Modeling of 3D technological fields and research of principal perspectives and limits in productivity improvement of selective laser melting

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Abstract – Nowadays the technological perspectives of selective laser melting are limited by available equipment on the market. Most of the manufactures produce SLM-machine with the maximum power of laser system 200 W, this makes processing very slow and it significantly reduces the field of potential applications for the technology. Meanwhile the limits of laser power are linked to a problem of its effective use. In the current work, the future perspectives of technology are investigated by modeling of 3D technological fields.

Key words: Selective laser melting / technological fields / perspectives / modeling / technological limits

1 Introduction

Nowadays selective laser melting is one of the most perspective technology of metallic parts' production. It was developing very active for the last twenty years and today it steps from production of plastic models to production of functional 3D-objects with guaranteed properties close to the required level of casting metals. The technology includes the steps of pre- and post-production, when the main process consists of layer-by-layer growing of solid 3D-object. A laser beam melts the each layer; a program, which was generated automatically by a control system of SLM-machine, controls the laser beam movement. The main advantages of the technology are an absence of mechanical treatment and relative simplicity of approach (absences of plural operating and machining steps, which only enlarge the quantity of problems related to efficient referencing of a part on a worktable or on a pallet of the machine for implementation of each step of the production).

Modern additive manufacturing has a huge economical annual growth and progress. By data of famous industry analyst Terry Wohlers [1], the US corporation Boeing produced already more than 20 thousand products by method of selective laser melting. Moreover about 30 different metallic components are already used in production of each Boeing 787 Dreamliner. The European

corporation Airbus S.A.S. produces the 50–70% weight-lighted brackets by SLM. Another good example of the parts' production for the purposes of machinery industry is company ACTech GmbH (Germany), which is specialized on production of final functional products by additive manufacturing methods from metallic and plastic powder materials. More than a half of orders is individual or small-serial production. More than 75% of products are consumed by automotive industry; aviation sector, heavy engineering and energetic industry consume the rest by equal proportions (around 5–7%). Three fourth of the products are aimed to satisfy needs of the European market [2].

The last scientific publications [3–7], which are related to the current topic, aimed to search the solution for the known disadvantages of SLM technology. One of the most important disadvantages is production time. The technology is strong limited by the efficiency of laser beam power use. Practice showed that direct increase of laser beam power gives an opposite effect, makes processing simply impossible. Most of material evaporates, active material granules emission occurs, material enters into active interaction with the environment on physical and chemical levels.

The current research aim of the study is pointed to a problem of reduction of the influence of the described negative effects on the quality of the final 3D-object obtained by SLM and to search of possible improvement of processing efficiency. The research is based on obtained

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Fig. 1. Experimental setup: (1) laser beam source, (2) collimator, (3) pi-Shaper, (4) mirror, (5) scanator, (6) F-theta lens, (7) laser illumination, (8) high speed CCD camera, (9) laser beam travel path, (10) short range IR-camera, (11) mirror, (12) pyrometer lens, (13) signal receiver, (14) optic fiber, (15) pyrometer, (16) BCube optic mirror, (17) attenuator, (18) LaserCam-HRTM CCD camera, (19) working platform, (20) moving piston, (21) electronic micrometer, (22) computer.

experimental data and includes modeling of 3D technological fields in area out of the technological limits of the equipment.

2 Experimental setup

The experimental setup is presented on the Figure 1. The main principles of construction of the experimental stand are performed in accordance to typical construction of the SLM-machine [7–9]. The setup was supplied by an optical diagnostic system and by a system of laser beam modulation. All experiments have been performed using the developed optical diagnostic system.

Cobalt-chromium alloy (Tab. 1) has been chosen for the experiments as a powder material according to his excellent heat resistivity and neutral reaction to the absence of protective atmosphere. The granulometric characteristics of the powder were controlled by an OC-CHIO 500 NANO optical granulometer (a resolution of the camera with 6,6 mln. pixels; lens type is telecentric buzzer; lens resolution is $0,38 \div 4,7$ micron/pixel) (Figs. 2, 3). Powder material layer nominal thickness in this study has been $30 \div 40 \mu\text{m}$ and controlled by an optical microscope.

During the experiments, two main SLM factors were varied as laser beam power P and laser beam scanning speed V . Laser power P was varied from 10 to 200 W, scanning speed was varied from 5 to 100 mm/s. Plenty of the authors obtained these main factors and their influences on the SLM-formation of single tracks [10–13]. The third varied factor was laser beam power density distribution. On the experimental setup three different laser beam power distribution was obtained (Gaussian, Flat-top and Inverse Gaussian) [7–9]. For the last 25 years plenty of the authors firstly proved the mathematical possibility of other laser beam power density distributions [14–17]; next they developed the optical principles and obtained them in their experiments, searched their possible application in the context of technology and machinery [18–24].

For each combination of the factors (laser beam power, scanning speed and laser beam mode), the ten-layer-3D-objects were produced. The length of the objects was 10 mm, each layer consists of 10 laser beam paths. The strategy, which was used to obtain the objects, was double hatching, one of the most wide-spread for object production in the conditions of real manufacturing.

The temperature in the molten pool was controlled by a multiwave pyrometer MPL4-900/2500: a range of measured temperatures is $1000 \div 2500 \text{ }^{\circ}\text{C}$, a range of

Table 1. Chemical composition of CoCrMo powder.

Element	Co	Cr	Mo	Si	Mn	Fe	C	Ni
Content, %	60–65	26–30	5–7	>1	>1	>0,75	>0,16	>0,1

(a)

(b)

Fig. 2. SEM images of CoCrMo powder $\times 1200$ (a) and $\times 4000$ (b).

Fig. 3. Granulometric analysis of CoCrMo powder.

Table 2. Average temperatures on the surface of molten pool measured by pyrometer in accordance with SLM-processing factors.

Laser beam power density distribution (Mode)								
Gaussian			Flat-top			Inverse Gaussian		
P, W	V, mm/s	T_{av} , °C	P, W	V, mm/s	T_{av} , °C	P, W	V, mm/s	T_{av} , °C
30	5	1719	50	10	1899	70	5	1849
30	10	1682	70	5	1949	70	10	1838
30	20	1703	70	10	1918	100	5	1937
50	5	1931	70	20	1760	100	10	1923
50	10	1719	130	40	1943	100	20	1804
50	20	1565	130	50	1930	130	5	1986
70	5	1922	130	70	1902	130	10	1962
70	10	1886	130	80	1748	130	20	1929
70	20	1786	150	50	1997	150	40	1877
130	50	1963	150	60	1918	150	60	1850
130	60	1936	150	70	1804	150	70	1842
130	70	1906	170	40	2042	150	80	1857
150	50	1999	170	50	1963	170	40	1933
150	60	1808	170	60	1875	170	50	1899
150	70	1799	170	70	1873	170	60	1904
150	80	1763	170	80	1807	170	70	1873
170	50	2032	200	40	2060	170	80	1917
170	60	1917	200	50	1990	200	40	1949
170	70	1885	200	60	1950	200	50	1928
170	80	1828	200	70	1855	200	80	1939

NB: P, W – laser beam power; V, mm/s – laser beam scanning speed; T_{av} , °C – average temperature on the surface of molten pool.

working wave lengths λ is $0.60 \div 0.95 \mu\text{m}$, an instrumental error is $\pm 0.5\%$.

3 Experimental results

During the SLM-operating temperature was measured by on four different wave lengths λ (0.651, 0.748, 0.840, 0.927). The received pyrometer data were compared with the used input factors of SLM-processing. For each experiment was accounted average temperature of the molten pool surface. The received data were represented for each of laser beam mode (Tab. 2). The data were obtained only for the samples, which was formed on the appropriate way as formed 3D-objects. The samples with the defects were not taken in account.

Based on the received data, the 3D-graphs of dependence between average temperature and used SLM-processing factors were obtained (Fig. 4). The graphs show a different picture of the dependences, which can give a wide field of the theoretical research the technological limits of SLM-processing and better understanding the nature of processing for increasing of technological productivity with extra high values of the laser power: from 200 W, which are already available on the industrial samples of SLM-machine, to 1 kW, which could be more desirable for future development of the technology in the frames of real industrial needs.

For each of the experiment in accordance with obtained diameter of laser beam spot on the surface of the powder and used factors of SLM-processing, the energetic

Table 3. Parameters of obtained laser beam spot on the surface of the powder for different types of laser beam power density distribution.

Type of laser beam power density distribution (Mode)	Effective diameter, mm
Gaussian	0.109
Flat-top	0.200
Inverse Gaussian	0.300

contribution was accounted by next formula:

$$E_C = \frac{P}{D_E \times V}$$

The obtained by optical method the effective diameters D_E (J/m²) of laser beam spot measured by CCD-camera LaserCam HRTM on the surface of the powder are represented in the Table 3.

The results of the calculation of energetic contribution is represented in Table 4. For the convenience of calculation, the all parameters in millimeters were transferred in meters.

The linear tends of the dependences between measured temperatures in the molten pool and calculated energetic contributions presented on the Figure 5. Picture shows that graphs, obtained for Inverse-Gaussian laser beam power distribution has more smoothly character and has more tendencies for improving of the energetic contribution impact into processing with the possibility to stay in the range of the SLM-processing working temperature of the molten pool with the purpose to enlarge

Fig. 4. 3D-graphs of dependence between average temperature and used SLM-processing factors, where: (a) for Gaussian laser beam mode, (b) for Flat-top laser beam mode and (c) for Inverse Gaussian laser beam mode.

Table 4. Calculated energetic contribution of the laser beam.

Gaussian laser beam mode (effective diameter = 0.109×10^{-3} m)								
V, m/s								
P, W	0,005	0,01	0,02	0,04	0,05	0,06	0,07	0,08
30	6,E+07	3,E+07	1,E+07	7,E+06	6,E+06	5,E+06	4,E+06	3,E+06
50	9,E+07	5,E+07	2,E+07	1,E+07	9,E+06	8,E+06	7,E+06	6,E+06
70	1,E+08	6,E+07	3,E+07	2,E+07	1,E+07	1,E+07	9,E+06	8,E+06
130	2,E+08	1,E+08	6,E+07	3,E+07	2,E+07	2,E+07	2,E+07	1,E+07
150	3,E+08	1,E+08	7,E+07	3,E+07	3,E+07	2,E+07	2,E+07	2,E+07
170	3,E+08	2,E+08	8,E+07	4,E+07	3,E+07	3,E+07	2,E+07	2,E+07
Flat-top laser beam mode (effective diameter = 0.200×10^{-3} m)								
V, m/s								
P, W	0,005	0,01	0,02	0,04	0,05	0,06	0,07	0,08
50	5,E+07	3,E+07	1,E+07	6,E+06	5,E+06	4,E+06	4,E+06	3,E+06
70	7,E+07	4,E+07	2,E+07	9,E+06	7,E+06	6,E+06	5,E+06	4,E+06
130	1,E+08	7,E+07	3,E+07	2,E+07	1,E+07	1,E+07	9,E+06	8,E+06
150	2,E+08	8,E+07	4,E+07	2,E+07	2,E+07	1,E+07	1,E+07	9,E+06
170	2,E+08	9,E+07	4,E+07	2,E+07	2,E+07	1,E+07	1,E+07	1,E+07
173	2,E+08	9,E+07	4,E+07	2,E+07	2,E+07	1,E+07	1,E+07	1,E+07
Inverse Gaussian laser beam mode (effective diameter = 0.300×10^{-3} m)								
V, m/s								
P, W	0,005	0,01	0,02	0,04	0,05	0,06	0,07	0,08
70	5,E+07	2,E+07	1,E+07	6,E+06	5,E+06	4,E+06	3,E+06	3,E+06
130	9,E+07	4,E+07	2,E+07	1,E+07	9,E+06	7,E+06	6,E+06	5,E+06
150	1,E+08	5,E+07	3,E+07	1,E+07	1,E+07	8,E+06	7,E+06	6,E+06
170	1,E+08	6,E+07	3,E+07	1,E+07	1,E+07	9,E+06	8,E+06	7,E+06
173	1,E+08	6,E+07	3,E+07	1,E+07	1,E+07	1,E+07	8,E+06	7,E+06

significantly the productivity of the process. Meanwhile the graphs obtained for Flat-top laser beam power density distribution has the same character as the Gaussian one on the energetic contribution level, which was proved by the described previous experiments for the formation of the single tracks as well [7]. To obtain more details for the presented data, continuation of the experimental and calculation work is needed.

In Figure 6 the results of the modeling for the research of principal perspectives and limits in productivity improvement of selective laser melting with the factors in range for scanning speed V from 0 up to 200 mm/s and power P from 0 up to 500 W for each of the developed mode of laser beam. The picture was obtained by calcu-

lation of the formula of temperature fields of the molten pool (formula for each mode is presented on the following graph) based on the empiric data received by the described experimental work. The picture of the temperature fields significantly shows that continuation of the research in the direction of direct linear enlargement of the laser beam power for Gaussian laser beam mode and Flat-top laser beam mode has no technological sense with the proportional linear enlargement of the scanning speed, which is obvious in this case. The principal perspectives in the improvement of the SLM-processing productivity can be achieved by use of Inverse-Gaussian laser beam mode in the next meanings: laser beam power from 130 up to 500 W; laser beam scanning speed from 60–80 mm/s up

Fig. 5. Tendencies and linear prognosis of the possible increase of the SLM-processing productivity with the evaluation of the energetic contribution for different laser beam power density distributions.

to 140–160 mm/s for Co-Cr powder. The range of working temperature of the molten pool was defined from 1680 up to 2060 °C. More interest in the context of the described objective in the current work has an area of the technological gap in the frames of the power from 450 to 500 W and scanning speed from 130 to 160 mm/s.

4 Conclusions

On the developed experimental setup, the temperature data for different laser beam power density distribution were obtained by pyrometer. The data were compared with the used SLM-processing factors as laser beam power and laser beam scanning speed. Based on it, the 3D-graphs of the dependences between average means of measured temperatures and used factors were modeled. The tendencies of Inverse Gaussian laser beam power density distribution has a potential for the purpose of the work to enlarge significantly the productivity of SLM-processing with the rise of the laser beam power and with the rise of laser beam scanning speed. In this case, the temperature of the molten pool could stay in the limits of the range of working temperatures (from 1680 to 2060 °C). Otherwise the energetic contribution into the SLM-processing can be too much low (not enough for starting of melting processes) or too much high, which leads to formation of the plasma cloud and active evaporation of the material from the surface of molten pool,

including possible sublimation (direct evaporation of the material without liquid phase formation).

For the used range of the SLM-processing factors, the energetic contribution was calculated for each group of the experiments. The obtained calculated data was compared with the measured temperature. The modeling of the linear prognosis for each laser beam power density distribution confirmed that Inverse Gaussian laser beam mode has a huge potential for the increase of SLM-processing productivity. For further modeling of the behavior the tendencies of the dependences between laser beam energetic distribution and measured working temperatures in the molten pool, it is necessary to continue the experiments on the developed experimental setup.

The future perspectives of the improvement of the productivity for SLM-processing can be in the direction of the enlargement of the laser beam power from 500 W up to 1 kW; meanwhile the enlargement of the scanning speed should be in the range from 130 mm/s up to 200 mm/s. For the evaluation of these perspectives needs more data to precise the formulas for the modeling.

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Fig. 6. Results of the modeling for the research of principal perspectives and limits in productivity improvement of selective laser melting with the factors in range for scanning speed V up to 200 mm/s and power P up to 500 W: (a) for Gaussian mode; (b) for Flat-top mode; (c) for Inverse-Gaussian mode.

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