Development Algorithm of the Technological Process of Manufacturing Gas Turbine Parts by Selective Laser Melting

A V Sotov †, A V Agapovichev1, V G Smelov 1 and R R Kyarimov 1
1Samara State Aerospace University (National Research University), Moskovskoe sh. 34, Samara, 443086 Russia

*Corresponding author: SotovAnton@yandex.ru

Abstract. The technology of the selective laser melting (SLM) allows making products from powders of aluminum, titanium, heat-resistant alloys and stainless steels. Today the use of SLM technology develops at manufacture of the functional parts. This in turn requires development of a methodology projection of technological processes (TP) for manufacturing parts including databases of standard TP. Use of a technique will allow to exclude influence of technologist’s qualification on made products quality, and also to reduce labor input and energy consumption by development of TP due to use of the databases of standard TP integrated into a methodology. As approbation of the developed methodology the research of influence of the modes of a laser emission on a roughness of a surface of synthesized material was presented. It is established that the best values of a roughness of exemplars in the longitudinal and transversal directions make 1.98 μm and 3.59 μm respectively. These values of a roughness were received at specific density of energy 6.25 J/mm² that corresponds to power and the speed of scanning of 200 W and 400 mm/s, respectively, and a hatch distance of 0.08 mm.

1. Introduction
Additive technologies (the three-dimensional printing) appeared in the late 80’s of XX century. ASTM F2792-12a [1] defines the term additive technologies in the standard of the American Society for Testing and Materials, which like « a process of joining materials to make objects from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing methodologies».

One of dynamically developing directions of the additive technologies (AT) is the process of selective laser melting (SLM) of metal powder. This method is based on layer-by-layer formation of a product by laser scanning of powder layer applied on a substrate.

SLM technology makes it possible to produce the parts from powders of aluminum [2, 3], titanium [4, 5], heat-resistant alloys [6, 7, 8] and stainless steels [9, 10, 11].

Interest in production of functional GTE details by AT method is synthesizing. In this regard the issue of development of the technological process methodology for manufacturing gas turbine parts from metal powders, in particular heat tubes of combustion chambers. This methodology includes optimization of technological modes in order to obtain products with the given production characteristics. Development of the technological process methodology will allow to exclude influence of qualification of the technologist on quality of the made products, and also to reduce labor input and energy consumption by development of TP, selection of the optimum processing conditions at the expense of the created databases of the SLM parameters integrated into the methodology.
2. Development algorithm of the technological SLM process

Development of TP of manufacture of details by SLM method is a complex, multivariate task that requires the consideration of a large number of various factors [12].

Proposed technique assumes work in two modules (CAD and CAE modules), as well as the use of developed TP database of typical details consisting of databases on allowances for machining, support material design and heat sinks cones, and the modes of melting. The algorithm for sequence designing of SLM technology is shown in figure 1.

As input parameters the design drawing of the part (1), which requires the development of TP appears. The assessment of a possibility of manufacture of a part with use of SLM technology can be detected only by the results of the technological analysis of the part drawing (2). At this stage appointment and operating conditions of a part is defined, the design and geometrical characteristics is described, the analysis of processability on material, the analysis of processability on accuracy of the sizes, forms and arrangements of surfaces, the analysis of processability on quality of the surface layer is carried out. These results will be input data for a task of the direction of printing of a part (3), and also for the feasibility study (4) uses of the SLM method.

Results of the carried-out technological analysis and the feasibility study should be formulated in a technical specification (TS) design of TP of a part (5) [13]. The requirements formulated in TS will allow carrying out the analysis of the standard parts which are available in the TP database (6) and by its results pass to formation of the working file of manufacture of it, or to model operation of preparation of the synthesizing part (7).

Process of workpiece modeling includes CAD and CAE modules, and also use of the developed databases, the appeal to which happens immediately when developing TP. The CAD module, in charge of preparation of a 3D model of a part for synthesizing process, includes such works as modeling of additional allowances (8), design of support material and heat sinks (9).

Final properties of selected material manufactured part will immediately depend on the choice of laser melting modes (10). For determination of parameters of the processing conditions it is necessary to solve the inverse problem of heat conductivity which will allow creating requirements to distribution of power influencing energy flows. This problem is planned to be solved in the CAE module with specification of part material, the processing conditions and boundary conditions in a preprocessor (11), with calculation of distribution problems of temperature profiles, residual stresses and an assessment probability of destruction in the processor (12), the analysis of the received results in the post-processor (13). The post-processor will allow estimating distribution of temperature profiles in a powder layer, and also will allow estimating the penetration of the powder particle and will give the chance to choose parameters of a laser melting. The problem of this module consists in achievement of the required qualities of a product, excepting neither optimum, non economic methods, in particular, a trial and error method which is often used at selection of laser parameters of SLM technology.

The developed algorithm for selective melting modes will allow selecting the optimal ratio of laser parameters for formation of required material structures formulated in the technical specification for part. The optimum ratio of parameters is characterized by the amount of transmitted energy by means of the specific density of energy (SDE). The SDE is equal to the ratio of emission power to the scan speed and laser spot diameter, expressed as, [J/mm²].

After setting the range of SLM laser parameters and preparing the CAD model for synthesizing process, the final CAD model of the part (17), converted to the STL format, is formed. After formation of final CAD model of detail of SLM process (18) follows directly. After manufacture of workpiece part one of the important stages is additional machining (19) [14, 15]. This includes removing support material and finishing the surface.

The part (20) received during 3D printing has to undergo control (21) of the required surfaces according to the appointed TS. Only after that the stage of bench tests (22) in the conditions which are brought really closer to operating conditions of the made part follows. The analysis of test data defines a possibility of use of the synthesizing part in this or that external environment. Bench tests determine
the functionality of the manufactured part, where, with a negative result, it is necessary to return to the stage of modeling the workpiece.

Figure 1. Algorithm of TP process development.

After completing all the above-described development stages of TP part manufacture the stage of execution of technological instructions (23) where specify the sequence of workpiece processing, the main SLM technological parameters, accuracy of the dimensions to be performed, the surface roughness value and the equipment used are indicated. The result of the developed technique is the designed TP for manufacturing the part by SLM method.

Approbation of the developed algorithm of SLM process was carried out for a heat tube of
combustion chamber of a small-sized GTE. Process and result of manufacture is presented on figure 2. The separation of part from build platform was made with use of electro-erosive processing technology.

![Figure 2. Process of heat tube production by SLM method (a), result of production after printing (b) and after machining (c).](image)

Considering the high demands placed on roughness of a surface of heat pipes of GTE combustion chamber, as the experimental results the research of influence processing conditions of a laser emission on a roughness of the surface layer of synthesized material is presented. This research corresponds to the block 16 of the developed algorithm of projection of TP (figure 1).

3. Research methodology
The research of a roughness of a surface of synthesized material was conducted on exemplars in the transversal and longitudinal directions. Exemplars were made on 3D SLM 280HL machine. Print time at build layer of 50 μm made 3.5 hours. Production of parts was carried out on a build platform with size of 100x100 mm.

As the operated modes of laser scanning of a surface of metal powder parameters were taken: power of laser emission, P, W; scanning speed of powder surface, V, mm/s and hatch distance, H, mm.

For the studied exemplars values of specific density of energy in the range of 3.13...6.25 J/mm² were taken, the hatch distance for values of an overlapping coefficient equal to 1, 0.5 and 0 made 0.04 mm with laser beam spot diameter equal to 0.08 mm.

An investigation of the influence of above parameters was carried out for synthesized contour of a part. It is considered optimum to outline at first borders (contour) of the made product, and then to scan an interior. Values of the technological modes for the studied samples are reduced in table 1.

| № sample | Power (W) | Scan speed (mm/s) | Hatch distance (mm) | SDE (J/mm²) | Overlapping coefficient |
|----------|-----------|-------------------|---------------------|-------------|------------------------|
| 1        | 100       | 0.04              | 0                   | 3.13        | 1                      |
| 2        | 100       | 0.08              | 0                   | 4.69        | 0.5                    |
| 3        | 150       | 400               | 0.04                | 4.69        | 0.5                    |
| 4        | 0         | 0                 | 0                   | 0           | 0.5                    |
| 5        | 0         | 0                 | 0                   | 6.25        | 0                      |
| 6        | 0         | 0                 | 0                   | 6.25        | 0                      |
| 7        | 0         | 0                 | 0                   | 0           | 0.5                    |
| 8        | 200       | 0.04              | 0                   | 6.25        | 0                      |
| 9        | 0.08      | 0                 | 0                   | 0           | 0                      |
The measurement of a roughness of surface was carried out in three directions: transverse and longitudinal directions and melted plane. For each plane about three measurements were carried out.

4. Experimental results and discussion

Outer examination of the made samples did not reveal apparent defects on a surface material. Figure 3 shows the appearance of a sample surface. On the surface of synthesized and on a lateral area of an exemplar unmelted particles of metal powder were found, and on a lateral area of similar particles it is more. Results of measurement surface roughness of synthesizable samples are shown in table 2.

![Figure 3. Appearance of a sample surface in melted plane (a) and on the lateral surface (b)](image)

| № sample | Transverse direction (μm) | Longitudinal direction (μm) | Melted plane (μm) |
|----------|---------------------------|-----------------------------|-------------------|
| 1        | 13.08                     | 13.72                       | 16.58             |
| 2        | 11.55                     | 9.38                        | 23.91             |
| 3        | 12.48                     | 8.26                        | 17.36             |
| 4        | 4.90                      | 2.67                        | 9.03              |
| 5        | 5.79                      | 3.07                        | 9.37              |
| 6        | 4.78                      | 3.81                        | 8.13              |
| 7        | 4.56                      | 3.19                        | 8.95              |
| 8        | 3.98                      | 2.33                        | 9.32              |
| 9        | 3.59                      | 1.98                        | 7.90              |

For the obtained data graphs of dependence of a surface roughness in longitudinal and transverse directions for all planes from specific density of energy and a hatch distance were plotted. The received graphs are represented in figures 4.

Analysis of the results showed that at number 9 in the longitudinal and transversal directions the best values at specific density of energy of 6.25 J/mm² have an sample roughness that corresponds to power and scanning speed of 200 W and 400 mm/s with respectively, and hatch distance of 0.08 mm.
5. Conclusion
The algorithm developed in this work reflects all main stages that need to be realized when testing of experienced TP SLM at manufacture of the functional parts. The created algorithm will allow reducing labor input and energy consumption by development of TP due to use of the databases of standard TP integrated into methodology.

As an approbation of the developed methodology the research of influence of the modes of a laser emission on a surface roughness of synthesizable material was presented. It is established that the best values of a roughness of samples in the longitudinal and transversal directions make 1.98 \( \mu m \) and 3.59 \( \mu m \) respectively. These values of a roughness were received at specific density of energy of 6.25 J/mm\(^2\) that corresponds to power and scanning speed of 200 W and 400 mm/s with respectively, and hatch distance of 0.08 mm. The research of influence synthesizes modes allowed to determine the Pareto area of optimal values of a surface roughness.

Acknowledgements
The research was supported by the Ministry of Education and Science of the Russian Federation (Grant № 9.1299.2017/4.6).

References
[1] Standard Terminology for Additive Manufacturing Technologies 2013 – ASTM f2792-12a
[2] Kang N, Coddet P, Liao H, Baur T, Coddet C 2016 Wear behavior and microstructure of hypereutectic Al-Si alloys prepared by selective laser melting Applied Surface Science. – Vol. 378 pp 142-149
[3] Lin-zhi Wang, Sen Wang, Jiao-jiao Wu 2017 Experimental investigation on densification behavior and surface roughness of AlSi10Mg powders produced by selective laser melting Optics & Laser Technology. – Vol. 96 pp 88-96
[4] Agapovichev A V, Kokareva V V, Smelov V G and Sotov A V 2016 Selective laser melting of titanium alloy: investigation of mechanical properties and microstructure IOP Conf. Series: Materials Science and Engineering. Vol. 156 pp 1-6
[5] Yadroitsev I, Krakhmalev P, Yadroitseva I 2014 Selective laser melting of Ti6Al4V alloy for biomedical applications: Temperature monitoring and microstructural evolution Journal of Alloys and Compounds. Vol. 583 pp 404–409
[6] Kanagarajah P, Brenne F, Niendorf T, Maier H J 2013 Inconel 939 processed by selective laser melting: Effect of microstructure and temperature on the mechanical properties under static and cyclic loading Materials Science & Engineering. Vol. A 588 pp 188–195
[7] Sufiiarov V Sh, Popovich A A, Borisov E V, Polozov I A 2015 Selective laser melting of heat-resistant nickel alloy Tsvetnye Metally. Vol. 1 pp 79-84
[8] Jia Q, Gu D 2014 Selective laser melting additive manufactured Inconel 718 superalloy parts: High-temperature oxidation property and its mechanisms Optics & Laser Technology. Vol. 62 pp 161–171

[9] Riemer A, Leuders S, Thöne M, Richard H A, Tröster T, Niendorf T 2014 On the fatigue crack growth behavior in 316L stainless steel manufactured by selective laser melting Engineering Fracture Mechanics Vol. 120 pp 15–25

[10] Liverani E, Toschi S, Ceschini L, Fortunato A 2017 Effect of selective laser melting (SLM) process parameters on microstructure and mechanical properties of 316L austenitic stainless steel Journal of Materials Processing Technology Vol. 249 pp 255-263

[11] Smelov V G, Sotov A V, Agapovichev A V, Tomilina T M 2017 Implementation of the Additive Technology to the Design and Manufacturing of Vibroisolators with Required Filtering Procedia Engineering Vol. 176 pp 540-545

[12] Van Elsen, M. Complexity of selective laser melting: a new optimization approach: Phd dissertation / Maarten Van Elsen. – Hererlee, 2007

[13] Pechenin V A, Bolotov M A and Ruzanov N V 2014 Development of a method of ICP algorithm accuracy improvement during shaped profiles and surfaces control International Journal of Engineering and Technology Vol. 6, No. 5 pp 2229-35

[14] Nekhoroshev M V, Smirnov G V, Pronichev N D 2014 Computer simulation of high-speed anodic dissolution processes of geometrically complex surfaces of GTE details The Open Mechanical Engineering Journal. Vol. 8 pp 436-440

[15] Alexeev V, Balaykin A, Khaimovich A 2017 Influence of the direction of selective laser sintering on machinability of parts from 316L steel IOP Conf. Series: Materials Science and Engineering Vol. 177 doi: 10.1088/1757-899X/177/1/012120