Effect of part orientation on temperature stresses in the structure of a material during selective laser melting

A A Voznesenskaya¹, D A Kochuev¹, A S Raznoschikov¹, A V Zhdanov¹ and V V Morozov¹

¹Vladimir State University named after Alexander and Nikolay Stoletovs, 87 Gorky st., Vladimir, 600000, Russia

e-mail: 2obk@bk.ru

Abstract. In this paper, we consider the problems of thermal stress during selective laser melting. Using scanning electron microscopy, the average particle size and shape of the AlSi10Mg powder alloy were revealed. Details of complex geometric shapes have been grown by various construction strategies using the selective laser melting method. In the first case, the influence of supporting structures on the geometric shape of the part was considered. An optimal set of supporting structures has been developed in order to reduce the time spent on machining after selective laser melting, as well as to exclude supports in hard-to-reach cavities. In the second case, the location of the part on the construction platform was considered. It was found that changing the orientation of the parts allows to reduce the volume and number of supporting structures. The results are obtained on thermal stresses occurring in the process of growing a part by selective laser melting.

1. Introduction
At present, additive technologies are actively developing all over the world. Many studies have studied the use of materials such as magnesium, aluminum, titanium, and high-strength steels [1-6]. Additive manufacturing technologies, such as the selective laser melting method, make it possible to obtain complex three-dimensional structures [7, 8] and also reduce production time and costs. In [9] it was found that with the help of additive technologies it is possible to ensure production flexibility and reduce the number of assembly elements. But, despite the attractiveness of this technology, there are many difficulties in introducing into production. The main problems can be associated with physical processes when growing parts of complex geometry by selective laser melting (SLM). For example, in the manufacture of parts with complex configurations, there are limitations which include the need to add supporting structures to geometric protrusions forming an angle of less than 45° to the construction plane [10]. Due to significant temperature gradients and not optimal technology modes, defects can also be formed: stresses, deformations, inaccurate sizes, cracks, delamination, and porosity occur. The heat generated by the laser beam must be quickly transferred from the molten bath to prevent the formation of residual stresses. For this reason, the thermal conductivity of the materials (created part) should be high enough to reduce the amount of unwanted heat, thereby reducing the residual stress [11]. When the thermal stress exceeds the strength of the material, plastic deformation occurs. The deformation of the hanging elements of the part is also due to the absence of supports for fixing (reliable contact of the
formed) layer with the previous layers [12]. When constructing parts with complex geometric shapes, it is necessary to use supporting structures. Supports an important function in constructing a part using the SLM method [13]. For example, incorrect calculations of supports and the location of the part on the substrate can lead to increased thermal effects, and as a result, this will lead to defects and warping of the resulting part [14-18]. This experimental study was carried out in order to find the melting conditions that are most suitable for easy removal of supporting structures and reduction of deformations of the resulting part by selective laser melting.

2. Methods
The material used was aluminum alloy powder AlSi10Mg. The powder is made from alloys by spraying (spraying) the molten alloy with heated nitrogen with the subsequent separation of the obtained product into fractions of the required particle size distribution. Photographs of the powder material were obtained by scanning electron microscopy (Figure 1). Most particles have a spherical shape, the average fraction size is 40 microns. Technological preparation of the powder material was carried out by the method of mechanical mixing and phased sifting, in order to obtain the most uniform particle size distribution.

![Figure 1. SEM image of the powder material.](image)

Prototypes were grown on a selective laser melting facility (Concept Laser M2 Cusing, Germany), which is equipped with a 400-watt diode-pumped fiber laser. Aluminum powder material was deposited on the surface of the substrate, the thickness of the powder layer was 40 μm. The powder layer was subjected to continuous laser irradiation: the radiation wavelength was 1070 nm, the laser beam diameter on the treated surface was 50 μm. For the purpose of uniform heat exposure and reducing internal stresses, the following scanning strategy was chosen: the scanning area is divided into the smallest squares and processed by a laser beam in a random order. To exclude oxidation of the material during the laser treatment process, the working space is located in a nitrogen atmosphere.

3D model was prepared in the program Materialise Magics. In this software package, it is possible to check a part for construction errors and intersecting lines, it is also possible to split a part into layers, select the necessary support for constructing a part by the method of selective laser melting. For the study, a type of part with a complex shape configuration was chosen (Figure 2). Due to the presence in the construction of internal channels, the number and thickness of supports should be minimized in order to shorten the machining time and eliminate support in hard-to-reach places. Thus, a study was carried out on the optimal content of supporting structures in the construction of massive parts.
In the absence of supports of proper thickness, distortion of the part is observed due to sharp thermal fluctuations. Figure 2 shows samples with pronounced defects in the absence of supports. In the absence of support elements at an angle of less than 45 degrees [19], the geometry is broken due to the "sagging" of the powder material (Figure 2 sample on the left). In the case of the application of the optimal number of supports for the minimum thickness, the part is obtained with a slight distortion of the shape (Figure 2, sample on the right). Thus, the main defects that occurred during the manufacture of parts should be noted dross formation and deformation.

To study the position in the plane, a part was selected, shown in Figure 3. This model demonstrates the need for optimal positioning of the part in the plane during construction.

Several options for the location of the part on the substrate are considered, both without supports (Figure 3C) and with different types of supports (Figure 3 A, B, D). When constructing a part with supports from 0.1 to 1 mm needle-shaped with a distance between needles of 1 to 5 mm, detachment of the part is observed (Figure 3 B) and increased roughness on the part of the supports, but removing this type of support structure is very effective compared to supports volumetric shape with a column thickness of 25 mm (Figure 3 A, D), where labor-intensive mechanical post-processing is required. Nevertheless, with massive supports (Figure 3 D), the detail was able to grow completely with minimal geometry distortion. When positioned of the part at a certain angle (Figure 3 C), in order to exclude the supporting structures, the distortion of the part is also observed. When building a part with volumetric supports perpendicular to the substrate (Figure 3 D), heat transfer occurs much more efficiently, and the part is warped to an insignificant degree.
3. Results and Discussion
The calculation of the optimal parameters for the Al alloy on the Concept Laser M2 Cusing machine. Studies have shown that it is possible to obtain three-dimensional objects from a domestic Al alloy using SLM. The results show that the use of additive technologies will significantly help to reduce the complexity of manufacturing parts. It should be noted that the main part of the temperature heating goes to the massive substrate through thick supports, therefore the main focus is on modeling the optimal set of supports. Also in this study, it was found that changing the orientation of the parts allows to reduce the volume and number of supporting structures.

![Figure 4. Image of thermal stress propagation during construction: A) with no supports, B) with needle supports, C) with bulk supports.](image)

In the absence of supports, the formation of layers is possible when the condition of heat removal is satisfied, for example, in the volume of the part being created (Figure 4A). When building a new layer on the surface of the powder, preserving the geometry is difficult, due to the formation of a significant heat load. The removal of heat from the area of formation of the new layer into the powder material is difficult, since the amount of thermal conductivity of the powder is much less than the structure formed, or the substrate material on which the construction is carried out. In case of insufficient heat removal from the area of formation of a new layer, the geometry is disturbed, due to temperature warping, the quality of the formed outer surface significantly deteriorates, up to the destruction of the created layer. Any defects in the construction of the layer affect the uniformity of the deposition of the powder material to build the next layer, and as a result, the defect structure is inherited through multiple layers.

Creating needle supports helps to reduce temperature warping when building layers (Figure 4B), but tearing of the formed layer from supports is possible if the condition of excess heat removal is not fulfilled, and as a result, the geometry of the part created is disturbed. The created supports must ensure not only the mechanical confinement of the created layer during the construction of the model, but also provide the necessary heat removal, otherwise destruction of the point of contact can support the formation of subsequent layers and, as a consequence, violation of the geometry of the construction.
When constructing a part with due regard for the required cross-section of supports (Figure 4C), which provide the necessary heat sink, the violation of the geometry of the created part does not occur, or is negligible. Excessive heat load is removed with the help of supports.

4. Conclusions
The calculation of the optimal parameters for the Al alloy on the Concept Laser M2 Cusing machine. Studies have shown that it is possible to obtain three-dimensional objects from a domestic Al alloy using SLP. The results show that the use of additive technologies will significantly help to reduce the complexity of manufacturing parts. It should be noted that the main part of the temperature heating goes to the massive substrate through thick supports, therefore the main focus is on modeling the optimal set of supports. Also in this study, it was found that changing the orientation of the parts allows to reduce the volume and number of supporting structures.

Acknowledgements
This work was financially supported in the framework of the project 1187/20.

References
[1] Kuziak R, Kawella R and Waengler S 2008 Advanced high strength steels for automotive industry Archives of civil and mech. eng. 8(2) 103-117
[2] Kochetov D, Voznesenskaya A and Zhdanov A 2019 Influence of Surface Modification of Granules of Powder Material on the Dynamics of Selective Laser Melting Mater. Today: Proceed. 11 485-488
[3] Voznesenskaya A A, Kochuev D A, Chkalov R V, Kireev A V and Morozov V V 2020 Research of post-processing approaches for parts obtained by the method of selective laser melting J. of Phys.: Conf. Series 1439(1) 012028
[4] Li Z, Li J, Zhu Y, Tian X and Wang H 2016 Variant selection in laser melting deposited α+β titanium alloy J. of Alloys and Compounds 661 126-35
[5] Voznesenskaya A, Zhdanov A and Morozov V 2019 Study of the effect of scanning speed in selective laser melting on the physicomchemical properties of samples J. of Phys.: Conf. Series 1331 (1) 012007
[6] Yadollahi A, Shamsaei N, Thompson S M and Scely D W 2015 Effects of process time interval and heat treatment on the mechanical and microstructural properties of direct laser deposited 316L stainless steel Mater. Sci. and Eng.: A 644 171-83
[7] Osakada K and Shiomi M 2006 Flexible manufacturing of metallic products by selective laser melting of powder Intern. J. of Mach. Tools and Manuf.46(11) 1188-193
[8] Yan C, Hao L, Hussein A and Raymont D 2012 Evaluations of cellular lattice structures manufactured using selective laser melting Intern. J. of Mach. Tools and Manuf.62 32-8
[9] Parthasarathy J, Starly B, Raman S and Christensen A 2010 Mechanical evaluation of porous titanium (Ti6Al4V) structures with electron beam melting (EBM) J. of the mech. behavior of biomed. mater. 3(3) 249-59
[10] Kim T, Ha K, Cho Y R, Jeon J B and Lee W 2019 Analysis of residual stress evolution during powder bed fusionprocess of AISI 316L stainless steel with experiment and numerical modeling The Intern. J. of Adv. Manuf. Techn.105(1-4) 309-23
[11] Casavola C, Campanelli S L, and Pappalattere C 2009 Preliminary investigation on distribution of residual stress generated by the selective laser melting process The J. of Strain Analys. for Eng. Design 44(1) 93-104
[12] Calignano F 2014 Design optimization of supports for overhanging structures in aluminum and titanium alloys by selective laser melting Mater. & Design 64 203-13
[13] Järvinen J P, Matilainen V, Li X, Piili H, Salminen A, Mäkelä I and Nyrhilä O 2014 Characterization of effect of support structures in laser additive manufacturing of stainless steel Phys. Proced. 56 72-81
[14] Zaeh M F and Branner G 2010 Investigations on residual stresses and deformations in selective laser melting Prod. Eng. 4(1) 35-45
[15] Loh L E, Chua C K, Yeong W Y, Song J, Mapar M, Sing S L, Liu Z H and Zhang D Q 2015 Numerical investigation and an effective modelling on the Selective Laser Melting (SLM) process with aluminium alloy 6061 Intern. J. of Heat and Mass Transf. 80 288-300
[16] Hussein A, Hao L, Yan C and Everson R 2013 Finite element simulation of the temperature and stress fields in single layers built without-support in selective laser melting Mater. & Design 52 638-47
[17] 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 transact. on the built environment 85
[18] Liu Y, Yang Y and Wang D 2016 A study on the residual stress during selective laser melting (SLM) of metallic powder. The Intern. J. of Adv. Manuf. Techn. 87(1-4) 647-656
[19] Gan M X and Wong C H 2016 Practical support structures for selective laser melting J. of Mater. Process. Techn. 238 474-84
[20] Morgan D, Agba E and Hill C 2017 Support structure development and initial results for metal powder bed fusion additive manufacturing Proced. Manuf. 10 819-30