasticity, minimum strength and high activated state of the crystalline substance bound with its specific electronic and structural structure under conditions of superplastic deformation. This is very promising and it is important to model and apply in additive resource-saving technologies [2, 3].

To reveal the patterns of superplastic deformation, it is necessary to determine the quantitative relationship between the SP criteria and the factors.

One of the methods for obtaining such a connection is the simulation of the state of the SP and the construction of mathematical models that adequately describe the process of superplastic flow of the billet material, based on regression dependencies. The application of the theory of experimental planning in contrast to the "classical" methods of investigation makes it possible to best plan the experiment with a substantial decrease in the number of experiments.

Investigations of the effect of external temperature-velocity effects on stretching samples from steel P6M5 were carried out using the methods of optimal experiment planning.

The factors determining the process of superplastic deformation, in particular when stretching the workpiece, can be conditionally divided into constants and varied. Constant factors (process conditions) include chemical and phase compositions of the investigated object; structural state of the material; type of superplasticity; properties of metallic material.

Factors that can be varied include: the temperature of the deformation process, the rate of deformation, and the index of the stress state diagram.

When stretching smooth specimens, it was shown that after localization of the deformation in the neck of the sample, there is a triaxial extension and the average value of the stress state index varies from +0.6 to +1.1. Taking into account the latter, to simplify the calculations, the stress tensor is taken as +1.

To study the effect of superplasticity of steels using mathematical models, the following criteria were chosen:

- resistance to deformation,
- the coefficient of sensitivity of the deformation resistance to the change in the strain rate,
- relative extension.

Mathematical models of superplasticity can be represented in the form of polynomials. With this representation of mathematical models, one of the tasks is to determine the minimum degree of a polynomial that adequately describes the dependence of criteria on factors.

The highest degree of polynomial is needed to describe the dependence of the deformation resistance on the strain rate. Approximation of such a curve is possible by polynomials of odd degrees. The middle section of this curve can be approximated by a third-order polynomial model.

It is established that the effect of superplasticity in high-speed steel P6M5 is manifested in a narrow temperature region near the diffusion phase transformation, where the strength, plastic, thermal and physical properties vary abnormally.The work was performed by the L.N. Tolstoy Tula State Pedagogical University with financial support from the Ministry of Education and Science of the Russian Federation (Project 14.577.21.0271, project ID RFMEF157717X0271).

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TOWARDS DEVELOPMENT OF PERSONALIZED IMPLANTS WITH ANTIBACTERIAL BIOACTIVE COATING BY THE SELECTIVE LASER MELTING AND RF MAGNETRON SPUTTERING METHODS

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Ti-Nb system alloys are very promising material in the field of dentistry and orthopedics. Those alloys have a special mechanical property of reduced Young's modulus values in the range of (40-50) wt% Nb concentration in comparison to the other metallic implants made of steels, titanium alloys or Co-Cr alloys [1]. Also both Ti and Nb have an inherent property to be covered by the thin native oxide layer. As it is mentioned in the literature this layer provides the desired biocompatibility [2]. As Ti-Nb alloy has reduced Young's modulus it could be a promising solution to the problem of stress-shielding effect that is nowadays extensively researched. Thus, the use of Ti-Nb alloys in the field of tissue engineering is important and production of low modulus alloys is vital for the advances in the field of implantology and orthopedics.

Selective laser melting (SLM) is one of the methods of additive manufacturing. This method is cost effective and environmental friendly as it uses only necessary quantity of initial material and all the waste product could be recycled and used again. SLM could be advantageous for the personalized medical implants manufacturing, as it allows production of the material of special, unique and personalized size and shape especially designed for the needs of the exact patient. The SLM allows controlling the structural state (porosity, microstructure, etc.) of the produced implants. Moreover, this method allows formation of non-equilibrium phase state in the produced metallic products due to the high heating, melting, crystallization and cooling rates. So, due to the amount of features provided by SLM one can produce special porous medical implant made of Ti-Nb alloy with low Young's modulus and desired phase composition [3].

However, none of the metallic materials can provide bioactivity that has become recently important for the field of tissue engineering. It is crucial when we are taking in account the number of revision surgeries that are made due to the aseptic loosening of the implant or infection in the implantation site. Those challenges could be addressed by the deposition of bioactive coatings on the surface of metallic implants.

From the various methods of coating deposition for medical implants, radiofrequency (RF) magnetron sputtering is providing the best adhesion to substrate and many more useful features needed for the biomaterials production. Such as, for example, close resemblance of deposited coating and sputtered target. This is a viable factor when it is important to deposit a coating containing small volume of dopants that provide desired property of the thin film. With this method we were able to deposit thin Zn substituted hydroxyapatite coatings on the Ti-Nb SLMed samples.

As it was previously discussed [4], Zn is an essential element for bone remodeling and could also provide some antibacterial properties. In our work we used various analytical methods such as scanning electron microscopy, energy-dispersive microanalysis, x-ray diffraction analysis, transmission electron microscopy, the macro- and microstructure, phase and elemental composition were studied. The produced Ti-Nb alloy specimens are porous with the rough surface. The alloy is represented by two-phased state and has reduced Young's modulus of 82 GPa. The bioactive coating homogeneously covered the complex shape of the manufactured samples repeating the topology of the surface. The elemental composition of the coatings is presented by a Ca/P ratio which lays in between from 1.3 to 1.7 in our case.

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THE POSSIBILITY OF MODIFICATION OF SILUMIN BY AN ELECTRON BEAM

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In the paper hypereutectic cast silumin (22-24wt.%) was used. The primary structure was characterized by precence of intermetallides and primary silicon inclusions, pits and pores. Their size is hundreds of micrometers. Sum up this facts, It does not allow the use of material for the manufacture of machine parts.

The aim of the work is to modify the structure and properties of the hypereutectic silumin samples by a pulsed electron beam irradiation.

The irradiation was carried out by an intense pulsed electron beam of a submillisecond exposure time (setup "SOLO" (IHCE SB RAS)) [1-3]. The structure was studied by optical and scanning electron microscopy, X-ray phase analysis. The mechanical properties were characterized by the value of microhardness (PMT-3 device). The wear resistance studies of silumin were determined under conditions of dry friction in the disk-pin geometry at room temperature in a TRIBOtechnik installation.

It was established that multiphase structure of the submicron-range was formed. The structure`s thickness is up to 70 microns. It is happened as the result of high-speed melting and subsequent crystallization. Optimal irradiation mode is 18 keV, the energy density of the electron beam was 30-35 J/cm^2, the pulse repetition rate was 0.3 s^{-1}, the pulse duration was 200 μs and the number of pulses was 20.

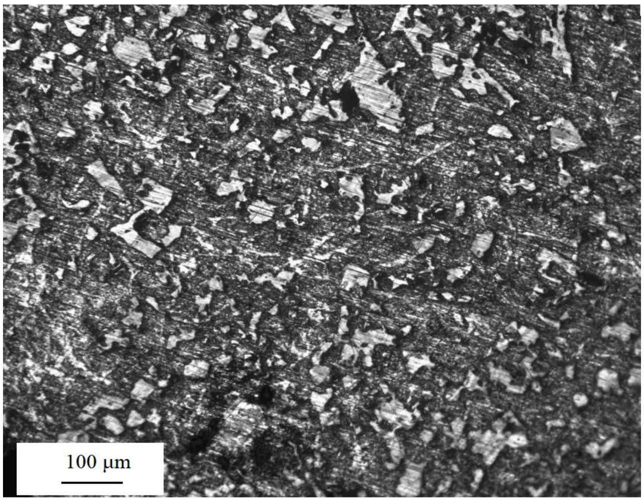

Figure 1. The structure of cast hypereutectic silumin

Acknowledgments

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PREPARATION OF SPHERES TREATMENT OF PARTICLES FLOW OF THERMAL PLASMA

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There is a growing need for hollow microspheres rising every year. Different techniques are developed to date for synthesizing hollow microspheres with diameter ranging from 5 to 300 μm. One of these techniques is based on sol-gel transformation [1]. It includes the dispersion of water sol of metallic oxide in a dehydrating liquid which extracts water from within sol droplets. One more production technique is sol-gel coating of pre-treated polymer or powdered glass followed by its burning [2]. Another methods include burning of sprayed liquid droplets or dry powder particles in a furnace or a gas-fired burner that leads to the formation of hollow microspheres [3, 4]. However, the raw material base for the microsphere production is particularly limited due to the high melting temperature of raw materials. To extend the range of raw materials for the microsphere synthesis is possible through the use of arc jets whose desirable levels of temperature surpass those in traditional thermal-treatment facilities (gas-fired burners) by tens of times. In order to obtain hollow microspheres based on refractory oxides and silicates, high-temperature carrier medium should be provided as the melting temperature of particles achieves more than 2000 K. The authors [5–10] suggested thermal plasma energy as a heating source for agglomerated particles. This type of energy provides 3000÷5000 K temperatures allowing to use raw materials possessing high melting temperatures.

The experiments on plasma treatment were performed in the Plasma Technology Lab at Tomsk State University of Architecture and Building. The test bench comprised the supply source APR-402, upgraded plasma jet VPR-410 (cathode), water-cooled anode assembly with the discharge outlet having 15 mm in diameter.

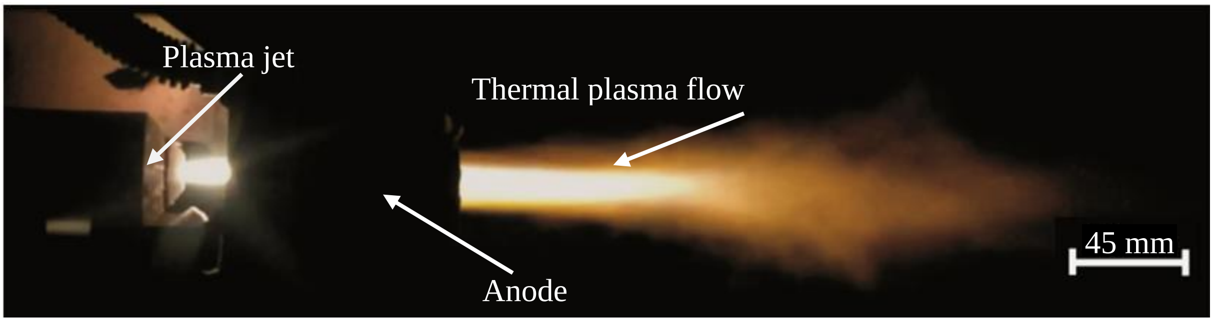

Figure 1. Thermal plasma flow in steady-state operating mode.

The powder was delivered through mains to the anode assembly. Injectors were installed tangentially on four sides. Specifications for the plasma jet included 0.05 l/s carrier gas flow; 4.7 kg/h raw-materials consumption; 0.4 l/s volume flow of pressurized air used as plasma gas; 39 kW heating capacity.

Consider Fig. 2, which illustrates the morphology of agglomerated particles and obtained microspheres. SEM image in Fig. 2*a* shows ash-based particles with the size ranging between 80÷250 μm.

The particle morphology represents a family of heterogeneously dispersed particles of irregular shape and a developed system of micropores. As a result of experiments, microspheres are obtained as shown in Fig. 2*b*, *c*. They are characterized by 0.3÷0.4 g/cm^3 bulk density, high degree of sphericity and diameter varying from 120 to 350 μm. The obtained microspheres have no surface defects (cracks, attached particles or clear pores) which are typical for those obtained by common methods at thermal power plants.

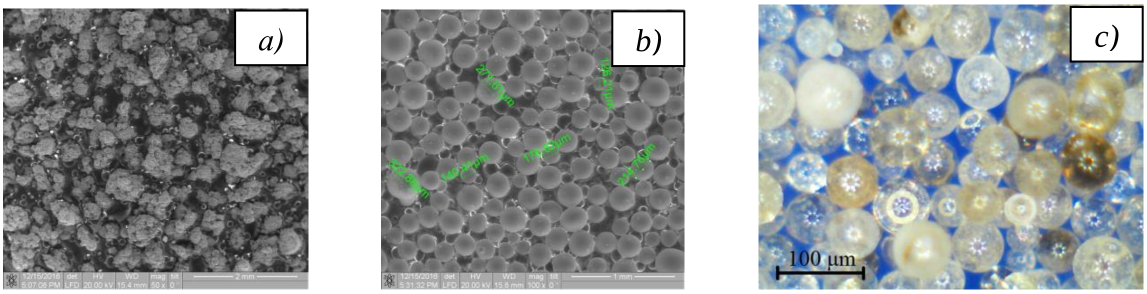

Figure 2. SEM images of agglomerated particles (*a*) and obtained microspheres (*b, c*).

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3D PRINTING AS A "NATURE LIKE" METHOD OF OPTIMIZED ENDOPROSTHESES FABRICATION

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Introduction. At present time the mankind is experienced of difficulties of sustainable development caused the shortage of energetic and biological resources. The scientists see the solution in creating of **"**nature like" technosphere. In effect, additive technologies (AT) is a **"**nature like" method of «growing» not only any partial element and even complex issues, for example, endoprotheses of joints.

The aim of the work is to improve the tribomechanical properties of endoprotheses and overcome difficulties of AT manufacturing in respect to these implants making from thermoplastic disperse-reinforced UHWPE composites [1].

Methods and results.

Finite element method has been applied for the creating of CAD-models of joint with gradient of mechanical properties on depth *z* according to the method described in [2]. For obtaining of corresponding structure the porosity of material has been currently varied during 3D printing.

The modeling shows that such important parameter as maximal contact pressure $p_{\max}$ increases almost 2 times for negative gradient of Young modulus $E'(z) < 0$ in comparison with positive gradient of $E'(z) > 0$. For homogeneous material the maximal contact pressure is characterized by intermediate value. When E = const, it was established that $p_{\max}$ corresponds to constant Poisson's ratio of material $\nu'(z) = 0$; for positive gradient $\nu'(z) > 0$ this parameter decreases more than two times and for $\nu'(z) < 0$ – more than three times.

Some problems of realization of 3D printing of endoprotheses have been discussed, namely, relatively low accuracy of sizes and repeatability layers geometry; high roughness and necessity of additional treatment of contact surfaces; obtaining of specified microporosity; comparability of strength and elastic modulus of materials fabricated by AT and traditional technologies.

Conclusions. The combination of additive technologies, bionic principles and FEM modeling of materials opens up wide possibilities for creating of individually adapted and optimal designed implants. Using of thermoplastic biocompatible and extrudable composites allow us to obtain the gradient of the porosity and elastic properties of endoprostheses, which ensures to minimize contact stresses in this **"**nature like" tribojoint of complex geometry.

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INVESTIGATION OF CLOGGING OF THIN CHANNELS DURING LASER SINTERING

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In the present work we investigate the clogging of thin cylindrical channels due to overheating of powder inside it during laser sintering. We consider a simplified two-dimensional transient model that able to predict the thermal state at the central cross section of long specimens with straight cylindrical channels (Fig. 1). In this model we take into account the heat conduction in the sintered part, supports, base platform, in the powder bed around part and inside the channels. Input heat from the laser is simulated by using simplified heat flux boundary condition without "moving source" effects and prescribed as the piecewise function of time at the top surface of the sintered part. Value of the heat flux density is estimated based on the given laser source power, spot area and velocity. Convection and radiation heat transfer at the outer surfaces as well as thermal resistance at the powder/solid interface are taken into account.

Numerical transient solution is obtained by using finite element simulations with layer-by-layer growth of the model [1]. At each step of solution, we add additional layer at the upper surface of the model which thickness equals to the one layer that is spreaded and sintered during manufacturing process. Shrinkage effects are neglected. Thermal state of the model at the last moment of time at considered step is used as the initial conditions for the solution at the next step assuming that newly added layer has ambient temperature. Mesh of the model is generated at each step of solution.

Considering stainless steel specimens, we obtain predictions for minimum channel diameters that can be obtained without undesirable overheating of the powder inside it and clogging. Preliminary experimental validation of the model is also presented.

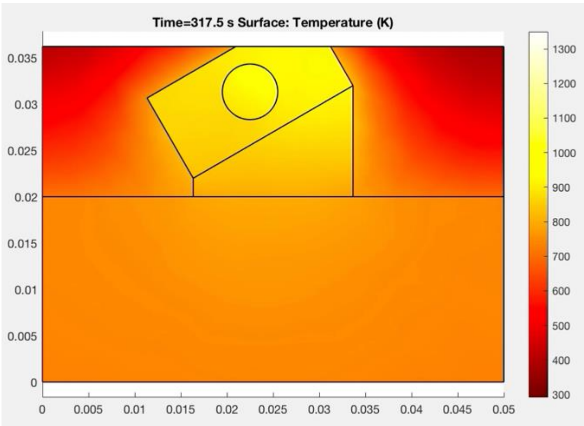

Figure 1. Thermal state at the central cross section of the specimen with straight cylindrical channel during sintering

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3 D PRINTING OF VIBRO-ACOUSTIC METAMATERIALS: THE PROBLEM OF MODEL AND EXPERIMENT COMPLIANCE

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This paper is devoted to the metamaterial structures and their "super" wave properties. The models of acoustic and vibro - metamaterials developed in IMASH RAS are presented. The problem of possible discrepancy between the properties of acoustic and vibro - metamaterials theoretically predicted and experimentally obtained on test 3D-printing samples is discussed. It is found that insufficient quality of 3D-printing strongly affects the acoustical (or strength) properties of the finished product and the test samples are inconsistent with the specified requirements. Two models were chosen for experimental study of the problem: the simplest design model of acoustic metamaterial with high sound absorption which is represented as a quasi-periodic cellular structure with the cell size corresponding to the operating frequency region, and vibration isolator model as a set of several thin washers of steel interconnected with each other on a chess-board order via small masses forming a grid-like structure which "super" wave properties are based on stopband effect. See Figure 1.

Figure 1. The sound absorber sample of resonant type made by PolyJet technology (left) and vibration isolator made by SLM technology (right).

Currently, the available 3D-printing technologies do not allow to print a sample with a cellular thin-walled internal structure as a whole, and it is necessary to develop special models and use post-processing [1]. In this case, the acoustic quality, that cannot be visually determined, may not be ensured.

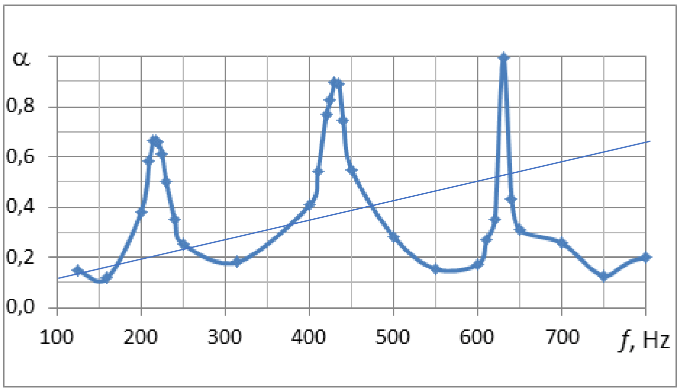

Figure 2. Sound absorption coefficient (frequency dependence) for a resonant sample (measured in the impedance tube); inclined line corresponds to the inaccurate reproduction of the internal structure by 3D-printing.

Figure 2 shows the experimental data of acoustical tests of two samples of the resonant type absorbers. They have the same geometry but absolutely different absorption coefficients. Physically it means that one sample operates not as a resonant but as a mass type absorber. It may happen when part of the air passes through the sample. That means that this sample has insufficient quality even the peculiarities of the synthesized process were preliminary studied and optimal parameters were found to provide the required shape of the samples.

A similar example of the loss of the initial "super" wave properties of the 3D-printed metamaterials refers to samples of SLM-made vibration isolators (VI). After manufacturing, the mechanical test of VI- elements was performed and metallographic studies of the synthesized material were carried out to analyze their material properties [2,3]. These tests showed that the strength properties are even higher than those of cast parts. The vibration tests of SLM-made VIs have also been successfully passed and the perfect vibration isolation effect has been verified. However, over time, the tests for cyclic loads of small amplitude showed a significant decrease in the filtering properties of these samples due to the formation of surface microcracks.

So, insufficient quality of 3D-printing is responsible for the discrepancies between the measurements and predictions. Unlike traditional technologies that use materials with well-known characteristics (for example, mechanical), on the basis of which the product is designed with the desired properties, the material and the product are created simultaneously in the additive technology (AT). The practical use of AT to create samples of acoustic and vibro-metamaterials indicates the instability of the results of 3D-printing. It is necessary to study this effect in order to obtain stable results in the use of these technologies in practice.

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STRUCTURAL-PHASE STATE OF THE WIRE-FEED ELECTRON BEAM ADDITIVE MANUFACTURED TI-6AL-4V ALLOY

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Titanium alloys are among the most important of the advanced materials that are key to improved performance in aerospace and terrestrial systems and are even finding applications in the cost conscience auto industry. These applications result from the excellent combinations of specific mechanical properties and outstanding corrosion behavior exhibited by titanium alloys [1]. However, there are formidable challenges in refining, casting, forming and machining titanium, which result in end products that are considerably more expensive than their steel or aluminum counterparts [2].

The high cost of parts made of titanium alloys is determined by the high material consumption during machining, poor machinability caused by low thermal conductivity and high chemical reactivity with cutting tool materials, which is an obstacle to their widespread use. The use of additive technologies makes it possible to reduce production costs of titanium alloy components due to manufacturing of near net shapes. At the same time, the key requirement in manufacturing the near net shapes is to maintain high mechanical characteristics both of the base material and of the component as a whole. Wire-feed electron beam additive manufacturing has a great potential, both in terms of high productivity and obtaining materials with a unique structure and high mechanical properties.

The purpose of this report is to study the structure, the phase composition and microhardness of Ti-6Al-4V alloy samples obtained using wire-feed electron beam additive manufacturing.

Results and discussion. Samples were obtained using an experimental plant for growing wire products in vacuum. The electron beam was the source of heating followed by melting. The wire was applied to a commercial titanium substrate measuring 75 mm × 75 mm × 2.5 mm welded to a stainless steel plate with dimensions 110 mm × 110 mm × 7.8 mm welded by spot welding. The technological parameters of the samples' growing process are presented in table 1.

Table 1. Technological parameters of the growing process

Accelerating voltage, kV	40	40
Beam current, mA: - the first layer - the next layers	 16 14	 30 28
Diameter of the beam, mm	0,15 - 0,18	0,15 - 0,18
Focal length of the beam, mm	220	220
Beam scanning area	∅5 mm ring	∅5 mm ring
Scanning frequency, kHz	1	1
Step of displacement ΔX, mm	5	5
Layer height, mm	0,8	0,8
Number of layers, pcs.	3	3
Wire feed, mm / min	880	880
Wire feed angle, ^{0}	25	25
Angle between wire axis and X axis, ^{0}	45	45
Linear growth rate, mm/min	220	220

The structural evolution of Ti-6Al-4V alloy samples is obtained by layer-by-layer growth using the electron-beam wire additive technology is studied. Based on the data of the optical, scanning electron microscopy and X-ray diffraction analysis, Ti-6Al-4V samples are obtained by layer-by-layer growth, a heterogeneous microstructure, which is composed of, in addition to the columnar preceded β-grains with the mean size of <1.5 mm formed during epitaxial growth, the system of orthogonal plates of the martensitic α'-phase. At the same time, both the thickness of the α-phase and the amount of the residual, the phase is reduced along the building direction (from 4 μm and 10 vol% for the lower layer, up to 2 μm and 5 vol% for the upper layer). A good agreement with the Hall-Petch ratio shows the effect of increasing hardness. The effect of increasing the Vickers hardness values with the increase in the height of the deposited layers to values of the order of 3.5 GPa has been found. A good agreement with the Hall-Petch ratio shows that the effect of increasing hardness in the direction of layer-by-layer growth is mainly due to a gradient microstructure formed during complex thermal history.

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OBTAINING OF MATRIX OF DISPERSION NUCLEAR FUEL BY SHS METHOD

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Modern nuclear power engineering is an industry field that is developing rapidly. In the consequence of the increasing needs of mankind, there is a need to use new, high-quality and less expensive functional materials.

One of the most important elements in the nuclear industry is the fuel used. It is to him that the highest requirements must be established. The most important requirement is the high concentration of the fissile isotope to maintain the nuclear chain reaction. It is also important that the materials used in the fuel are radiation-resistant and retain their chemical, thermal and mechanical characteristics during long-term operation in a nuclear reactor. Also fuel connections should be characterized by high thermal conductivity to minimize thermal stresses and reduce the temperature gradient in the tablet, a high melting point that exceeds the operating temperature of the reactor facility, availability and cheapness, and mechanical strength.

Traditionally used ceramic nuclear fuel, represented by uranium dioxide, has a number of disadvantages, the main one of which is low thermal conductivity, which leads to thermal stresses in the volume of the tablet and cracking of the brittle ceramic at high temperatures.

Perspective replacement of ceramics can serve as a dispersive nuclear fuel (DNT), which is a matrix of inactive element with fuel particles dispersed into it [1]. A promising material for the matrix of dispersive nuclear fuel can serve intermetallic compounds, whose amazing properties have already manifested themselves in materials for space technology.

Intermetallic compounds can be obtained by economically advantageous method of self-propagating high-temperature synthesis (SHS). This method is based on the ability of some elements to enter into an exothermic reaction [2]. In itself, SHS does not require any sophisticated equipment, and it is also attractive for relatively low energy costs for the implementation of the reaction. Also it is possible to dilute the reagents with an inert additive, which can be fuel particles.

In this paper, the synthesis of the intermetallic matrix NiAl for DNT by the SHS method has been worked out and the effect of the addition of an inert additive on the thermodynamic parameters of the reaction has been studied.

When the content of the inert additive in the tablet is increased, the temperature peak of the reaction decreases. The reason for this is a decrease in the number of reacting particles, and, consequently, a decrease in the total released energy in the exothermic reaction.

But when reacting with a tablet containing 60% of an inert additive, deviations from the foregoing relationship are observed. This is due to the fact that there are too few reactive elements in the volume of the tablet, and therefore the reaction begins to proceed with an increase in the initiation temperature, which leads to an increase in the peak temperature.

It should be noted that when the mass fraction of the additive is on the order of 20-30%, the tablet overheats, as a result of which aluminum and nickel melts begin to form in volume, which leads to a change in the geometric shape and size of the tablet. A plurality of pores are formed, the compressed layers are separated. On the contrary, in the sintering of samples with an additive content of 50%, a low synthesis temperature is noted, which does not lead to negative consequences.

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NUMERICAL MODELING OF TEMPERATURE SEPARATION IN THE RANQUE-HILSHVORTEX TUBE

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The Ranque-Hilsch effect or the vortex effect was first discovered in the late 1920s by the French engineer Joseph Rank when measuring temperature in an industrial cyclone. Later, Robert Hilsch continued the study of the vortex effect. This effect is characterized by the separation of a liquid or gas into two parts when twisting in a cylindrical or conical chamber. In the central swirling flow there is a decrease in temperature, while on the periphery there is a temperature increase. The relevance of the study of this effect lies in the fact that the Ranque-Hilsh vortex tube, with a relatively technical simplicity of manufacture, allows to reach a large degree of temperature separation of the flow. Also, the device under consideration is economical, safe, compact and reliable in industrial operation.

The aim of this paper is to study the Ranque-Hilsch effect on the basis of a numerical modeling of the temperature separation of a flow in a vortex tube.

The energy separation process in the vortex tube is considered under the following assumptions: the gas flow is stationary, turbulent, swirling; the medium is an ideal viscous compressible gas.

The numerical solution of the system of governing equations is based on difference schemes of the second order of accuracy. It is realized in the Ansys-Fluent software package. Geometry and the construction of the mesh of the vortex device were carried out using the Gambit package.

The influence of the width of the throttle gap for the outlet of the heated flow(1 mm, 1.5 mm and 2 mm) on the value of the temperature separation was investigated. It is shown that as the width of the gap decreases, the temperature separation increases.

As a result of the calculations, the temperatures of the cooled and heated gas were obtained, depending on the pressure drop. The calculations demonstrated the presence of vortices which are formed due to the existence of two oppositely directed flows. There is shown the effect of turbulent viscosity on the flow region near the wall.

It is shown that the laminar viscous compressible gas model does not adequately describe the effect of temperature separation in the Ranque-Hilsch tube, whereas the turbulent flow model of a compressible gas as a whole correctly describes this effect, which confirms the hypothesis of interaction of turbulent vortices as the primary cause of temperature separation.

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Content

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МЕЖДИСЦИПЛИНАРНЫЕ ПРОБЛЕМЫ АДДИТИВНЫХ ТЕХНОЛОГИЙ

СБОРНИК ТЕЗИСОВ

IV ВСЕРОССИЙСКОГО НАУЧНОГО СЕМИНАРА
С МЕЖДУНАРОДНЫМ УЧАСТИЕМ

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