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The effect of laser surfacing modes on the geometrical characteristics of the single laser tracks

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ABSTRACT

Introduction. Laser surfacing is one of the leading trends in the field of additive technologies, which consists in layer-by-layer build of material using a laser as an energy source. To obtain a high-quality product, it is necessary to select the optimal building parameters correctly. The problem is that such optimization is necessary for all equipment, since minor differences in its characteristics can make significant changes in the parameters of layer-by-layer build. In order to determine the optimal build mode, it is enough to analyze the effect of various equipment parameters on the characteristics of single tracks. Therefore, **the purpose of this work** is to determine the most important parameters of laser radiation that affect the surfacing process and the optimal mode for building a single track of chromium-nickel steel. **The work investigated** single tracks obtained by laser surfacing of powder from austenitic chromium-nickel steel *AISI 316L*. The optimization factors included such characteristics as laser power, beam speed, flow rate of supplied powder and laser spot size. The wavelength of laser radiation was 1.07 µm. **Research methods.** To determine the quality and geometric dimensions of single tracks, the macrostructure of cross sections of specimens was studied using metallography and scanning electron microscopy methods. **Results and discussion.** It is established that the optimal mode for growing single tracks of steel *AISI 316L* is characterized by a laser radiation power of 1,250 W and a scanning speed of 25 mm/s. In this case, the optimal powder consumption rate is 12 g/min, and the laser spot size is 4.1 mm. The work shows that the powder consumption and laser spot size have the greatest influence on the coefficient of effective use of powder material. By changing it, the surfacing performance can be increased by 10–15 %.

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Introduction

Traditional steel preparation methods are still one of the most universal and basic ways for manufacturing products. However, the production of one type of finished product sometimes requires a huge number of parts with a preforming procedure and different ways of connecting it to each other. The use of additive technologies as a method of creating products has proven to be a promising way of direct manufacturing of metal parts of complex geometry with functional structure [1, 2]. This method can reduce waste and save raw materials. Also, many authors claim that due to the unique thermal conditions occurring during laser additive manufacturing, it is possible to regulate the chemical composition, influence metallurgy, obtain a certain microstructure and improve the mechanical properties of manufactured parts [3–5].

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At the moment, there are a huge number of techniques for layer-by-layer building of products, but one of the main methods of additive manufacturing is laser surfacing. The reason for this is the versatility, simplicity, and widespread use of the technology [6]. This technique allows obtaining parts with low surface roughness due to smaller laser beam size, smaller layer thickness and short step compared to other additive technologies. Also, this preparation method allows applying additional material on the finished product for the purpose of repair and restoration of the part [5–8]. Laser technology ensures the production of dense parts without oxidizing the surface during the building process due to the use of a protective gas environment and allows the use of several materials in one assembly (*Functionally Gradient Material* or *FGM* specimens) [9–13].

Nowadays there is a huge amount of research on various aspects of laser additive technologies and one of the most common topics is optimization of processing parameters. Precisely because of the correctly selected modes of layer-by-layer build-up it is possible to assess the presence of physical defects, which indicates the quality of the obtained products [5, 8], and allows to increase the efficiency of production [7]. The topic of parameter optimization has been dealt with by scientists using various research techniques. In [5], the authors selected modes of single-track formation for a fiber laser by enumerating the most used modes in the planning matrix. In study [14], the authors used regression analysis technique to determine the effect of coaxial nozzle fiber laser power, surfacing speed, and powder distribution in the feed jet on the generated tracks. They found that at constant laser power, the height and cross-sectional area decreased with increasing surfacing speed, while the height and cross-sectional area increased with increasing powder feed rate. At constant speeds and varying power, the cross-sectional area increases, and the powder distribution has no effect on the track geometry. Similar results were obtained by the authors of the paper [7] using the *ANOVA* (*analysis of variance*) technique. They concluded that different parameters affect the geometric dimensions of the track in different ways. The track height is mainly influenced by the surfacing speed and powder feed rate. The influence of power is about 1 %. However, in the track width study, power and scanning speed were the main influencing factors. In [15], the effect of different fiber laser modes on single track formation was also studied. The authors confirmed that increasing the powder feed rate negatively affects the bond quality between the surfaced track and the substrate, the laser travel speed negatively affects the cross-sectional area and positively affects the surfaced track width. The laser power has a significant effect on the height and width of the formed track, compared to the scanning speed and powder feed rate.

Since different studies use different equipment and different materials, despite the identical technology of layer-by-layer surfacing, the results obtained may differ significantly. Thus, this topic is still relevant. Therefore, the purpose of this work is to determine the most important laser radiation parameters affecting the surfacing process and the optimal mode for obtaining high-quality single tracks from *AISI 316L* steel with the use of a fiber laser.

Methods and materials

Investigated material

AISI 316L steel powder was used to investigate the influence of build-up modes on obtaining high-quality single tracks. The average particle size was 15–45 µm. Surfacing of steel powder was carried out on a plate made of *0.12 C-18 Cr-10 Ni-Ti* steel with dimensions of 50×50×5 mm. The chemical composition of the alloys used is presented in Table 1.

Table 1

Chemical composition of the materials under study

Material	Chemical element, wt. %								
	C	*Mn*	*Si*	*S*	*P*	*Ti*	*Cr*	*Ni*	*Fe*
AISI 316L	0.025	0.84	0.68	0.015	0.01	0.71	18.69	8.84	Bal.
0.12 C-18 Cr-10 Ni-Ti	0.11	1.082	0.447	0.002	0.027	0.002	17.15	7.85	Bal.

Equipment

Surfacing was carried out by the *direct laser deposition* method. With this method, laser radiation is focused by means of a lens onto the substrate, forming a "bath" of melt. The powder mixture is supplied coaxially to the laser radiation through a coaxial nozzle. As the laser beam moves, the melt bath solidifies to form a deposited bead. Formation of single tracks was carried out on the equipment "Cladding and welding complex on the basis of a multi-axis arm and fiber laser" with the power of ytterbium laser 3 kW (produced by *IPG-photonics*) and wavelength of radiation 1.07 μm (Fig. 1). Argon was used as a carrier gas and as a protective medium during the growth process.

Fig. 1. Automated laser complex

The *Olympus LEXT OLS 3000* optical microscope and *Carl Zeiss EVO 50 XVP* scanning electron microscope (core facility "Structure, mechanical and physical properties of materials" NSTU) were used to determine the size and quality of the formed tracks. Cross-sections of specimens for the study were prepared according to the standard grinding and polishing technique. Etching was performed using a chemical etchant of the composition $HNO_3 : HCl = 1 : 3$

Experimental conditions

Equipment parameters, energy density, scanning speed, gas flow rate and other parameters play an important role in determining microstructure features, part quality and process performance. Therefore, to determine the optimal modes of building a steel product by direct laser deposition, it is necessary to investigate the material behavior during the formation of single tracks. The choice of initial parameter values is based on literature data [16–23]. The range of values of the main parameters was as follows: laser power 1.000–1.500 W, scanning speed 15–35 mm/s, powder flow rate 12–36 g/min (feed disk speed 4–12 % respectively) and laser spot size 2.9–5.6 mm. Such parameters as powder flow rate and laser spot size were changed after determining the optimal power and scanning speed.

Selection conditions

In the additive manufacturing process, various surfacing defects may occur due to peculiarities of the study material, equipment parameters and growing modes. Therefore, to determine the optimal building mode, the geometric dimensions, wetting angle with the substrate, the presence of pores and cracks in the junction zone of the obtained single tracks and the substrate were analyzed. In this work, the ratio between the thickness and width of the surfaced layer equal to 1:3 is evaluated, since if this ratio is not met in the process of the solid formation interlayer pores may form [8, 24]. Also, in this paper the concept of effective build-up ratio is introduced – the coefficient of effective materials consumption, based on the ratio of the surfaced metal mass to the rate of powder consumption. This characteristic evaluates the loss of material during the surfacing process.

Results and discussion

Macrostructure and geometrical dimensions of the obtained tracks

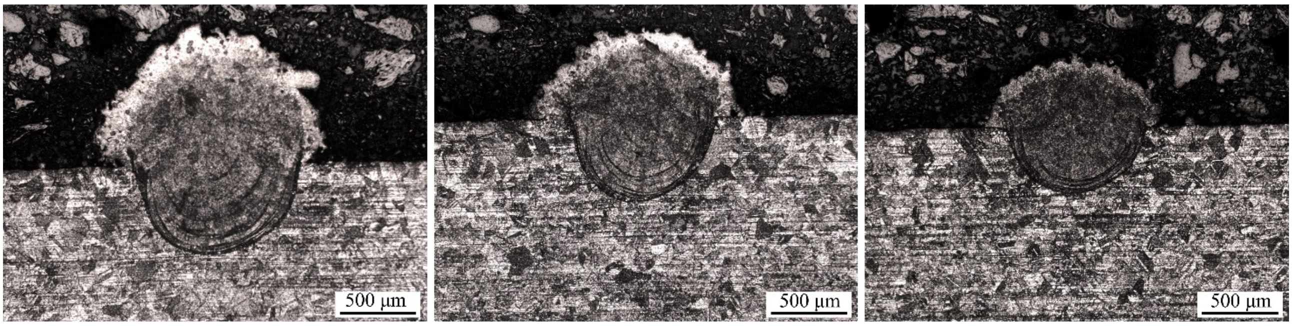
The geometric dimensions and the presence of defects in the zone of the surfaced layer at single tracks should be evaluated to determine the most suitable build-up mode for solid construction. Table 2 shows the geometric characteristics of the surfaced steel powder.

The macrostructure of the cross sections of steel *316L* is presented in Fig. 2–6. As one can see, with increasing speed, the height of the investigated tracks decreases, which further increases the width of the surfaced layer (Fig. 2–4). This can be explained by a decrease in linear energy consumption (formation of a smaller melt bath), and a decrease in powder mass flow rate per unit length at constant feed rate. Increasing the power similarly changed the geometrical dimensions of the track (Fig. 2–4).

Table 2

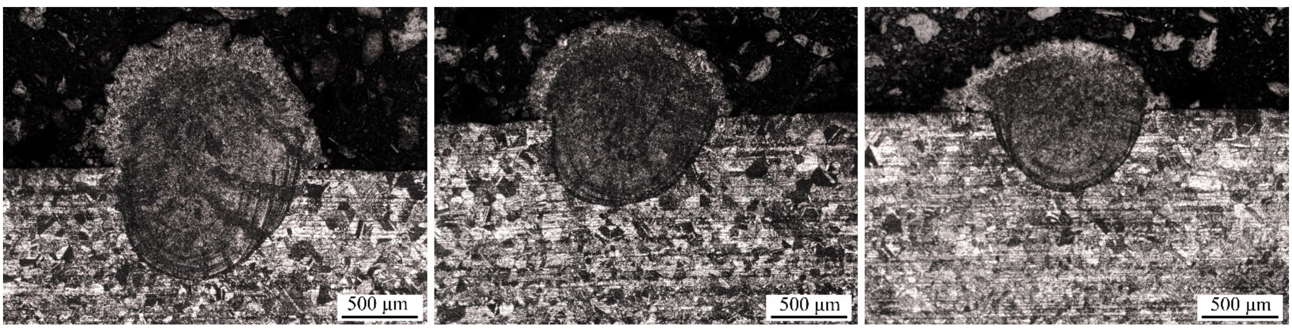
Geometric dimensions of single tracks

Power, W	Speed, mm/s	Consumption, %	Beam diameter, mm	Height, µm	Width, µm	Penetration depth, µm	Contact angle, °
1.000	15	8	2.9	825	1,177	579	38
1.000	25	8	2.9	540	1,285	552	132
1.000	35	8	2.9	402	1,100	431	117
1.250	15	8	2.9	935	1,305	738	43
1.250	25	8	2.9	620	1,213	571	47
1.250	35	8	2.9	445	1,202	534	143
1.500	15	8	2.9	790	1,485	1,286	33
1.500	25	8	2.9	540	1,527	1,089	117
1.500	35	8	2.9	397	1,312	969	77
1.250	25	4	2.9	245	1,642	872	155
1.250	25	12	2.9	765	1,197	485	67
1.250	25	4	4.1	305	1,567	655	130
1.250	25	4	5.6	345	1,775	552	134



a *b* *c*

Fig. 2. Cross sections of tracks obtained at a power of 1,000 W, powder consumption 24 g/min, laser spot size 2.9 mm, speed 15 mm/s (*a*), 25 mm/s (*b*), 35 mm/s (*c*)



a *b* *c*

Fig. 3. Cross sections of tracks obtained at a power of 1.250 W, powder flow rate 24 g/min, laser spot size 2.9 mm, speed 15 mm/s (*a*), 25 mm/s (*b*), 35 mm/s (*c*)

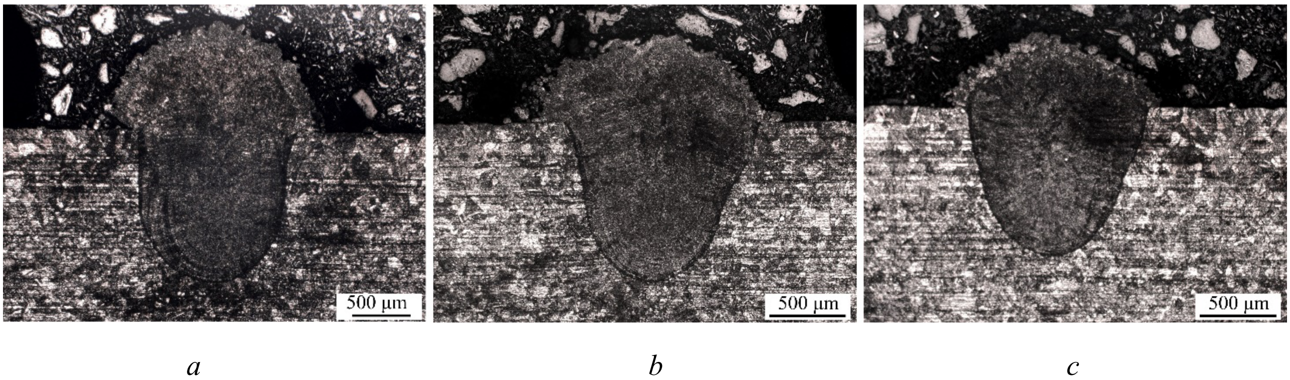


Fig. 4. Cross sections of tracks obtained at a power of 1.500 W, powder flow rate 24 g/min, laser spot size 2.9 mm, speed 15 mm/s (*a*), 25 mm/s (*b*), 35 mm/s (*c*)

The wetting angle of the deposited layer with the substrate is one of the most important parameters determining the track homogeneity. In some specimens, at minimum speed values, a negative lateral angle was detected (Fig. 2, *a*; 3, *a*; 3, *b*; 4, *a*), which can cause delamination of the material from the substrate and the presence of interlayer pores. With increasing power and scanning speed, the wetting angle increased to the contact with the substrate boundary due to changes in the geometric dimensions of the track (Fig. 2–4).

Also, the main geometric parameter necessary to identify the optimal growth mode is the depth of penetration. With increasing power, the depth of the melted area increases, but the opposite effect occurs with increasing scanning speed (Fig. 2–4). The maximum penetration depth (1.286 µm) corresponds to the highest power value with the minimum scanning speed (1.500 W and 15 mm/s). The reason for this is the large amount of power applied to the local melting point. This effect indicates that when using the maximum scanning speed, the laser power should also be a maximum.

Based on the analysis of the obtained data, the power and build-up rate of 1,250 W and 25 mm/s were chosen as the parameters of the optimal mode, respectively, since neat tracks without large pores were formed in this mode, and minimal sparking was present in the surfacing process (Fig. 3, *b*). However, the condition described in [8] was not fulfilled because not all parameters were varied. Therefore, based on this mode at constant scanning power and speed, the effect of powder consumption and laser spot size on single tracks was further investigated.

When using a powder feed rate of 12 g/min, a minimum track height was formed, since with an increase in this characteristic, the mass consumption of the powder increases (Fig. 5). However, when the laser spot size was increased, the track height increased (Fig. 6).

With increasing scanning power, the depth of the molten substrate increases due to an increase in the amount of laser energy penetrating the substrate (Fig. 7). However, as the scanning speed increases, the

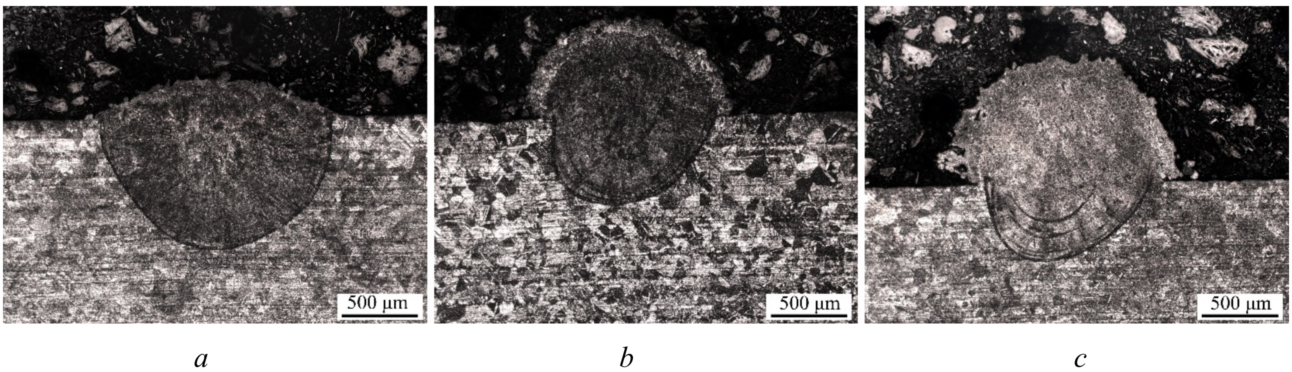


Fig. 5. Cross sections of tracks produced at a power of 1.250 W, speed 25 mm/s, laser spot size 2.9 mm, powder consumption 12 g/min (*a*), 24 g/min (*b*), 36 g/min (*c*)

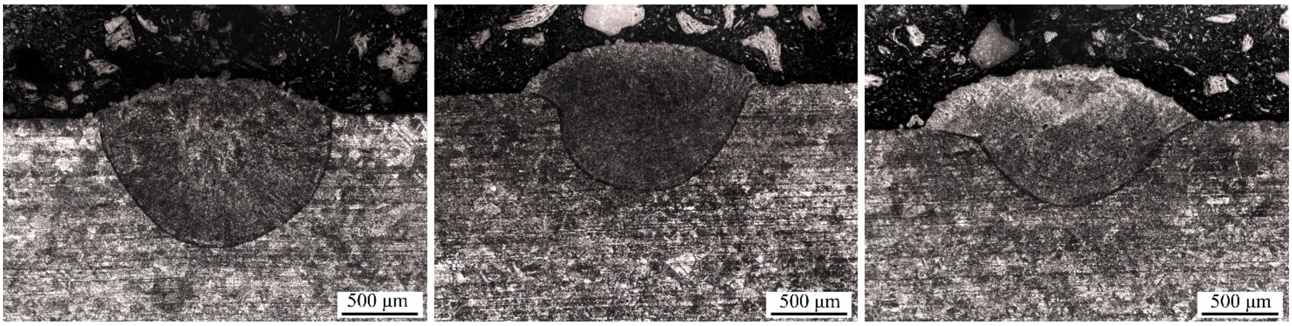


Fig. 6. Cross sections of tracks produced at a power of 1,250 W, speed 25 mm/s, powder consumption 12 g/min, laser spot size 2.9 mm (*a*), 4.1 mm (*b*), 5.6 mm (*c*)

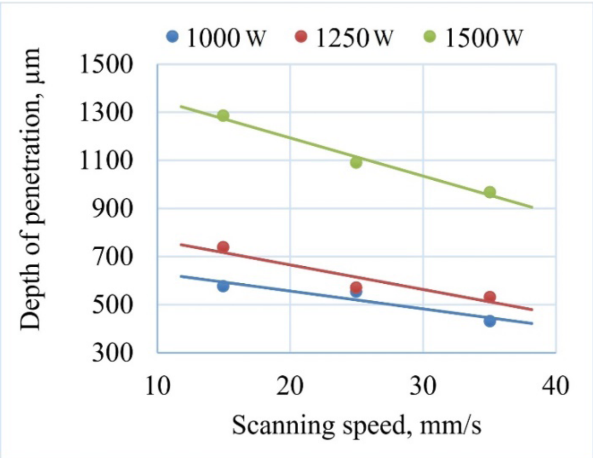


Fig. 7. Change in penetration depth with varying power and build-up speed, laser spot size 2.9 mm, powder consumption 24 g/min

layer penetration depth decreases due to the decrease in the specific laser energy during the cladding process. Increasing the powder consumption and laser spot size decreases the layer penetration depth for a similar reason (Fig. 8, 9).

In the specimens at the minimum scanning speed, as well as at high powder consumption, cracks caused by tensile stresses were formed at the interface between the melted material and the substrate (Fig. 10).

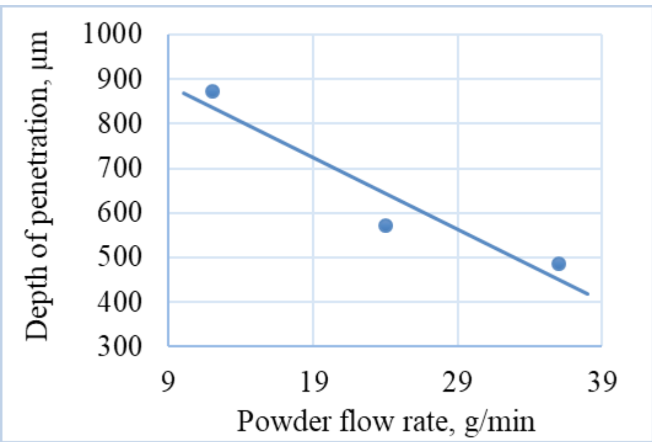


Fig. 8. Dependence of penetration depth on powder consumption at a power of 1.250 W, scanning speed 25 mm/s, laser spot size 2.9 mm

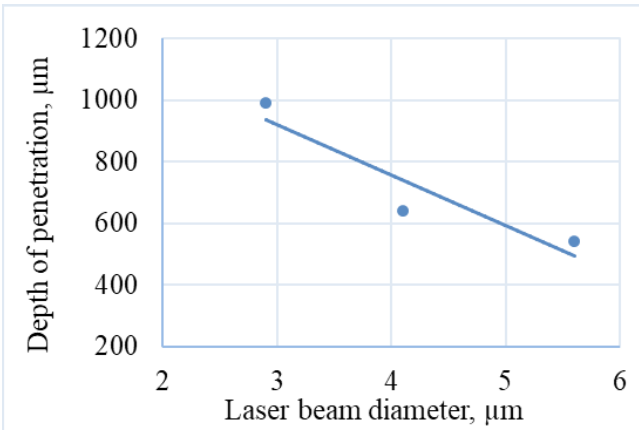
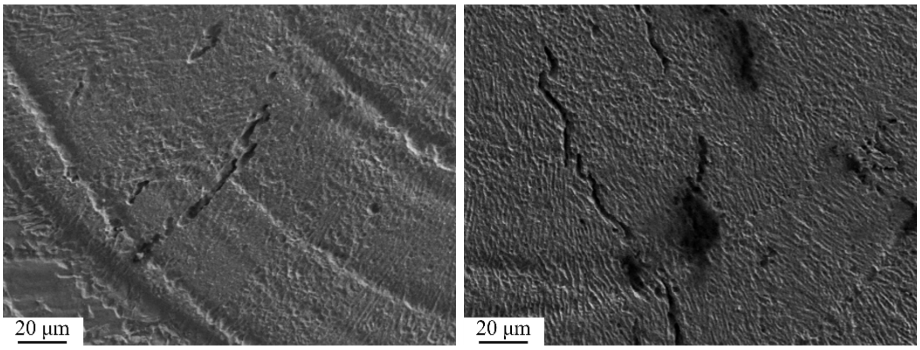


Fig. 9. Effect of changing the size of the laser spot on the penetration depth at a power of 1.250 W, speed 25 mm/s, powder flow rate 12 g/min



a *b*

Fig. 10. Presence of cracks in the fused layer:
a – power 1.000 W, scanning speed 15 mm/s, powder flow rate 24 g/min;
b – power 1.250 W, speed 15 mm/s, powder flow rate 24 g/min

Coefficient of effective materials consumption

Determination of the coefficient of useful consumption of materials was carried out according to the equation [25]:

$$K_u = \frac{m}{P},$$

where ***m*** is the mass of the surfaced layer determined by the volume of surfaced material per minute, g/min; ***P*** is the powder consumption in the build-up process, g/min.

The mass of the surfaced layer was determined by the cross-sectional area of the obtained tracks. The obtained values are presented in Table 3. The average coefficient of effective materials consumption in the process of direct laser deposition was 20–23 %. A similar result was obtained in [26]. Analyzing Fig. 11, we can conclude that with increasing the speed and power of laser radiation, the powder mass loss during the build-up process changes insignificantly, thus indicating the absence of influence of these two parameters on the build-up performance.

Increasing the powder flow rate increases the material consumption ratio (Fig. 12) due to the interaction of more particles with each other. However, changing the laser beam diameter during the growing process showed a significant increase in the coefficient of useful consumption (Fig. 13). This is explained by the increase in the spot diameter on the material.

Table 3

Surfacing efficiency coefficient

Power, W	Speed, mm/s	Powder consumption, %	Beam diameter, mm	Coefficient, %
1.000	15	8	2.9	21.1
1.000	25	8	2.9	21.4
1.000	35	8	2.9	20
1.250	15	8	2.9	24.8
1.250	25	8	2.9	26.5
1.250	35	8	2.9	24.6
1.500	15	8	2.9	23.3
1.500	25	8	2.9	23.7
1.500	35	8	2.9	21.9
1.250	25	4	2.9	24.6
1.250	25	12	2.9	28.5
1.250	25	4	4.1	32.2
1.250	25	4	5.6	43.1

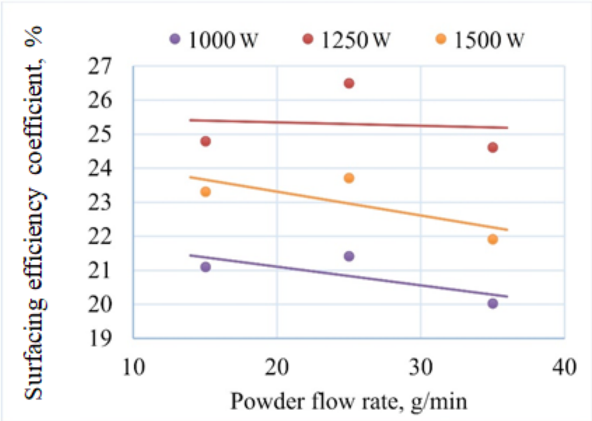


Fig. 11. Effect of power changes on the coefficient of useful material consumption: beam diameter 2.9 mm, powder flow rate 24 g/min

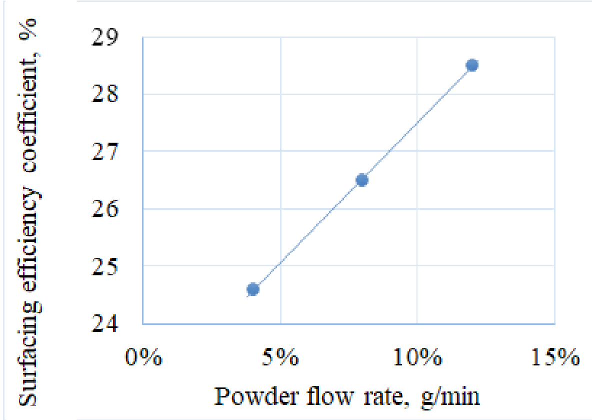


Fig. 12. Effect of changes in powder consumption on the coefficient of useful material consumption; power 1.250 W, speed 25 mm/s, beam diameter 2.9 mm

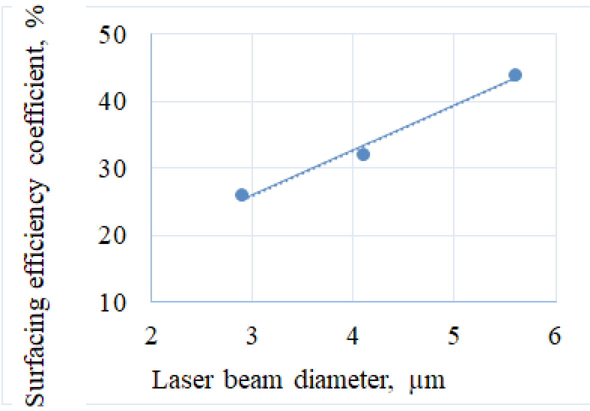


Fig. 13. Influence of the laser beam diameter on the coefficient of useful material consumption; power 1.250 W, speed 25 mm/s, powder flow rate 12 g/min

Conclusion

The effect of deposition parameters on the geometric dimensions of single tracks from austenitic steel *316L* using a fiber laser is investigated in this work. During the study, it was confirmed that with increasing scanning speed and laser power there is a decrease in the height of a single track with an increase in its width. Based on the analysis of geometrical dimensions, wetting angle with the substrate, presence of pores and cracks in the zone of connection between the obtained single tracks and the substrate, the optimal growth mode is determined, laser power and scanning speed for which were 1,250 W and 25 mm/s, respectively. When the laser power increases, active sparking occurs, which is accompanied by an increase in the penetration depth and an increase in surface roughness. Changing the parameters of powder flow rate and laser beam diameter results in single tracks characterized by lower roughness and complete wetting of the surface. The optimal powder flow rate is noted at a disk rotation speed of 4 % (respectively, the powder flow rate is 12 g/min). The beam diameter, at which the characteristics of single tracks are optimal, is 4.1 mm.

The productivity of direct laser deposition in this work was about 20–23 %. It is found that such characteristics as powder flow rate and laser beam diameter have the greatest influence on the coefficient of effective materials consumption. Changing these parameters allows increasing the productivity by 10–15 %.

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Conflicts of Interest

The authors declare no conflict of interest.