Effect of hot isostatic pressing on the quality of metal parts obtained by selective laser melting

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Abstract. In this work, an approach to improving the quality of material obtained by the method of selective laser melting is considered. The analysis of powder material of stainless steel is carried out. A number of samples were obtained with subsequent HIP-processing. The structure was analyzed, and the hardness of the obtained samples was measured before and after HIP treatment.

1. Introduction
One of the topical areas of application of additive technologies is medicine and the production of unique medical products. This area has a need for individual and structurally complex parts that work in extremely critical places and areas. In addition to strength, an important parameter is the density of the resulting structure of the part [1,2]. Selective laser melting (SLM) is one of the additive manufacturing technologies, a feature of which is the piece production of complex parts. SLM assumes layer-by-layer growing of a powder metal part in an inert gas environment. In the process, the part is heated in the area of laser action and non-equilibrium cooling. This leads to uneven shrinkage of the metal. In the process of manufacturing a part by the SLM method, internal residual stresses associated with the presence of a temperature gradient, the quality of the powder material, as well as incorrectly selected parameters for growing parts are inevitable. This leads to cracks and pores. [3]. The research results [4, 5] show the influence of certain parameters of the part growing on the final roughness and porosity of the product surface. These defects are unacceptable in the manufacture of critical parts for medical purposes in contact with biological tissue. Their elimination is possible not only by optimizing the SLM parameters, but also by post-processing [6]. Hot isostatic pressing (HIP) is a successful method for reducing microporosity in detail. HIP is a well-known process for reducing porosity and producing relatively large, bulky and dense parts. The process consists in supplying an inert gas under high pressure when heated to high temperatures in a special working chamber. The pressure is isostatic and therefore preserves the geometry of the component. Simultaneously, high temperature and pressure eliminate internal pores or defects [7, 8]. Reducing the size and number of pores in the final product is an urgent task.

2. Materials and methods
The production of samples took place on an industrial machine Concept Laser M2 cusing. This unit operates on the technology of selective laser melting and is designed for the production of parts of complex geometric shapes from reactive and non-reactive metal powders. Stainless steel powder with the following chemical composition was used as a starting material:
**Table 1.** Chemical composition of the powder material.

| Mass fraction of elements, % |
|-----------------------------|
| Fe  | C   | Si | Mn | Cr   | Ni  | Mo | S   | P   | O   |
| base | 0.07 | 0.75 | 2 | 16-18 | 10-14 | 2-3 | 0.02 | 0.03 | 0.10 |

Investigation of the particle size distribution was carried out by methods of optical and scanning electron (SEM) microscopy.

**Figure 1.** Image of powder particles: a - SEM, b - optical microscopy.

In figure 1 (b) it can be seen that the particles inside have a continuous structure and the pores are completely absent. Most of the particles are spherical, deformed particles are rare, the average fraction size is 40 μm. The powder material was exposed to laser action. The laser radiation wavelength was 1.06 μm. The scanning speed was varied from 500 to 1600 mm / s. Layer-by-layer melting occurs according to the following strategy: the grown layer of the part is fragmented into square areas, called "islands" with a size of 5 x 5 mm [9]. Laser melting of each individual "island" is performed. The fragments are melted according to a predetermined algorithm that allows localizing the internal stresses of the metal in a small area. Each "island" is processed by hatching, perpendicular to the neighboring areas, which allows stresses to be reduced to a minimum. When the next layer is fused, the dividing step shifts, the direction of the hatching inside the "islands" is rotated, providing a dynamically changing hatch pattern. All "islands" are fused with each other by completely melting the edges of the "island" - this allows to achieve the most homogeneous and dense structure with minimum porosity [10, 11]. The production of prototypes was carried out in a nitrogen atmosphere.

A group of samples was selected for further processing by hot isostatic pressing. HIP-processing was carried out using an isostatic press, which has the ability to process samples with stepwise heating up to 2000 C at a pressure of up to 2000 Bar. The HIP treatment process took place under the following operating parameters: operating temperature - 1000 ° C, operating pressure 1500 bar, temperature rise rate and fall rate - 6 seconds, holding time - 7 hours.

**3. Results**

The structural-phase composition was studied on a D8 Advance (Bruker). The material, which was not subjected to isostatic pressing, corresponded to a solution of chromium, nickel, and other components in iron, without the precipitation of other individual phases (Figure 2).
Figure 2. Structural phase analysis of powder samples.

The study defects are revealed by obtaining a thin section and etching of the transverse and longitudinal surface of the sample, followed by examination by means of optical microscopy. The initial samples have cellular structure contours typical for the SLM technology [12]. After processing, the samples have a mosaic structure typical of HIP [13]. Image acquisition and analysis of the porous structure was performed using an Altami microscope and AltamiStudio 5.0 software.

Figure 3. Microstructure of the obtained samples: a - the original sample, b - after HIP.

It was found that pores up to 8 μm in size were observed in the initial samples. The use of HIP reduces the maximum pore size to 1 micron, while the porosity of less than 1 micron is completely tightened and the material has a more uniform structure.
Hardness was measured at random points in planes 1, 2, and 3 (Fig. 4). Before HIP in area 1, the average hardness is greater than the average hardness in planes 2 and 3, this is due to the inherent anisotropy of mechanical properties in SLM, caused by the build strategy. In Figure 4, the growth trajectory Z is the direction of heat removal to the build substrate. Accordingly, directional crystallization of the melt pool is observed, which leads to an increase in hardness in the direction of solidification, rather than in planes 2 and 3.

Figure 4. Planes of hardness measurement.

Thus, the average hardness of the original samples is 90-92 HRB, after HIP processing the average value decreased to 88-90 HRB, the results of measuring the hardness of surfaces 1-3 are at the same level. Also, as a result of HIP processing, there is a decrease in porosity, which is also reflected in [14, 15].

4. Conclusion
In this work, experimental data on the melting of stainless steel by the SLM method are obtained. The results of the study of the phase transformations of the material, the physical and mechanical characteristics of the parts obtained using the integrated technology by the SLM and HIP processes are reflected. Thus, as a result of the analysis of the porosity of a group of samples, the effect of HIP on a decrease in the quantity and size of pores, as well as on a decrease in hardness, was established.

Acknowledgements
This work was supported by the Russian Foundation for Basic Research (Grant 20-08-00310).

References
[1] Shishkovsky I V, Yadroitsev I A and Smurov I Y 2013 Manufacturing three-dimensional nickel titanium articles using layer-by-layer laser-melting technology Tech. physics letters 39(12) 1081-1084
[2] Smurov I Y, Movchan I A and Yadroitsev I A 2011 Laser-aided additive production Vestn. MGTU Stankin 2(4) 144-146
[3] Tillmann, W, Schaak C, Nellesen J, Schaper M, Aydinöz M E and Hoyer K P 2017 Hot isostatic pressing of IN718 components manufactured by selective laser melting Additive Manufact.13 93-102
[4] Tarasova T V, Nazarov A P and Prokofev M V 2015 Effect of the regimes of selective laser melting on the structure and physicomechanical properties of cobalt-base superalloys The Phys.of Metals and Metallography 116(6) 601-605
[5] Kamat A M and Pei Y 2019 An analytical method to predict and compensate for residual stress-induced deformation in overhanging regions of internal channels fabricated using powder bed fusion Additive Manufact. 29 100796
[6] Leuders S, Thöne M, Riemer A, Niendorf T, Tröster T, Richard H A and Maier H J 2013 On the mechanical behaviour of titanium alloy TiAl6V4 manufactured by selective laser melting: fatigue resistance and crack growth performance Int. J. Fat., 48 300-307
[7] Lavery N P, Cherry J, Mehmood S, Davies H, Girling B, Sackett E and Sienz J 2017 Effects of hot isostatic pressing on the elastic modulus and tensile properties of 316L parts made by powder bed laser fusion Materials Sci.and Eng.: A 693 186-213
[8] Sames W J, List F A, Pannala S, Dehoff R R and Babu S S 2016 The metallurgy and processing science of metal additive manufacturing Int. Materials Review 1–46
[9] Voznesenskaya A A, Kochuev, D A, Kireev A V, Zhdanov A V and Raznoschikov A S 2020 Optimization of laser melting parameters of martensity-aging steel powder IOP Conf. Series: Materials Sci. and Eng. 896(1) 012132
[10] Boschetto A, Bottini L and Veniali F 2017 Roughness modeling of AlSi10Mg parts fabricated by selective laser melting J. of Materials Proc. Tech. 241 154-163
[11] Kruth J P, Deckers J, Yasa E and Wauthlé R 2012 Assessing and comparing influencing factors of residual stresses in selective laser melting using a novel analysis method Proc.of the institution of mech.eng., Part B: J. of Eng. Manufact. 226(6) 980-991
[12] Usov S, Tochilin I, Voznesenskaya A and Zhdanov A 2019 Evaluation of microstructure and physical and mechanical properties of bulk parts obtained from Russian and German steel powder by selective laser melting J. of Phys.: Conf. Series 1331(1) 012021
[13] Raznoschikov A S, Kochuev D A and Voznesenskaya A A 2020 Selective Laser Melting of Stainless Steel with Subsequent Processing In Materials Sci. Forum 989 845-849
[14] Santorinaios M, Brooks W, Sutcliffe C J and Mines R A.W 2006 Crush behaviour of open cellular lattice structures manufactured using selective laser melting WIT transactions on the built environment 85 481-490
[15] Gan M X and Wong C H 2016 Practical support structures for selective laser melting J. of Materials Proc.Tech. 238 474-484