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Process Conditions of Forming the Surface Layer of Aluminum Powder Product by Layer-by-layer Laser Sintering

N A Saprykina[a], A A Saprykin, E A Ibragimov, D A Arkhipova
Yurga Institute of Technology, Tomsk Polytechnic University, Tomsk, Russia

E-mail: [a] saprikina@tpu.ru

Abstract. The paper presents data on state of the art in selective laser sintering of products. Layer-by-layer sintering is shown to be a future-oriented technology, making it possible to synthesize products of metal powder materials. Factors, influencing the quality of a sintered product, are revealed in the paper. It presents outcomes of experiments, focused on the dependence of surface layer thickness of sintered aluminum powder PA-4 on laser processing conditions. Basic factors, influencing the quality of a sintered surface layer include laser power, speeds of scanning and moving the laser beam on the layer of powder. Thickness of the sintered layer varies from 0.74 to 1.55 mm, as the result of changing the laser processing conditions.

1. Introduction

The present day economy makes use of layer-by-layer laser sintering technologies in order to reduce production time and manufacture competitive products. These technologies enable synthesizing products of any configuration from metal powder materials with a preset accuracy on the base of a 3D CAD-model, requiring no preliminary costs for tooling preparation. These technologies have an extra advantage; it is a considerable material economy when manufacturing products of complex configuration [1-4].

A 3D CAD-model is separated in layers when manufacturing a product by layer-by-layer laser sintering. Some powder is fed into the area of sintering; a layer coinciding with the section of a product is formed via moving a laser beam on the section area in preset conditions. This process is completed as soon as a product is made. Layer-by-layer laser sintering has one more advantage: a powder material is used efficiently, since it is possible to reuse non-sintered powder.

Alongside with advantages additive technologies face some restrictions regarding high cost of the equipment and powder materials, as well as their assortment. Poor quality of formed surface layer of products, insufficient mechanical strength and probable delaminating are burning issues highlighted by the authors [7, 8, 9].

Further development of layer-by-layer laser sintering is possible provided that new powder materials are applied, functionally graded structures are made [10]. Synthesizing a product of special quality, with certain mechanic strength from metal powder materials requires taking into consideration factors, influencing the quality of sintered surface and its inner structure:

- thermal impact (surface bulging, cracking, delaminating, and melting) [11];

- process conditions of layer deposition (compaction, speed of deposition, layer displacement when depositing a powder) [12];
- process conditions of sintering (density of irradiation power, impulse energy, speed of laser beam moving, diameter of a laser spot) [13];
- material of powder (heat-transfer properties, physical and chemical characteristics, dimensions and configuration of powder) [14].

Factors mentioned above emphasize that a functional product can be manufactured in a certain range of laser impact only, which is specified experimentally for each powder material, and accuracy of a prototype depends mainly on the sintered layer thickness.

This paper presents outcomes of experiments focused on the influence of laser processing conditions on the surface layer thickness of aluminum powder PA-4 produced by layer-by-layer laser sintering.

Aluminum powder is widely used in engineering due to its good physical properties, but industry making the most use of it is aircraft construction. Powder PA-4 is produced from primary aluminum at melting temperature 660 ºC. It consists of active aluminum (not less than 98%), ferrum (0.35%), silicon (0.4%), and copper (0.02%).

2. Results and Discussion

The effect of sintering process conditions (laser beam speed V, laser power P, and scanning step S) on the surface layer thickness of the sintered aluminum powder PA-4 is studied in this paper. Experiments were carried out using a specially developed machine of layer-by-layer laser sintering, which supports adjustability of all process conditions of sintering. This is a laser beam machine to form the surface of products with a complex physical configuration, which consists of ytterbium fiber laser LK – 100 – V (wavelength 1.07 μm), a three-dimensional table, a PC, a CNC system, and specially developed software. A stepping motor is used for moving in coordinates X, Y, Z [15].

Since layer-by-layer laser sintering is used for product manufacturing, we should know the thickness of a sintered layer when separating a CAD-model in layers. The same value is also needed when manufacturing a product. Unless a sintered layer is thick enough, it is difficult to deposit the top powder layer as the bottom one gets destructed. Increasing the thickness of powder to be deposited leads to delaminating of a sintered product. Layer thickness is important for the quality of a steplike side face. The height of each step approximates to the thickness of a sintered layer. Process conditions of sintering are to be assigned properly, so the product meets standard dimensions within necessary tolerance of quality. A method providing high accuracy of separating in layers a virtual 3D model of a product is proposed in patent of invention 2262741 RF [16]. Thickness of layers can't exceed a nominal profile tolerance range of a model surface; a nominal profile of the model surface coincides with the midline of cross layers, so that is an actual profile. Thickness of the layer is assigned in the range:

$$Zmin \leq Z \leq Zmax, \quad (1)$$

where Zmin and Zmax – minimal and maximal thickness of a layer, respectively, provided by technological equipment.

Assignment of appropriate process conditions of sintering makes it possible to produce a three-dimensional product with a complex physical configuration [17].

Samples of a sintered 20 mm long and 10 mm wide layer were produced for the purposes of experiments. Laser beam movement is shown in Figure 1.

Process conditions of laser sintering tested in experiments were pre-determined in exploratory experiments. Appropriate conditions for manufacturing a sample of powder PA-4 with standard mechanical strength are as follows: P = (10-20) W, V = (1000-3000) mm / min, S = (0.1-0.2) mm. The geometry of the sintered surface was analyzed by means of a specially developed technique based on Digital Microscope toolkit.

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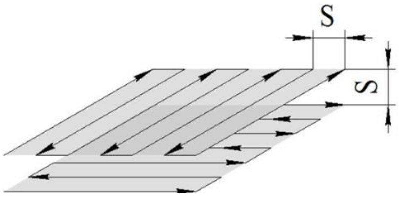

Figure 1. Scanning of layers

Figures 2-3 show, how the laser power influences on the quality of a sintered surface layer. Power varying from 10 to 20 W at constant speed V = 1000 mm / min, sintering temperature t = 26 ºC and scanning step S = 0.2 mm cause the increase in thickness of a sintered layer from 0.765 to 1.55 mm. In Figure 3 one can see more coagulated particles because of the increased density of energy.

Figure 2. Physical configuration of the sintered PA-4 surface (x2), process conditions of sintering: V=1000 mm/min, t=26 °C, S=0.2 mm, P=10 W.

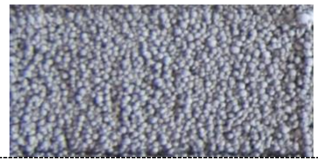

Figure 3. Physical configuration of the sintered PA-4 surface (x2), process conditions of sintering: V=1000 mm/min, t=26 °C, S=0.2 mm, P=20 W.

Mechanical strength of samples gets decreased as the result of reducing the power to 10 W. Assigning the following process conditions: power 20 W, V = 3000 mm / min, t = 26 ºC, S = 0.2 mm is the reason that the sintered sample has thickness of 1.33 mm (Figure 5).

Figure 4. Physical configuration of the sintered PA-4 surface (x2), process conditions of sintering: V=3000 mm/min, t=26 ºC, S=0.2 mm, P=10 W.

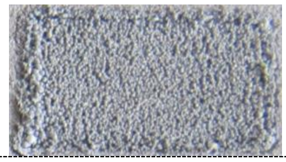

Figure 5. Physical configuration of the sintered PA-4 surface (x2), process conditions of sintering: V=3000 mm/min, t=26 ºC, S=0.2 mm, P=20 W.

Figures 6-7 show, how the surface of sintered powder PA-4 changes in dependence on the speed of laser beam movement. The increase in the speed of laser beam movement from 1000 to 3000 mm / min, at P = 20 W, t = 26 ºC, S = 0.2 mm leads to the decrease of thickness in the sintered layer from 1.55 to 1.33 mm, (Figures 6-7).

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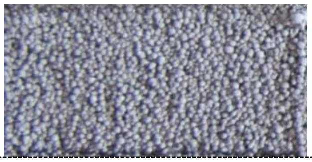

Figure 6. Physical configuration of the sintered PA-4 surface (x2), process conditions of sintering: V=1000 mm/min, t=26 ºC, S=0.2 mm, P=20 W.

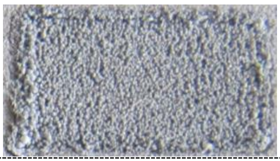

Figure 7. Physical configuration of the sintered PA-4 surface (x2), process conditions of sintering: V=3000 mm/min, t=26 ºC, S=0.2 mm, P=20 W.

Comparing the samples one can see that increasing the speed of laser beam movement can cause the decrease in the thickness of sintered layer.

In Figures 8-11 one can see physical configuration of sintered PA-4 surface regarding the scanning step.

Increasing the scanning step from 0.1 to 0.2 mm (process conditions of sintering: P = 10 W, t = 26 ºC, V = 1000 mm / min (Figures 8-9) results in the decrease of sintered layer thickness from 0.74 to 0.765 mm.

Figure 8. Physical configuration of sintered PA-4 surface (x2), process conditions of sintering: V=1000 mm/min, t=26 ºC, S=0.1 mm, P=10 W.

Figure 9. Physical configuration of sintered PA-4 surface (x2), process conditions of sintering: V=1000 mm/min, t=26 ºC, S=0.2 mm, P=10 W.

In samples obtained in process conditions of sintering: P = 15 W, t = 26 ºC, V = 3000 mm / min, scanning step varies from 0.1 to 0.2 mm (Figures 9-10), as the results, thickness of the sintered layer increases from 1.0 to 1.2 mm.

Figure 10. Physical configuration of the sintered PA-4 surface (x2), process conditions of sintering: V=3000 mm/min, t=26 ºC, S=0.1 mm, P=15 W.

Figure 11. Physical configuration of the sintered PA-4 surface (x2), process conditions of sintering: V=1000 mm/min, t=26 ºC, S=0.2 mm, P=15 W.

Increasing the scanning step causes the growth of the thickness of sintered PA-4 layer. No visible defects are detected on the sintered samples.

Our studies suggest a significant influence of power on quality of the sintered surface layer. Unless power is assigned correctly samples are deformed. The speed of a laser beam movement is also important for the quality of the surface layer. In some cases, to form a surface one needs to increase the speed for reducing the thickness of the sintered layer. Scanning step is not so relevant for the quality of the sintered surface layer. When sintering aluminum powder increased scanning step causes the growth of the sintered layer thickness. This allows to determine the number of layers in the finished product and to produce a three-dimensional product of any geometrical shape. In Figure 12 a three-dimensional sample, consisting of 10 layers is shown. The increment thickness of layers is 200 μm, sintering was carried out in the shielding atmosphere of argon.

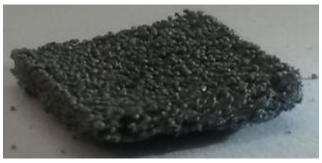

Figure 12. Physical configuration of a three-dimensional sample (x2). Process conditions of **s**intering: V=1000 mm/min, t=26 ºC, S=0.1 mm, P =60 W, increment thickness of layers 200 μm, sintering in argon

The surface of the sample is rough, gapless grooves are seen, in particular along the path of laser beam movement. Typical beads, coagulated from the melt, are 1-1.5 mm; that differs by a factor of ten from the initial size of mixed powder composites. This fact makes it obvious laser power is sufficient for coagulation of particles of the melt into bigger formations. A developed inner porosity has a positive effect on adhesion of layers.

3. Conclusion

The authors have pointed at the possibility of wide range changing the sintered surface layer due to variation of process conditions of laser sintering. Increasing the speed from 1000 to 3000 mm/min results in augmentation of layer thickness by 16 % in conditions: P=20 V, S=0.2 mm, t=26 ºC. Increasing the power from 10 to 20 V results in augmentation of sintered layer thickness by 200 %, in conditions: V=1000 mm/min, S=0.2 mm, t=26 ºC. Scanning step does not have a considerable effect on the thickness of sintered layer. The increase in S from 0.1 to 0.2 mm in conditions: P=10 V, V=1000 mm/min, t=26 ºC leads to augmentation of sintered layer thickness by 3 %.

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