Regularities of Crystallographic Texture Formation in Products Obtained by Selective Laser Powder Melting

Margarita Isaenkova¹, a), Yuriy Perlovich¹, Anatoliy Rubanov¹, b), Vladimir Fesenko¹, Artiom Yudin²

¹National Research Nuclear University “Moscow Engineering Physics Institute”, Kashirskoe shosse, 31, Moscow, 115409, Russian Federation
²JSC “RPA “CNIITMASH”, Moscow, Russian Federation

a) Corresponding author: isamarg@mail.ru
b) toly.rubanov@yandex.ru

Abstract. As examples of austenitic steel 316L, nickel alloy (Inconel 625) and titanium alloy VT1-0, the regularities of the development of crystallographic texture in monolithic samples and lattice structures obtained by selective laser melting (SLM) of powder are considered. Crystallization of all of these alloys is carried out by the formation of crystals with a cubic structure {100} <001> (bcc or fcc). Upon subsequent cooling, the titanium samples additionally undergo a $\beta \rightarrow \alpha$ phase transformation while maintaining the Burgers orientation relation. A sharp cubic texture {100} <001> is formed in the middle-height layers of a monolithic product, which determines the anisotropy of the properties of SLM samples. The layer-by-layer change in the crystallographic texture is associated with the growth of columnar crystals of the cubic phase, which are formed due to the thermal effect of the molten region on the underlying layers, which determine the orientation of the crystal during its crystallization. This texture is typical for both the fcc-phase of steel and the bcc-titanium phase. In the case of the formation of lattice structures, columnar crystals with a preferred orientation of <001> along the growth direction are formed in the central part of the ribs and nodes along the diameter of the structural elements. On the basis of the crystallographic texture of the steel lattice structures and the mechanical properties of the monolithic specimens, the strain curves of the lattices under their compression were calculated.

1. Introduction

The development of additive technologies presupposes a comprehensive analysis of the physical processes of crystallization that occur in the zone of material formation. At present, a large number of scientific studies are carried out on the construction of models for the development of the structure of products obtained by the method of selective laser powder melting (SLM) [1, 2]. A huge number of experimental results have been obtained on the study of the structure and properties of SLM samples from powders of different alloys: steel [3, 4], titanium [5, 6] and nickel [3, 7]. These questions are of great practical importance, since the listed materials are used for the manufacture of critical structural parts in various fields of science and technology. These are rocketry and the aviation industry, the nuclear industry and medicine [8]. As a rule, such parts have a complex shape (for example, blades of a gas turbine engine [9] or a hip joint [10]), and the technological process of their manufacture is a laborious task.
The method of SLM of powders is a very promising technology for producing objects of complex shape [11, 12]. Interest in additive technologies, i.e. to the "direct growing" of metal products, arose, first of all, in the aviation industry, space industry, power engineering, medicine and a number of other industries that require the manufacture of parts of complex geometry [13]. It is there that this technology is most relevant and is already widely used as an alternative to traditional technological methods for the production of not only prototypes, but quite marketable products. Moreover, the motivation here is not the ability to create something unique, with unusual properties, but economic feasibility. In the course of selective synthesis, rapid crystallization of the material occurs, which is accompanied by a high cooling rate, as a result of which a specific structure is formed in the material, which has a nonequilibrium nature. The structural-phase state of such a material can be controlled by various technological factors. One of the most effective levers of influence on the structure of the material is the energy parameters of the laser.

In the manufacture of products by the SLM method, the features of the location of the part in the working area of the 3D printer and its geometric shape determine the mode of forming the part, and, therefore, can lead to different properties of the resulting products. As was shown in the work [14] about the regularities of the structure formation in a steel product during SLM, the crystallographic texture is a source of information about the features of the crystallization process, which is influenced by the parameters of the technological process (radiation power, scanning speed, track width, etc.)

The structure formed as a result of crystallization determines the properties of the manufactured product.

In the manufacture of products by the SLM powder method, the part is formed from successively applied layers of powder under the action of laser radiation (LR) when the laser beam is scanned over the surface of the part being manufactured in accordance with a predetermined trajectory. According to the results of work [15], the processes occurring in the material after powder melting and crystallization can be divided into two stages. At the first stage, the material is in the zone of local melting by LR near the surface and is subject to rapid heating to temperatures close to the melting temperature, followed by rapid cooling, as a result of which a nonequilibrium structure is formed. At the second stage, as new layers are formed, the material is in the heat-affected zone, away from the area of direct exposure to LR, resulting in a decrease of temperature, heating and cooling rates, which contributes to stabilization (annealing of the material) and the formation of a more equilibrium structure. The crystallographic texture, the predominant orientation of the crystallographic axes of grains relative to the outer directions, is a sensitive indicator of the physical processes of grain growth in the manufacture of products by the SLM method.

Thus, the objectives of the work are to establish the regularities of the formation of the structure and texture of the different materials (steel, titanium and nickel alloy of the Inconel type), the mechanical properties of monolithic and lattice products obtained by SLM of powders; as well as to predict their mechanical properties based on the results of structural and texture analysis and available properties for massive SLM materials.

2. Samples and research methods
The paper presents the results of layer-by-layer changes in the crystallographic texture along the product construction direction. The formation of a crystallographic texture in 316L austenitic steel, Inconel nickel alloy, and VT1-0 titanium is considered. The listed alloys have different crystal structures under normal conditions: fcc and hcp, however, the formation of the material structure is set by their high-temperature modifications, which are formed in the melt zone. The most common high-temperature modification is cubic structures. For the indicated alloys, such structures are fcc and bcc subsection.

The regularities of the formation of a crystallographic texture in cubic samples obtained by selective laser alloying of powders of different alloys were studied on monolithic cubic samples 6x6x6 mm or 10x10x10 mm in size and lattice structures of two types – 8x8x8 mm and 12x12x12 mm. The samples were printed using the following mode [6]: a laser power is equal 220-357 W, a scanning...
speed – 700-850 mm/s, a scanning step – 60-80 μm and a powder layer thickness – 50 μm. A powder with a spherical shape of particles and an average size of 40-50 microns was used. Namely such mode allows to obtain solid, low-porous samples [16]. At the same time, for different types of products, the optimal modes were selected, which made it possible to obtain monolithic samples with maximum density or lattice structures with cells of the correct shape.

Various scanning strategies were used in the manufacture of samples: 1) single-pass scheme; 2) cross, with a change in the scanning direction in the next layer by 60 or 90°; 3) checkerboard scanning scheme (figure 1). The Z direction (figure 2) is the product construction direction, the X direction is the main scanning direction of the laser beam and Y is the secondary scanning direction. In the case of using the scanning strategy 2 and 3, the Y and X directions are equal (equivalent).

![Diagram](image1.png)

**Figure 1.** Alternating layers with different directions of the laser beam scanning.

![Diagram](image2.png)

**Figure 2.** Layers of the studied samples. Z – the product construction direction; X – direction of the laser beam scanning.

Texture analysis was carried out by X-ray methods by constructing direct pole figures (DPFs) for a surface perpendicular to the Z-direction [17, 18]. The measurements were carried out on a D8 DISCOVER X-ray diffractometer using different radiation. For each layer of the material, 4 incomplete DPFs were measured, on the basis of which the grain orientation distribution function (ODF) and full DPFs were reconstructed in accordance with the MTEX software [19].

### 3. Experimental Results

Figure 3 shows changing the complete DPFs \{110\} or (0001) in height of the investigated steel, nickel and titanium products obtained according to the cross strategy. Since titanium has a hexagonal lattice at room temperature, the distribution of basal axes was constructed for such a crystal lattice, which are parallel to the <110> axes for the high-temperature modification of the bcc. Since the formation of the crystallization texture is initiated in the high-temperature phase, the distribution of basal axes characterizes the orientation of the bcc lattice. Figure 4 shows the graphs of changes in the pole density of the texture components <110> and <100> along the direction of the specimen growth. For hcp Ti-metal the distribution of basal normal corresponds cubic symmetry due to Burgers orientation relation between hcp and bcc-phases: (0001)||{110} and <1120>||<111>. This allows to calculate from DPF (0001) fractions of different texture components <100> and <110> for high temperature bcc-phase in which hcp metal initially crystalized at the molten metal cooling.

According to the results presented, the middle layers of all specimens are characterized by a sharp crystallographic texture \{001\}<100>. However, in the lower layers or at the beginning of the specimen formation from a powder, an axial texture with a predominance of the <111> component along the Z direction is observed on the supporting structure. At a distance of 0.5 mm, a change in the main texture component to <110> is observed, which becomes limited and then is replaced by a stable one <100> for the rest of the specimen. Only in the uppermost layer this specimen is violated due to the stoppage of the building process. This sequence of the crystallographic texture development can be traced for all samples, regardless of the Bravais lattice type at crystallization temperature: fcc or bcc.
4 Discussion

When the scanning strategy is changed to a single-pass one, an axial texture component appears on the DPF, which causes blurring around the X direction, the scanning direction of the laser beam. Figures 5-a, b show typical {100} DPFs for a plane perpendicular to the Z direction in the case of a cross-beam scanning strategy (a) and a single-pass scanning scheme (b). It should be noted that the scanning direction of the laser beam X for both scanning patterns is horizontal. Figure 5-c shows the track
orientation diagram, the direction of heat removal and the main crystallographic directions in growing grains in the case of using a cross-scan strategy. For a single track, it was shown in numerous works [20, 21] that columnar crystals are oriented with the <100> axis along the direction of heat removal. Then the DPF {100} should look as shown in figure 5-b. The sharp crystallographic texture can be explained only if the lateral parts of the track are melted during the formation of the overlying layer. A constant shift with respect to the underlying layer or cross direction of the beam movement allows for the predominant growth of crystals of a single orientation. That is, when, in the process of forming the next layer, the lower part of the track of the previous layer acts as a seed for the molten material, and its side parts causing the scattering of the <100> orientation are melted and oriented in accordance with the existing columnar crystals. This process also explains the continuous improvement of the crystallographic texture with increasing a height along the product print direction and the texture scattering if the building process is stopped, i.e. in specimen surface layers (figures 3-c and 4-c).

![Figure 5. DPF {100} for Z-section of SLM-samples made by a cross (a) and single pass (b) scan strategies. Figure c shows the layout of the track relative to the external axes of the product with a single-pass scanning scheme; dashed arrows indicate the direction of heat removal during the crystallization of molten metal. Possible arrangements of successive layers of the product with a one-pass scanning strategy (d, e). Microstructure of SLM samples in the YZ section perpendicular to the scanning direction of the laser beam (f).](image_url)

The considered mechanism of the formation of the crystallographic texture explains the appearance of significant anisotropy of properties in such specimens, as shown in [22, 23]. When printing lattice structures in the nodes and in the middle part of the ribs, the growth of columnar crystals oriented in the direction of growth of the lattice structure is also observed. The severity of the axial crystallographic texture <100>||Z in a lattice structure [24] depends on the power of the laser radiation used to print it. In the samples obtained using the minimum radiation powers, scattering of the axial texture is observed, which is caused by an increase in the number of chaotically oriented grains with a simultaneous decrease in the volume of columnar, strictly oriented crystals located mainly near the axis of the ribs of the lattice structure. The sharpness of the texture in lattice samples with a small void size is higher than in samples with a large void size. Based on the results of measuring the mechanical properties of bulk products, crystallographic texture and type of lattice structures, their deformation behavior under compression was predicted [12].

5 Conclusions
1. It was found that as the product is formed along the Z axis, the crystallographic texture of successive layers changes. For all studied materials (austenitic steel, nickel alloy and titanium) it was observed the common regularities of texture formation. Crystallites of the lower layers are characterized by an axial texture with the preferred orientation of the <111> axis along the Z direction and; at a distance of 0.5 mm, a change in the main texture component to <110> is observed, which becomes limited and then is replaced by the component <100>, which is stable for the rest of the
product. Only in the uppermost layer this pattern is violated due to the stoppage of the building process.

2. It was found that the formation of texture in the middle layers of the product is due to the growth of columnar crystals of the cubic phase with the orientation {100}<001>. In this case, the upper layers inherit the texture of the lower layers. The texture of the supporting structure does not affect the texture of the part itself, which begins to form at a distance of 0.5 mm.

3. A model of the formation of columnar crystals of a certain orientation in products produced by selective laser melting and the possibility of changing it by varying the beam scanning strategy is proposed.

4. A model has been developed for describing the deformation behavior of bulk and lattice specimens based on the results of the analysis of their crystallographic texture and properties of bulk materials.

Acknowledgment
The work was carried out within under Governmental Support of Competitive Growth Program of NRNU MEPhI (agreement No.02.a03.21.0005).

References
[1] Zinovieva O, Zinoviev A, Romanova V and Balokhonov R 2020 Additive Manufacturing 36 101521
[2] Zakirov A, Belousov S, Bogdanova M et al. 2020 Additive Manufacturing 35 101236
[3] Yakout M, Elbestawi M A and Veldhuis S C 2019 J. Mater. Process. Technol. 266 397-420
[4] Khodabakhshi F, Farshidianfar M H and Gerlich A P 2020 Additive Manufacturing 31 100915
[5] Li X P, Van Humbeeck J and Kruth J P 2017 Materials & Design 116 352-8
[6] Isaenkova M G, Perlovich Y A, Yudin A V and Rubanov A E 2018 Tsvetnye Metally 16 69–74
[7] Delcuse L, Bahi S, Gunputh U, et al. 2020 Additive Manufacturing 36, 101339
[8] Mengke Wang, Yuwei Wu, Songhe Lu et al. 2016 Prog. Nat. Sci. 26(6) 671-7
[9] Attard B, Cruchley S, Beetz Ch, et al. 2020 Additive Manufacturing 36 101432
[10] Bergmann C, Lindner M, Zhang W, et al. 2010 J Eur Ceram Soc. 30(12) 2563-7
[11] Isaenkova M G, Perlovich Y A, Yudin A V et al. 2020 Inorg. Mater. Appl. Res. 11(3), 692-8
[12] Isaenkova M G, Yudin A V, Rubanov A E et al. 2020 J. Mater. Res. Technol. 9(6) 15177-84
[13] Ngo T D, Kashani A, Imbalzano G, Nguyen K T Q et al. 2018 Compos. B. Eng. 143 172-96
[14] Perlovich Yu A, Isaenkova M G, Dobrokhотов P L et al. 2019 Russian Metallurgy (Metallofiz.) 2019 (1) 42–7
[15] Heeling T, Cloots M, Wegener K 2017 Additive Manufacturing 14 116-25
[16] Yudin A V, Beregovsky V V, Tret’yakov E V, et al. 2017 IOP Conf. Series: Materials Science and Engineering 218 012022
[17] Perlovich Yu, Isaenkova M and Fesenko V 2016 IOP Conf. Series: Materials Science and Engineering 130 012057.
[18] Perlovich Yu, Isaenkova M and Goitzev V 1996 J. de Physique IV Colloque C6, suppl. J. de Physique III 6 335-42
[19] Hielscher R and Schaeben H 2008 J. Appl. Crystallogr 41 1024-37
[20] Zhou X, Li K, Zhang D, Liu X, Ma J, Liu W et al. 2015 J Alloys Compd 631 153-64
[21] Yadroitsev I, Gusarov A, Yadroitsava I and Smurov I 2010 J. Mater. Process. Technol. 210(12) 1624-31
[22] Isaenkova M G, Perlovich Yu A, Rubanov A E and Yudin A V 2019 CIS Iron and Steel Review 18 64-8
[23] Kunze K, Etter T, Grässlin J and Shklover V 2014 Materials Science & Engineering A 620 213–22