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Research Article

MECHANICAL AND STRUCTURAL PROPERTIES OF STAINLESSSTEEL SPECIMENS WITH INTERNAL CHANNELS FABRICATED BY SELECTIVE LASERS INTERING

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ABSTRACT

The paper investigates the mechanical and structural characteristics of stainless steel specimens with different cross-sectional shapes. Samples were obtained on the EOSINT installation based on layered laser synthesis technology. From tensile tests, the mechanical properties of samples with a relief surface and samples with internal channels of small diameter were determined. To determine the internal structure of the samples, their study was carried out using the method of computed tomography. It is established that the presence of internal thin channels oriented in the loading direction leads to a decrease in the Young's modulus, the yield strength and the ultimate strength of the samples by 20-50%.

INTRODUCTION

The task of the work consisted in developing the technology for creating critical parts for the aerospace industry. The effect of the shape of the working cross section on the mechanical properties of metal samples obtained by laser layer-by-layer synthesis was studied. In total, three batches of samples were investigated. The first batch was synthesized in the form of standard blades for testing the rupture. In the second batch, the working part of the samples was made with a surface relief-cylindrical notches were made on one of the surfaces of the plate. In the samples of the third batch, thin channels directed along the working part were made (Lurie, *et al.*, 2011). All three types of samples were preliminarily constructed in a three-dimensional modeling system. Then the constructed CAD-models were transferred to the laser sintering system EOSINT M270, in which the samples were grown.

To determine the internal structure of the samples with channels, the method of computed tomography was used. The mechanical properties of the samples in three batches were determined from the tensile tests.

The problem under consideration seems to be relevant, since the method of laser synthesis makes it possible to obtain various parts with complex external geometry and the presence of internal cavities; however, the question of the presence of surface and bulk defects in the synthesized samples is open. It is important to determine how the properties of materials obtained using different synthesis regimes change. It is required to establish the effect of the direction of synthesis, the presence of shallow relief and cavities, stress concentrators in synthesized objects on their mechanical properties (Song, *et al.*, 2015).

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The practical application of laser synthesis technology can be very diverse, since the sizes of synthesized objects vary from several millimeters to tens of centimeters. With the help of the laser sintering method, microscopic parts with a complex structure, used in the aerospace industry for micro- and nanosatellites, and also the creation of a jet nozzle with an integrated cooling system in the form of thin channels can be obtained, it is possible to synthesize the elements of prefabricated structures for aerodynamic testing, blades of turbines and other elements of aerospace design with a complex geometric shape. In connection with the high requirements imposed on the aerospace industry, it is required to develop technological recommendations and a system of tolerances for products obtained by laser sintering. For this, a series of experimental tests is required to determine the physico-mechanical properties and structural features of the synthesized objects. The present study is aimed at evaluating the defectiveness of external and internal surfaces in synthesized samples with different cross-sectional shapes intended for tensile tests.

MATERIALS AND METHODS

The process of synthesizing samples by the laser sintering method makes it possible to obtain details of complex shapes, but this technology requires rather complex preparatory work. First of all, an engineer or designer develops a three-dimensional model of the future designs. Further, at the first stage of project preparation, the technologist determines, on the whole, the possibility of subsequent production of the part on the existing equipment, after which he analyzes the product and introduces necessary changes in the design, in coordination with the designer (Afanasyev, *et al.*, 2010a).

At the next stage, the original 3D model file is converted to the required format. This operation can be performed by a number of well-known and widely available CAD systems, an example of which can be called SolidWorks. Later the file is processed by a specialized package working with first models, mainly consisting of a set of triangular faces and their normals that describe its surface. Next, the model gets a binding to the equipment on which it will be produced – one of the most important parameters at the beginning of the project processing is the exact definition of the brand of the material of the future part, equipment and the task of the size of the equipment related to the dimensions of the working chamber. Then the lower or upper plane of the product is set, as a result the relative position of the part in space is obtained. When carrying out this operation, it is necessary to take into account the possible thermal stresses that will remain in the detail and can affect the quality of the work being carried out, which manifests itself in the form of warpage and changes in the actual dimensions of the part. Also, the position of the part relative to the base plate obviously affects the number of supporting structures (supports) required for the immediate construction and subsequent retention of the part during subsequent operations.

It should be noted that there is always a technological allowance in the form of a gap between the part and the base plate, which is from 2 millimeters, depending on the complexity of the geometry of the part.

Method of Synthesis of Samples using Laser Sintering Technology

At the next stage of project preparation, with the help of specialized software, the possible errors in the existing model are checked, and, if necessary, automatic correction of the model. Such errors can be attributed, for example, intersections of primitives.

One of the last operations is automatic generation of supports with subsequent manual correction. In some cases, experienced technologists refuse to automatically generate and design the system of supports themselves. This stage, in fact, forms the foundation of the produced part, and takes a large part of the time from all preparation (Guan, *et al.*, 2013).

At the end of the project preparation, the model is converted into its own format, which is a layer-by-layer division of the model, after which the project is transferred to the equipment and the work is started.

For the present studies, two types of samples with a complicated surface and bulk structural structure were chosen. First, samples with relief on the surface in the form of three cylindrical cuts (recessed into the surface by half the diameter) oriented in the direction of the working part of the plates were considered. This type of specimen corresponds to details with thin slots, protrusions or threads that can be used as structural elements of the structures. Secondly, samples were analyzed in which three parallel thin internal channels were located. The diameter of the channels was 1 mm, – this is the minimum recommended cavity diameter for the laser synthesis system used. Samples with channels are a simplified representation of structural elements with a system of internal cavities that can be used to create an integrated system for cooling the structure, for installing monitoring or detector devices and for reducing the weight of the structure (Afanasyev, *et al.*, 2010b).

In fact, both types of synthesized samples have stress concentrators on the surface or in the volume. Surface roughness and microdefects, which are formed during the synthesis, create additional sources of stress concentration, leading to a change in the mechanical characteristics of the samples. The temperature distribution in samples with a different shape of the working cross section during laser sintering can differ, as a result of which the nature of defect distribution on external and internal surfaces can also be different. That is why it was required to evaluate the influence of different shapes of the cross section of the samples on their mechanical properties.

The initial form of all the samples corresponded to the GOST 11701-8 standard for carrying out tensile tests. Blades with a thickness of 2 mm were synthesized, with a working width of 10 mm and a length of 20 cm. For comparison, a batch of standard samples of a solid material was created. In total, 15 samples were synthesized, 5 samples each with relief, with channels and a standard shape. The CAD models of the samples were constructed using the SolidWorks 3D modeling system. The type of models is shown in (Fig. 1).

Synthesis was carried out on an EOSINT M270 unit in an argon medium. The thickness of the sintering layer was 20 µm. The type of laser used is Yb-fiber laser, 200 W. Samples were synthesized in the "on the edge" position, as they are presented in (Fig. 1). For synthesis, a fine powder of pre-sintered and milled stainless steel EOS Stainless steel GP1 with a chromium content of 15-17%, nickel and copper of 3-5% was used (Yadroitsev *et al.*, 2009). This type of powder is usually used to synthesize small-scale and unique products, which are subject to increased requirements for corrosion resistance, ductility and impact strength. Dispersion of the powder was 5-10 µm. The standard characteristics of the steel obtained by laser synthesis for this type of powder are given in Table 1.

After the synthesis, the samples were cut from the substrate, technological support was removed from them, and grinding was carried out. The type of samples obtained with technological support and after grinding is shown in (Fig. 2).

Investigation of Structural Characteristics of Synthesized Samples Using the Method of Computed Tomography

When creating high-quality products with a complex system of internal cavities, it is required to carry out quality control of the internal geometry of the synthesized samples. For example, when creating thin-walled structural elements with integrated channels intended for a cooling system, it is required

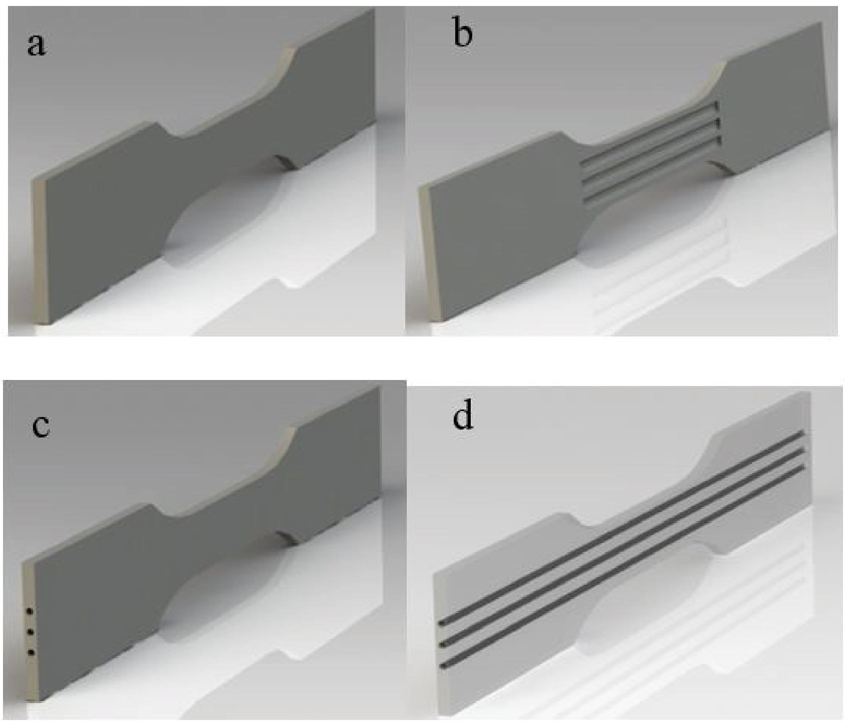

Fig. 1 Three-dimensional models of synthesized samples (a is a standard sample, b is a sample with a relief on the surface, c is a sample with internal channels, and d is a longitudinal section of the sample with channels).

to control the shape and thickness of the channels and even the roughness of the channels, since insufficient smoothness of the channels or local constrictions and distortions can lead to a decrease in the flow velocity and locking of the cooling liquid, resulting in damage to the structure.

Quality control of internal geometry of structures can be realized using modern methods of nondestructive testing, and, in particular, technology of computed tomography. This technology allows us to quantitatively analyze the complex internal structure of critical aerospace products without destruction. The result of the research is presented in the form of two-dimensional sections, graphs and three-dimensional images of the internal structure with the ability to detect and accurately measure the dimensions and spatial location of defects in the form of different densities, pores, cracks, inclusions, etc.

To study the internal structure of synthesized samples with internal channels, a BT-600XA tomograph was used, with sensitivity to local pore defects up to 0.1 mm^3 in size. Thus, samples with channels with a diameter of 1 mm make it possible to test, in practice, the limiting capabilities of a tomograph. In (Fig. 3) shows the obtained images of the internal structure of the sample with channels.

RESULTS AND DISCUSSION

The carried-out researches have shown presence of a roughness of an internal surface, the order, 200 microns. The synthesized samples have even channels, in shape as close as possible to the original three-dimensional model (angular error in the arrangement of the channels is less than 3°). In (Fig. 3a) that between the channels there are some structural features that are not pores see (Fig. 3b), high-frequency reconstruction), however, are apparently related to the peculiarities of synthesis and heat removal in narrow regions between the channels. In fact, in these areas there are some inclusions of the same steel material, but with an excellent structural structure, compared to the base material of the sample.

Investigation of Mechanical Properties of Synthesized Samples

To determine the mechanical characteristics of the synthesized samples, tensile tests were performed using the Instron 5960 test system. The tests were carried out at room temperature; the stretching rate was 5 mm/min. In (Fig. 4) shows the characteristic diagrams of stretching of different types of samples.

Table 1. Typical mechanical characteristics of steel synthesized from powder EOS Stainless steel GP1

Material of stainless steel powder	Strength limit, MPa	Fluidity, limit, MPa	Elastic modulus, GPa	KTP, 10^{-6} K^{-1}
EOS Stainless steel GP1	930 ± 50	586 ± 60	170 ± 30	14

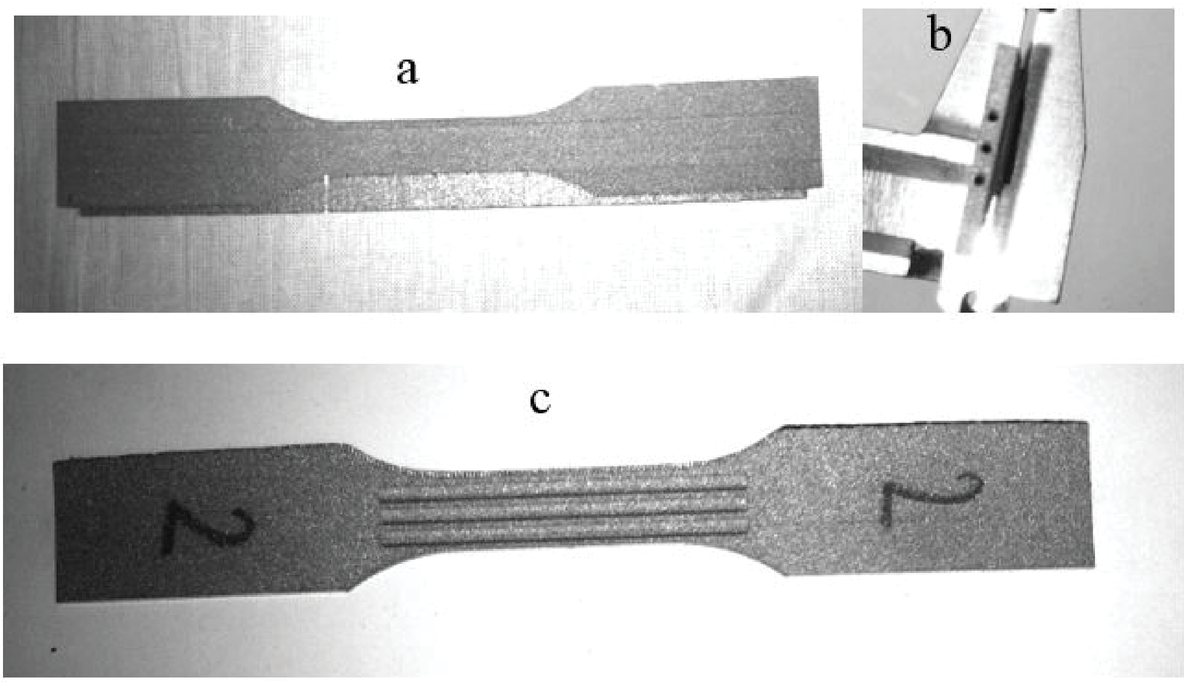

Fig. 2 Type of synthesized samples (a – sample with internal channels before removal of technological support, b – cross section of synthesized sample with channels, c – sample with relief on surface after removal of technological support).

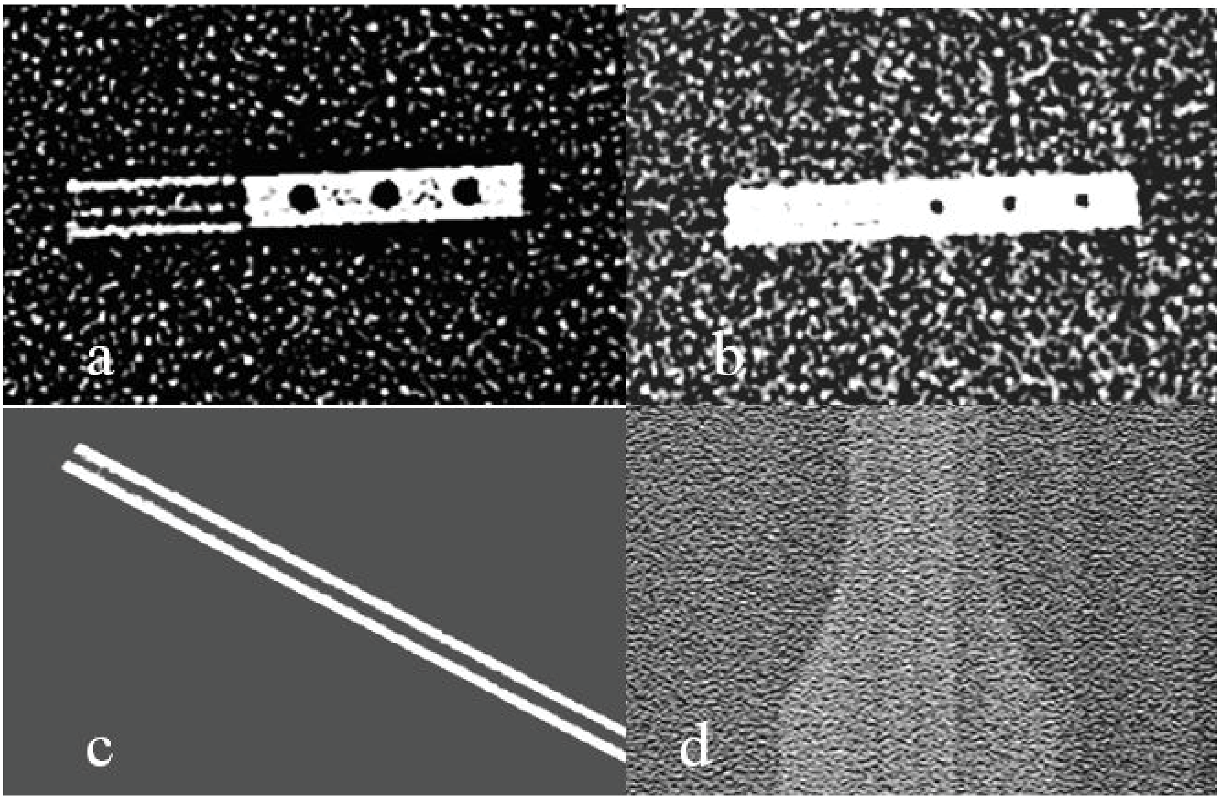

Fig. 3 Results of the investigation of the internal structure of the samples with channels on the VT-600X A tomograph (a is the low-frequency reconstruction of the cross section, b is the high-frequency reconstruction of the cross section, c is the tomography of the longitudinal section of the sample, and r is the x-ray diffraction pattern of the sample in the plane).

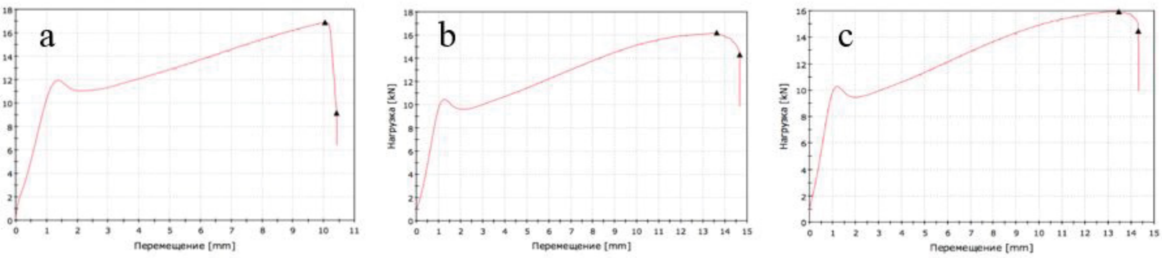

Fig. 4 Stretching diagrams of stainless steel specimens (a – solid samples, b – sample with relief, c – sample with channels).

Table 2. Results of mechanical tests of synthesized samples

Type of samples	Strength limit, MPa	Fluidity, limit, MPa	Young's modulus, GPa
Samples from solid material	856 ± 45	568 ± 25	154 ± 20
Samples with relief	775 ± 3	509 ± 6	107 ± 20
Samples with channels	760 ± 8	492 ± 2	104 ± 1

A characteristic feature of the steel under study is the presence of a peak in the region of transition from the elastic deformation zone to plasticity – this kind of diagram is characteristic of low-carbon steels. The averaged values of the mechanical characteristics of the samples are shown in Table 2. The strength and yield strengths were determined taking into account the different cross-sectional area of the samples. For standard samples, the cross-sectional area was 20 mm^2, for samples with relief and with channels – 17.64 mm^2.

The following important features should be noted in the obtained test results. Firstly, the obtained tensile strength of samples from solid material corresponds to the minimum value for the EOS Stainless steel GP1 powder used, which is the result of sufficiently long storage of the powder after grinding (~1 year).

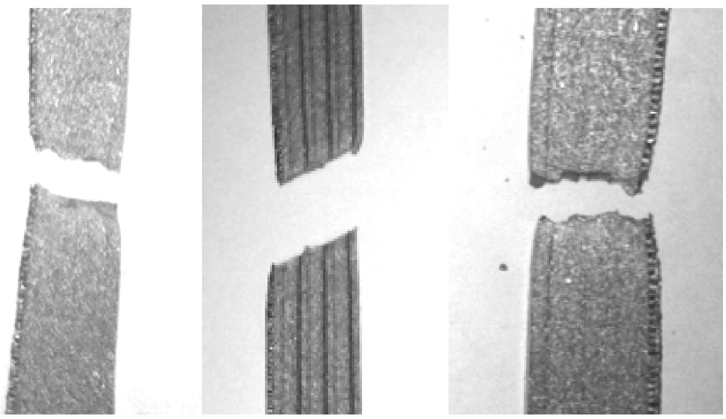

Fig. 5 The nature of the destruction of the samples (a is a sample of a solid material, b is a sample with a relief, and c is a sample with internal channels).

During this time, the oxidation of the powder occurred and the properties of the synthesized steel decreased due to an increase in the oxygen content. Samples with relief and channels have an even lower strength and lower elastic moduli, but this should be explained not only by the properties of the powder used, but also by the synthesis of samples with a more complex surface shape. The presence of a small-sized relief on the surface and cavities in the volume in the structure of the part leads to the formation of mycrocdephents in the process of laser synthesis. Probably, in the synthesis of small parts, the sintering rate slows down and more heating occurs and, consequently, an increased concentration of residual thermal stresses in the finished sample. Defects and roughness of material surfaces are stress micro-concentrators, which, together with residual stresses, lead to a decrease in the mechanical properties of the steel. The nature of the fracture surfaces of samples of various types is shown in (Fig. 5).

It should be noted the spread of values in certain mechanical characteristics. The greatest dispersion was obtained for samples of solid material, which, in principle, is an unusual result, since samples with relief and with channels have structural stress concentrators and should behave more unpredictably. It can be assumed that the spread of values for a continuous material is related to the sintering technique used, in which for samples with a larger cross-sectional area the probability of occurrence of inhomogeneities and defects at the level of the microstructural structure is higher.

CONCLUSION

Thus, to improve the mechanical properties of products with a complex volumetric and surface structure, it is recommended to select sufficiently high tempering temperatures to reduce the level of residual stresses. In order to eliminate microdefects and roughness on the internal surfaces of the cavities, it is possible to carry out additional etching treatment. In general, as follows from the test results, for solid materials obtained by layer-by-layer synthesis, sufficiently large tolerances for mechanical characteristics should be given. For samples with a complex structural structure, the range of deviation of properties may be negligible; however, the reduction in the mechanical properties of the material should be taken into account, due to an increase in the area of defective surfaces and the appearance of residual stresses.

The presented work presents the results of the first series of studies on the feasibility of using layer-by-layer laser metal synthesis technology to produce critical elements of complex aerospace structures.

At present, one of the most urgent tasks is related to the need to increase the operating parameters and characteristics of the jet nozzle. At the moment, methods are used to solder the corresponding cooling channel, which imposes certain limitations on the possibility of improving the nozzle part of the engines, and also significantly complicates the design. Therefore, the solution of the problem of creating high-precision channel systems in thin-walled structures with the use of layered laser synthesis technologies is relevant. Such technologies can be used to create jet engines for small unmanned aerial vehicles.

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