Investigation of the surface overhanging elements of parts manufactured by the SLM

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Abstract. The work considers the task of modelling the mode of thermal action on the system of solid material and one aluminium granule. To improve the properties of synthesized parts and decrease porosity of the surface overhanging elements optimal processing parameters were calculated. The paper shows the result of modeling and predict surface roughness and porosity with four parameters pair of scanning speed and laser power.

1. Introduction
The problem of obtaining complex parts, included thin-walled elements, by selective laser melting method is a relevant topic of current research. This problem caused by a violation of the mode of homogeneous melting of the granules of the powder material [1]. It is especially important to reject heat from the treatment area in the production of thin elements or elements forming at an angles [2].

There are 2 opposite situations: if not enough energy was used, the part won’t build, but as opposite if too much energy was used, the problem of heat transfer will appear. Further, that leads to increase surface roughness [3]. There is no opportunity to test every pair of laser power and scan speed, because high duration and cost of experiments. Hence, we need to analyze the problem, pick a few main working mode and do math model of thermal impact. The usage of math analysis can significantly reduce amount of mode that we need to examine.

The object of the study (Fig. 1) is an impeller pump, that contain horizontal thin-wall parts (blades of impeller) and a volumetric object (a base of screw).

Figure 1. The object of the study, thickness of horizontal part is in the order of particles radius.
2. Math model

There is impossible to rearrange the object relative to the working plane, therefore math modeling of an influence a scanning speed and laser power to final surface quality was been done. Based on the result, allowable ranges of parameters were defined for single track or monolayer.

The resulting surface relief, according to the calculated data, has the roughness around 10-15μm. Defects of this magnitude can only be removed by mechanical processing. Modelling the modes of thermal action on the system “solid part and one granule” (Fig. 2) illustrates the melting of the granule surface and mutual mixing of materials.

![Figure 2. Model geometry: 1 – heat loading plane, 2 – monolayer of solid part, 3 – nitrogen, 4 – granule with diameter 30μm at a distance of 10 μm.](image)

The radiation heat transfer problem between solid part and one particle was considered. There is thermal expansion space between them. In this numerical experiment oxidation coating was ignored (in real cause this problem has a solution [4]).

**Table 1. The material parameters**

| Parameter                   | Value         |
|-----------------------------|---------------|
| Thermal conductivity        | 150 W/(m*K)   |
| Thermal heat capacity       | 900 J/(kg*K)  |
| Thermal expansion rate      | $2 \times 10^{-5}$ (1/K) |
| Kinematic coeff. of viscosity | 0.002 (m²/s) |
| Fusioning temperature       | 580 °C        |
| Density                     | 2680 kg/m³    |

The medium between the area of the material and the granule is nitrogen gas. Figure 3 shows several results showing different pairs of parameters based on other articles and sources. Colors in the diagram correspond to the melting point of aluminum.

In the model the process of heating a section of the material does not take into account the processes occurring when converting the energy of laser radiation into thermal energy and attraction force between particles, only "useful" heating of the surface is taken into account.

Based on the simulation results, the range of two certain parameters [5] (laser powers and scanning speeds) of laser radiation was determined, taking into account follows factors: absorption capacity of the material, optical properties of the surface exposed to laser radiation, thermal conductivity and thermal expansion rate of the powder material and the material obtained as a result of selective laser melting. These parameters determine the conversion of optical energy into thermal energy.
There is main equation for calculate heat and moving change in particle:

\[ pC_p \left( \frac{dT}{dt} + u_m \cdot \nabla T \right) + \nabla q \]

There is \( p \) is the density (kg/m\(^3\)), \( C_p \) is the specific heat capacity (J/(kg·K)), \( u_m \) is the velocity vector of translational motion (m/s), and \( q \) for heat flux as sum of radiation and conduction in particle. The equation was solved numerically.

3. Results and Discussion
The initial solid and powder granule boundaries are indicated by a thin gray outline. Heat is transferred to the system through the left edge of the solid material.

![Figure 3. The results obtained corresponds to:](image)

- a) scanning speed is 2000 mm/s, laser power is 150 W
- b) scanning speed is 1300 mm/s, laser power is 200 W
- c) scanning speed is 1000 mm/s, laser power is 200 W
- d) scanning speed is 2000 mm/s, laser power is 350 W
In case of insufficient heating (Fig. 3a) in the process of exposure to laser radiation, the formation of pores is possible. Pores can form as a result of the fusion of granules with each other, or when the wettability of granules is disturbed due to a large air gap, the presence of an oxide film, the presence of thermal resistance in the form of small granules acting as elements of thermal resistance [6]. Non-fusion can also be caused by an incorrect particle size distribution of the powder mixture, as a result of which the powder material has a low bulk density [7]. This cause doesn’t calculate in the model. The obtained results of the numerical experiment show insufficient heating of the granule surface, much lower than the melting point of aluminum. In real cause the results of the study can be used to determine a mode that ensures the formation of a thin-walled geometry with a minimum value of surface roughness, where no fusion of granules occurs, located in some proximity to the affected area, but not exposed to laser radiation. The roughness of surface (Fig. 4a) is minimum when scanning speed is around 2000 mm/s.

![Figure 4. Results of using simulated modes: a) surface roughness (µm), b) surface porosity (%)](image)

With a longer heat exposure, partial fusion of the surface of a solid material and a powder granule. Material wetting occurs as a result of heating both the base material and the granule as a result of radiation transfer of thermal energy. Heating leads to a decrease in the surface tension of the base material and to "spreading" of the right edge (facing the powder granule) relative to the original boundary. Partial wetting is observed. In this thermal regime (Fig. 3b), the granule "sticks" to the surface of the solid material, but can be removed as a result of mechanical action, since partial wetting has occurred without mixing both materials [8]. Similar defects can be observed in the structure of a solid material, when the entire granule is wetted by the material, but there is no mutual mixing of the solid material and the granule material due to the presence of thermal resistance, oxide film, rapid cooling of the base material [5].

When constructing a real object, the results of the study can be used to determine the mode when forming a geometry that has a difficult heat removal during construction. This mode can be applied when the requirement to ensure the density - the minimum content of pores (Fig. 4b) in the structure of the resulting material - is preferable to ensuring the quality of the outer surface of the product. That is, during construction, dynamic mixing of the melt occurs in the region exposed to laser radiation with partial capture of the material of neighboring regions as a result of radiation heat transfer, or an increase in the contact time of the heated material and the surface of neighboring granules with hindered heat removal. Usually, the elimination of these defects from the outer surface of the resulting part does not cause problems when using sandblasting. When such defects appear in the inner surface of parts, it is possible by using water-jet polishing. This type of processing is quite effective when processing cavities, holes, channels with a diameter of more than 0.15 mm.
A further decrease in the scanning speed of the laser beam (Fig. 3c) leads to intensive melting of the nearby granule. Not only wetting is observed, but also the formation of a common pool of the melt, followed by joint solidification of the solid material and the material of the granule. An increase in the time of thermal exposure leads to an increase in thermal energy generated as a result of exposure to laser radiation. A change in the geometry of the right edge of the material is observed, the material of the powder granule effectively wets the main part, as such the granule is not observed. Processing with this mode of exposure is not desirable, since it leads to the melting of the nearby powder material due to excess heat.

In the real synthesis of thin-walled model elements, thermal warpage is also observed, which often leads to a violation of the integrity of the part (destruction or cracking) due to high thermal stresses. In this model, the interaction of the main material and an isolated granule of the powder material was considered; in real conditions, the space is filled with smaller granules. Thus, this area will be a piece of material containing both completely melted granules and partially (as discussed in the previous case). When the laser beam passes along the next track of the present layer, and the formed structure is additionally melted, gas pockets formed as a result of the fusion of many granules outside the area of influence will lead to a violation of the melting mode and the formation of spherical pores in the structure of the base material [7].

When using this mode of exposure, if we consider the formation of a mono track (single track) not as a set of tracks forming a sintered layer of powder material, then we can only observe a violation of the geometric dimensions of the planned area of influence. When performing the operation "shell" in accordance with the described mode, the defects will be only on the surface of the resulting part. It is impractical to build a part in this mode.

The resulting surface relief, according to the calculated data, has a roughness of more than 50 µm, which can only be eliminated by mechanical processing. Hydro-abrasive action can lead to deviations in the dimensions of the part (during the processing, protruding elements of the work piece will also suffer), if initially the increase in the dimensions of the elements was not laid down for the execution of this post processing.

Defects associated with internal porosity formed as a result of fusion of nearby powder granules and subsequent clogging of gas bubbles during the subsequent passage of the laser beam can be eliminated by hot isostatic pressing [9]. In this case, a volumetric "pore healing" occurs (Fig. 4b). This operation is laborious and quite expensive, its use is justified only when the cost of the part is high and it is impossible to use another synthesis mode, for example, as a result of the peculiarities of the material used.

The last mode (Fig. 3d) illustrates the almost complete melting of the granule with mutual mixing of materials. There is a change in the boundary of the main material and the material of the granule relative to the previously occupied positions (the boundary of the surface of the material is indicated by a gray strip, the boundary of the granule is a gray circle). When constructing a body of a part, this mode will lead to a violation of the geometry of the part being created and a pronounced temperature distortion, which will probably lead to the impossibility of construction due to the destruction of the elements of the part during the construction process.

The use of this mode is possible when constructing a shell, since it will ensure reliable melting of the resulting surface of the part, which will also make it possible to form a layer for subsequent surface treatment. To predict the fusion of nearby granules, it is necessary to introduce additional bodies into this model. Within the framework of this model, predicting the reflow of neighboring areas / nearby granules during real processing is not correct.
4. Estimate surface quantity

The power density was calculated by the formula:

\[ H = \frac{W \cdot T}{S} \]

There are \( W \) is laser power in Watt, \( T \) is exposure time \((1/\text{scanning speed})\), and \( S \) beam area. For a qualitative assessment of the surface, the indicator “poor surface” (Fig. 5) was introduced. Porosity and surface roughness have been normalized to a range from 0 to 1. Poor surface is the arithmetic average of the two normalized indicators. The data shows that surfaces at high angles have greater surface roughness compared to horizontal surfaces created under the same regime [10,11].

5. Conclusions

As a result of this work, the exposure time of the heat source relative to the investigated area was established. Based on the results obtained, it is possible to establish the range of the scanning speed of the laser beam and the power of the laser radiation exposure, having data on the spot size, the absorption coefficient of laser radiation by the material, the thermos-physical properties of the real material, the particle size distribution of the powder, and the thickness of the powder layer.

The best processing mode looks to first process the entire layer with a scan rate of 2000 mm/s and 200 watts, and then pass a high power along the edge of the sample to bake the remaining particles.
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