Influence of technological factors on porosity in the mass production of inlet guide vanes using additive technologies.

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Abstract. Stainless steel products manufactured using additive technologies are widely used in many branches of modern industry (aviation, medicine, engineering, etc.). One of the main defects in this type of production is porosity. Surface treatment with high-current pulsed electron beams (HPEB) allows not only to increase microhardness and corrosion resistance, but also to reduce surface roughness and porosity in the recrystalized layer. This article presents studies of the microstructure of stainless steel samples, as well as the structural and phase state of the surface layer of samples before and after irradiation with HPEB.

1. Introduction
The topic of this article can be considered relevant as the use of additive technologies makes it possible to manufacture parts with a complex profile (front devices and fuel injectors made of heat-resistant alloys), as well as parts with internal cooling channels (heat exchangers with a complex system of cooling channels of any shape) and technological equipment (complex molds). In addition, with the use of SLM technology, the production cycle of products is reduced several times, while it is possible to obtain new functional and design features of parts with a new set of operational properties. The blades of the input guide device are one of the most important components of an aircraft engine. The design of the blades, as a rule, is characterized by a high level of originality of technical solutions, a special design with a rather complex mechanism for regulating their angle, ensuring the preservation of a constant air supply speed, reducing the load on the compressor, as well as many other requirements. Modern methods of calculation and the state of the theory and practice of designing the geometry of the input guide blades do not allow us to reliably predict the results of design decisions. Therefore, the main criterion for the reliability of design solutions remains the results of a deep and extensive experimental study. For example, currently, to create an effective blade design, up to dozens of different options need to be tested. Outdated technologies for manufacturing complex structures do not meet the requirements either for the terms of the project or for the cost of work. New breakthrough technologies are needed for fast and precise manufacturing of a wide range of stainless-steel parts. SLM technology is one of the innovative ways to solve these tasks. In the production of GTE in recent years, there have been revolutionary changes associated with the creation and expanding use of new technologies that can radically improve the quality of products and production conditions. They are called priority, key, or critical technologies. Such technologies, in particular, include technologies for directly obtaining three-dimensional objects based on a mathematical model of the product [1]. These technologies are called additive technologies.

As a rule, in the conditions of pilot production, the time spent on the production of the blade is about one month. The traditional technological process includes more than 25 operations. It is possible to reduce the time required for developing a technological process by using SLM technology.
The aerospace industry is interested in SLM technology as an alternative to traditional manufacturing methods for functional parts. This is a new approach to designing and manufacturing parts compared to traditional methods. The main advantages of replacing traditional parts technologies with the SLM process is to reduce the production cycle time of small-scale production by an order of magnitude; to reduce and simplify the process chains. With the use of SLM technology, the production cycle of the input guide blades will be reduced several times, while it is possible to obtain new functional and design features of parts with a new set of operational properties. The development of the technological process of manufacturing the input guide blades using the SLM method is a complex, multi-option task that requires taking into account a large number of various factors. The method of designing such manufacturing technologies, with the identification of the optimal angle of construction of the input guide blades, will reduce the labour intensity and cost of developing new experimental technological processes.

2. Materials and research methods
This research project was carried out on cylindrical samples taken from the construction plate of blades made by additive technologies from stainless steel powder. In the course of the study, a batch of these blades was modelled and produced according to the process that would have been followed in serial production. To determine the optimal angle of blade growth, the experience of Rolls-Royce was analysed. Before irradiation, samples of stainless-steel powder were cut into five equal parts in order to be able to irradiate the same sample under different modes. Treatment with high-current pulsed electron beams was performed from the outer surface.

![Figure 1. The appearance of the blades from the side of the trough.](image-url)
Figure 2. Fragments of large particles of fused powder.

Based on an analysis of the production of these blades, the following conclusions can be drawn:

- there are large particles of fused powder on all blades near the exit holes of the internal channels to the surface on one side;
- the maximum wall thickness is at the input edge. When comparing thicknesses slightly away from the input edge, the wall thickness on the back side is slightly greater than or equal to the wall thickness on the trough side;
- the wall thickness away at the input edge varies from 0.73 mm to 0.89 mm;
- the wall thickness away from the input edge varies from 0.41 mm to 0.48 mm;
- the size of the opening (internal channels) is 0.24...0.29 mm;
- the minimum pore size is equal to 0.003 mm, the maximum – 0.080 mm;
- there is a large accumulation of pores with a size of 0.003..0.077 mm in the holes of internal channels near the exit to the surface of the longitudinal section of the pen;
- there is no overheating (melting) and burning, no cold and hot cracks in the microstructure of the blade material.

3. Experimental data and discussion

For further research, the microstructure of the input edge of the two blades located at the end of the construction plate was analysed. These blades, the microstructure of which is shown in Fig. 3, have the most optimal location, since they have the least porosity.

Figure 3. Microstructure of the input edge near the upper trunnion of the blades located at the end of the construction plate.

The next stage of this study is to test the modes of irradiation with high-current pulsed electron beams, which will reduce porosity, roughness, and increase the microhardness of the surface layer, which will not only remove additional material that is needed for subsequent machining, but also reduce residual stresses, increase wear resistance, and corrosion resistance due to the release of chromium to the surface.
Figure 4. Appearance of the sample from the construction plate, on which the optimal irradiation modes were determined.

Samples obtained by additive manufacturing from stainless steel powder were used as research objects. Irradiation of samples was performed after etching on a complex automated electron-beam installation "GEZA-MMP" at various modes and the number of pulses. The appearance of stainless-steel samples before and after irradiation with the HPEB is shown in Fig. 5.

Figure 5. Appearance of stainless steel powder samples before irradiation (left) and after irradiation (right).

It is well known that this treatment leads to a redistribution of elements during irradiation, which is carried out strictly in accordance with the values of equilibrium distribution coefficients of impurities, according to the basic provisions of the theory of directional solidification: an impurity with a distribution coefficient \( K_0 < 1 \) is pushed by the solidification front to the surface, for stainless steel, chrome and nickel. While components with \( K_0 > 1 \) for stainless steel, molybdenum should be concentrated in the area of the “recrystallized material-matrix alloy” interface. This process usually occurs at low crystallization rates (several cm/min [2]). When processing HPEB, we are dealing with very high crystallization rates \( V \approx 10^7 \text{K/sec} \). It should be considered that in the case of conventional
directional crystallization and conventional zone melting, the thickness of the molten zone \( L_m \) is several tens of mm. When irradiated by HPEB at “GEZA-MMP”, the \( L_m \) values of stainless steel do not exceed 27\( \mu \)m (Fig. 6). Therefore, the redistribution of elements during the crystallization of the material in the molten electron beam zone is quite possible.

**Figure 6.** Optical microscopy of the samples irradiated at the “GEZA-MMP”.

The obtained results of the study of the influence of irradiation modes on the chemical composition of the surface layers of samples made by the additive method from stainless steel powder allow us to draw preliminary conclusions about the most promising parameters of electron-beam processing. Rather specific conclusions can be drawn about the choice of the energy density in the pulse. These conclusions are based on the following considerations. When irradiating samples made by the additive method from stainless steel powder, it is advisable to obtain a surface that does not contain macro - and microdefects, which are stress concentrators under fatigue loading. This requirement is met by the surface of a stainless-steel sample irradiated in the mode \( W=33-37 \) J/cm\(^2\). The microstructure in the surface layer of the stainless-steel sample is shown in Fig 7.

**Figure 7.** Microstructure of a stainless steel sample irradiated in the mode \( W=33-37 \) J/cm\(^2\) at “GEZA-MMP”.

Processing of a stainless steel sample with high-intensity pulsed electron beams in the mode \( W=33-37 \) J/cm\(^2\) allows achieving a preferential yield to the surface of chromium, which increases the ability of steels to thermal hardening, their resistance to corrosion and oxidation, provides increased strength at elevated temperatures, and also increases the resistance to abrasive wear. The introduction of innovative processes in modern aircraft engine manufacturing, such as SLM technology, will significantly reduce the traditional manufacturing process of blades, and will also allow obtaining complex-profile designs of stainless steel blades.
The influence of HPEB irradiation modes on the surface roughness of stainless-steel powder samples was studied in order to select the energy density and the number of pulses that reduce the initial surface roughness.

When studying the microstructure of samples before and after irradiation with high-current pulsed electron beams with a number of pulses greater than two, a significant decrease in roughness was observed. When irradiated on “GEZA-MMP” this equaled to approximately 3.5 times in stainless steel.

| № sample’s | Irradiation modes | Irradiated layer | Basic material kgs/mm² |
|------------|-------------------|------------------|------------------------|
| W, J/cm²  | n, pulse | Middle kgs/mm² | Edge 1 kgs/mm² | Edge 2 kgs/mm² | |
| 1 | 25-28 | 1-3 | 245; 245; 233 | 222; 212; 233 | 233; 233; 245 | 203; 203; 195 |
| 2 | 28-31 | 1-3 | 245; 233; 233 | 222; 233; 233 | 222; 222; 233 | 195; 195; 203 |
| 3 | 31-35 | 1-3 | 212; 212; 222 | 212; 222; 212 | 212; 222; 203 | 222; 195; 212 |
| 4 | 28-31 | 3-6 | 279; 270; 261 | 270; 251; 261 | 251; 233; 222 | 195; 203; 203 |
| 5 | 33-37 | 3-6 | 212; 222; 233 | 212; 212; 222 | 245; 251; 245 | 203; 203; 203 |

Table 2. Roughness of the samples during irradiation on the "GEZA-MMP".

| № sample’s | Irradiation modes | Before irradiation | After irradiation | Thickness of the irradiated layer S, μm |
|------------|-------------------|-------------------|-------------------|---------------------------------------|
| W, J/cm²  | n, pulse | Roughness, Rₐ | Roughness, Rₐ | |
| 1 | 25-28 | 1-3 | 5,4 | 2,8 | 14,62-33,18 |
| 2 | 28-31 | 1-3 | 5,2 | 2,2 | 15,34-55,13 |
| 3 | 31-35 | 1-3 | 5,3 | 2,4 | 11,52-55,3 |
| 4 | 28-31 | 3-6 | 5,5 | 2,4 | 7,97-33,92 |
| 5 | 33-37 | 3-6 | 5,6 | 1,6 | 10,79-87,02 |

4. Conclusion
It is shown that a high-current pulsed electron beam of microsecond duration is a highly effective tool for modifying the surface of alloys obtained by additive technologies from stainless-steel powders. The study of the microstructure of the selected samples before and after irradiation with HPEB revealed the absence of cracks, which are inherent in traditional processing methods, as well as a significant decrease in the surface roughness of samples made of stainless-steel powder, the roughness decreased by about 3.5 times. The most promising mode for further study is the mode with an energy density of W=33-37 J/cm², n=3-6 pulses, and a thickness of the modified layer reaching 87 microns. It should be noted that the irradiation mode with a lower energy density, but with a larger number of pulses, allows achieving a surface roughness of Rₐ 1.6. This has the potential to completely remove mechanical processing in the production of those parts where this roughness allows using it freely in operation.

5. References
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