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Automation of the single-track study for L-PBF additive manufacturing processes (for AlSi10Mg powder)

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Abstract. When using a new powder material in each individual selective laser melting unit, the process engineer has to conduct process development works (PDW) to find the optimal combination of process parameters. The results of the PDW are analysed manually by the process engineer without the use of process decision support tools. Due to the expanding technological capabilities of the equipment and the available range of material properties, the possible set of parameters is also expanding, complicating the already non-trivial process of searching for printing process parameters. In order to reduce the PDW time, in this paper we proposed a rapid analysis tool to select individual experimental results with single welded tracks of AlSi10Mg powder. The process of conducting the experiment on domestic equipment was reviewed and the efficiency of the automation tool was investigated in comparison with the traditional manual selection approach. It is concluded that it is possible to apply the developed tool for materials and installations of additive manufacturing not considered in the study.

1 Introduction

Since the beginning of the 21st century, additive manufacturing has formed a unique and intensively developing technological segment in mechanical engineering. While 3D printing used to attract only enthusiasts, today its advantages have been appreciated by such major aircraft corporations as General Electric and Boeing. The attention of the major 'players' in the market is also supported by practical results and an expanding list of technological opportunities that additive technologies provide [1]. Such opportunities are, in particular: high material utilisation rate, possibility to create products of unique shapes, close in complexity to organic (nongeometric) shapes, and high efficiency of the technology at the stage of pilot works. The possibility of making products from various metal-powder compositions (including by selective laser melting) determines the use of grown PAU as fully functional products [2-5].

The advantages described lead to the growth of the nomenclature of equipment and materials for the synthesis of products [6]. Currently, the process of growing a product by selective laser melting differs depending on the additive manufacturing setup and the

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material used. The process of searching for an optimal set of technological parameters of the synthesis process for a new material and equipment can be singled out as a separate stage of the OCTD, because each time it represents a separate multifactor problem solved by the process engineer at the stage of the TPP. The result of solving this problem may be a delay in the stage of OCTD or the use of parameters that will not achieve the required characteristics of the final product [7].

In connection with the above, a promising area of research is to improve the process of technological preparation of additive manufacturing by selective laser melting with the use of technological decision support tools.

In the previously performed works at the Department of "Engineering Graphics" of the Moscow Aviation Institute with equipment and materials for additive manufacturing it is shown that data on technological parameters of the process of selective laser melting often cannot be effectively analysed without the help of any express-analysis tools. Due to the expanding technological capabilities of the equipment and the available range of material properties, the possible set of parameters also expands, complicating the already non-trivial preparation of the technological process [8-9].

In order to address the shortcomings of the existing technology (and its preparation process), it is important to develop tools to provide an efficient process for selective laser melting, taking into account the existing limitations associated with technology, equipment and materials [10].

1.1 Parameters of the technological process

There are several parameters of the technological process of selective laser melting, which in one form or another can be changed by the process engineer and the operator of additive manufacturing equipment before the start of the fusion process. The totality of the interrelationships of these parameters affects the flow of the VLP process and, as a consequence, the various quality criteria discussed earlier.

These parameters can be categorised into:

- Process parameters related to material characteristics;
- Parameters determined by the control programme;
- Parameters related to the characteristics of the plant;
- Parameters related to the geometry of the grown product.

Varying these parameters allows the technologist to control the process of selective melting up to a certain limit and influence the quality of the synthesised product. Optimisation of parameters is carried out in order to improve the quality of both the melting process and the final part [11].

1.2 Structure of works on search of technological parameters of melting process

Despite the differences in approaches to finding the optimal parameters, researchers agree on a general approach to the development of VLP process parameters related to the control programme [12]. In general terms, such process development work consists of a series of sequential material and plant experiments.

During the planning of PDW, as a rule, most of the parameters affecting the growing process are fixed. This is the case, for example, with the equipment parameters, the process environment and the properties of the metal powder composition in the start-up. These values are frozen, thus recording them in the initial data for the solution of PDW tasks. In turn, the parameters of the control programme affecting the energy input are varied in order to increase the efficiency and quality of the VLP process. Thus, an optimisation problem is formed, which is solved by conducting a series of experiments [13-15].

Each of the subsequent experiments narrows the funnel of process parameters, until a set is found that provides optimal process characteristics in accordance with the condition of the optimisation problem.

2 Methods and Materials

2.1 Material and setup for selective laser melting

AlSi10Mg alloy powder produced by Russian Aluminium (UC RUSAL, Moscow, Russia) was used in this work. The material is supplied in the form of spherical powder with nominal particle size from 20 to 63 μm. The chemical composition (Table 1) and morphology of the granules are controlled by the material supplier [16].

Table 1. Chemical composition of AlSi10Mg material

Alloy grade	**Elemental content, %**										
	i	l	e	n	i	u	g	n	b	i	n
A lSi10Mg	1.00	7.1	.55	.45	.05	.05	.45	.1	.05	.15	.05

Fabrication of single welded track samples was performed on the Addsol D50 machine (LLC "Titan-Avangard", Russia), the control programme for which was developed in the PC TPP software package (developed by FSBEI HE "MAI");

2.2 Experimental parameters

The experiment with scanning of single welded tracks makes it possible to determine the character of formation and parameters of the molten pool depending on the scanning parameters - laser power P and scanning speed V [17]. For this purpose, the other process parameters are "frozen" for the purposes of the experiment, and these parameters are varied in order to find the tracks corresponding also to the continuity criterion.

For the experiment conducted, the laser power was varied from 40 to 400 W and the scanning speed from 200 mm/s to 2000 mm/s, which is 90% of the corridor of parameters possible on the Addsol D50 machine [18].

The single tracks were composited into a 9x11 matrix. The step of laser power variation is 36 W. The step of speed variation is 225 mm/s. Printing was carried out in an inert argon environment. The percentage of oxygen content during growth did not exceed 0.8% [19].

Tracks with a length of 10 mm were fabricated (Fig. 1.3).

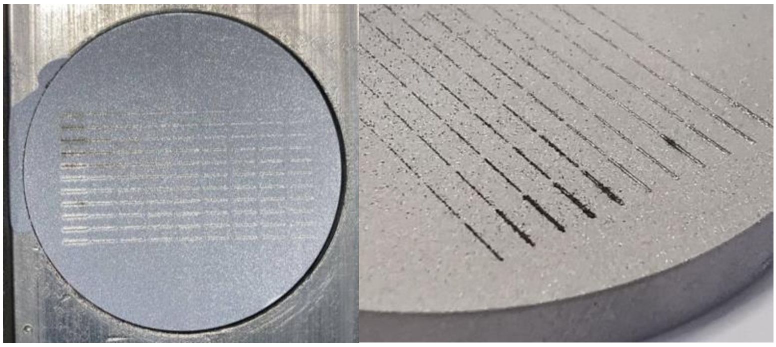

Fig. 1. Single tracks produced on the AddSol D50 VLP machine

The single tracks after printing were analysed on a Saike Digital SK2700HDMI-AF optical microscope (PRC) [20-21]. A set of 99 photographs of the top view of the tracks was prepared. The set was then examined using express analysis tools to find the required values of the linear energy contribution parameters, which is a combination of the parameters of the laser radiation power applied to the powder layer as well as the scanning speed [22]. In the case of volumetric objects, the formula is used:

$$E_v = \frac{P}{V \cdot h \cdot d};$$

here:

V – scanning speed (laser spot movement), mm/s;

P – laser power, W;

h – height of the applied powder composition layer, mm;

d – diameter of the laser spot on the surface of the powder layer, mm.

To analyse the experiment with single tracks, a simplified version of the formula is used to calculate the linear energy contribution:

$$E_l = \frac{P}{V};$$

2.3 Algorithm of work of the software component of express analysis of single tracks

A software tool for express analysis of single-track images in the top view has been developed in Python language.

The program consists of two parts - a handler and a visualisation block [23].

2.3.1 Automated processing of experimental data

A set of images of single welded tracks obtained with an optical microscope is fed to the "input" of the programme. For each image, a mask showing the area occupied by the track in the image is generated (Fig. 2.2).

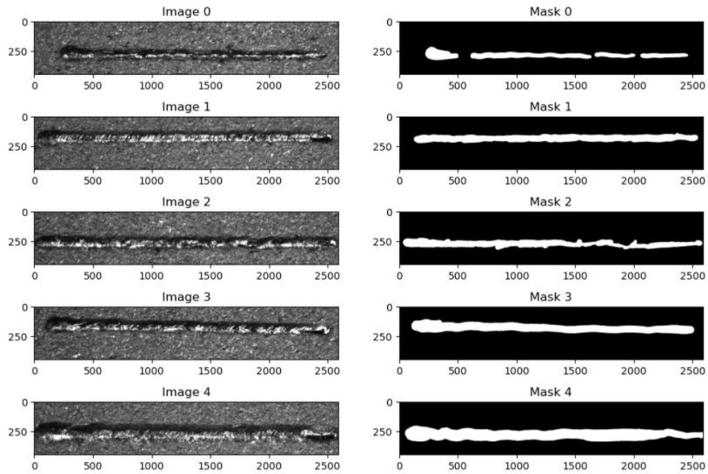

Fig. 2. Automatically obtained single track masks

The black and white images are based on the binarisation method, which allows to separate the track from the plate at given threshold values. In the process of searching for a suitable algorithm, many methods were tried.

As a result, based on a combination of factors, the Otsu algorithm [24] is used to obtain thresholds (masks that highlight the track in the top view). For each image, a histogram of the intensity distribution of the halftone image is constructed, and then the threshold value at which the intra-class variance is minimised is found, σ_w :

$$\sigma_w^2 = \frac{w_1^2\sigma_1^2 + w_2^2\sigma_2^2}{w_1^2 + w_2^2},$$

where w_1 and w_2 are the class sizes, σ_1 and σ_2 define class dispersions.

After that the image is divided into two classes, the material (white colour - 1) and the background (black colour - 0) using the found threshold value. To process the track mask obtained by the Otsu method, the morphological operation of "opening" and "closing" is used, allowing a clearer separation of the track and the background, removing unnecessary noise due to this symmetric operation. The resulting track mask is used to select the track in the image and to calculate the track area [25]. A tool allowing to determine track continuity in the image has been developed. The mask obtained at the previous step is segmented - "islands" of the mask are selected (Figure 2.3).

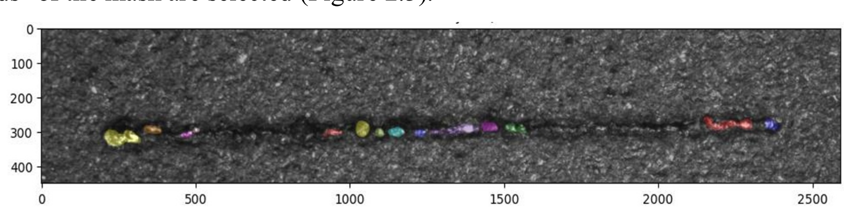

Fig. 3. Segmentation of mask fragments for an intermittent track

Photographs of discontinuous tracks thus contain several segments. Non-melting of a single track is a clear indicator of insufficient energy input during laser impact on the metal powder layer. Therefore, this track and a pair of "power-velocity" parameters are excluded from further consideration.

2.3.2 Visualisation of processed experimental data

Thus, the second part of the programme includes continuous tracks, where the mask is not split into separate, unrelated segments. Further, the Python library "skimage" is used for the work of the visualisation block [26]. The library "scikit-image" (skimage) is designed for image processing and analysis in the Python programming language. It contains many functions to perform various image processing tasks such as segmentation, filtering, resizing, object detection and many others. This paper uses "measure.label", a function from the skimage library, to obtain labels for each connected object in a binary image. Labels are unique numeric identifiers that are assigned to each cohesive object in the image [27].

Next, the area, width, length and the "extent" parameter is calculated for each track. This parameter defines the ratio of the area of the track mask to the total area of the dimension rectangle that describes the track image (Figure 2.4).

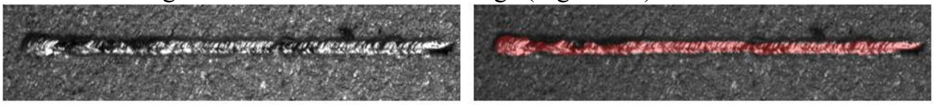

Fig. 4. Example of track mask selection with respect to an overall rectangle describing the track image

Based on the data on the "extent" parameter, known values of power and velocity, a bubble diagram is constructed to visualise the results of the single track experiment (Fig. 2.5)

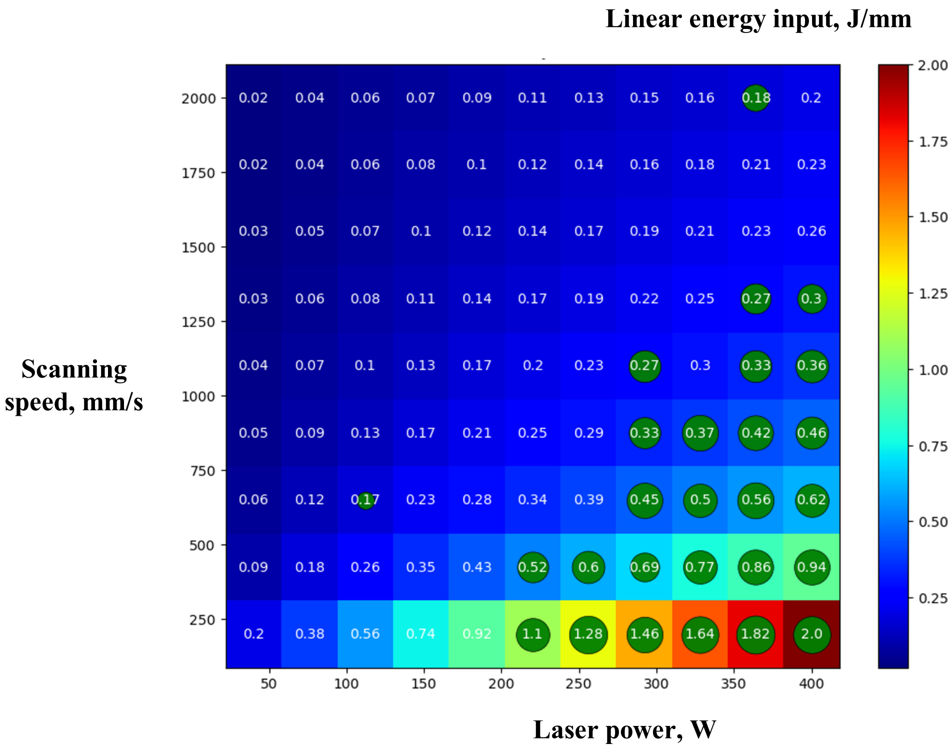

Fig. 5. Bubble diagram of the experiment results

The bubble diagram allows you to visually show the tracks with the highest "extent" parameter, as a result of which the process engineer can refine the range of the next experiment (e.g., printing test volume samples). In the case of the above diagram, the range can be reduced from [40:400], W (for radiation power) and [200:2000], mm/s (for scanning speed) to [220;400], W and [200;1400], mm/s, respectively. This reduction will allow in future experiments either to reduce the number of samples or to significantly (by a factor of two) reduce the step of parameter variation while maintaining the number of samples, which will increase the accuracy of the experiments performed [28-34].

3 Results and Discussion

The proposed tools become the basis for the methodology of processing, analysis, and visualisation of the experiment data with single tracks. The work according to the formed methodology allows us to promptly analyse and systematise the results of the initial stages of PDW without the need for careful manual review of a large number of photographs.

For the considered experiment and the obtained dataset (99 track images), the use of the proposed methodology allows to reduce the time spent on the analysis and systematisation of the data of the single-track scanning experiment. In parallel to the automated analysis of experimental data, manual analysis was also performed (Fig. 3.1).

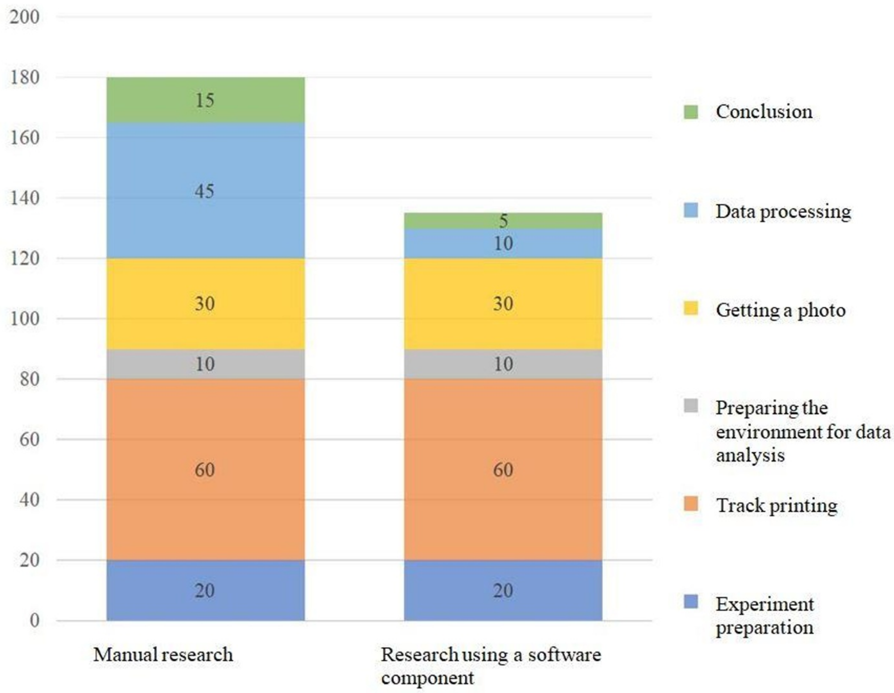

Fig. 6. Comparison of time spent on one cycle of experiments: manually and using automated analysis tools

The methodology also reduces the human factor and the risk of error caused by the need to analyse the larger the amount of experimental data, the smaller the step of variation of the process parameters - power and speed, and the larger their possible range (maximum permissible for a particular VLP unit).

4 Conclusion

The paper considers the methodology and algorithm of the express analysis of the results of experimental work to search the optimal parameters of energy input in the process of selective laser melting of metal-powder compositions.

The essence of PDW on search of optimum parameters of the printing process by VLP method is considered in detail.

The proposed methodology and the software component of express analysis can become a working tool for a techno-scientist for research work in additive manufacturing.

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