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High speed laser metal deposition process: development of technology and equipment using robotic systems

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Abstract

Intensive progress of additive technologies leads to improvement of the developed equipment. Such developments are only possible if there are serious theoretical and technological researches. In recent years many theoretical and experimental articles, devoted to additive technologies and their applications has been published. The paper presents results of theoretical and experimental researches devoted to stability of products formation from different metallic alloys with complex geometry form and the development of equipment using robotic systems. Designed equipment uses technology of high-speed laser metal deposition process.

Keywords: additive technology, high-speed laser metal deposition, robotic systems, heterophasic process, mechanical properties, powder, metal alloys, ultrafine structure.

1. Introduction

Additive technologies are actively implemented into in most industries: shipbuilding, medicine, aircraft industry, engine construction, etc. The additive technologies have most popularity and become the foundation of a new industry, bringing together digital production, design and through manufacturing cycle.

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Methods of selective laser melting (SLM) is already integrated in the world (Seabra M. et all, 2016, Ageev R.V. et. all, 2013, Dorochov A.F. et. all, 2015, Kianiana B. et. all, 2015].

However, the most productive technology – laser metal deposition is gaining momentum on the introduction in the industry (HSDMD, HSDLD, DMD, DLD). This technology based on forming product geometry by 3D cladding of metal powder with laser beam as a heating source (Wilson Michael J. et.all, 2014, Turichin G.A. et. all, 2015). DMD technology has high productivity, allows building parts for the few minutes, the common growing period for SLM technology is hours [Olakanmi E.O., et. all, 2015].

The authors carried out comprehensive theoretical studies on high-speed laser metal deposition process (Glukhov et. all, 2015, Turichin et. all, 2016). As a result new equipment was development. In addition, different types of units were manufactured. Using this equipment products from different metal powders were examined on microstructure and mechanical properties. In all equipment principles of heterophasic laser powder metallurgy are realized. As a result of researches the prospects of direct metal deposition technology was shown.

2. Theoretical research

Direct metal deposition is difficult and multiple factor process, which result of growing depends on many technical parameters. Research must be all-round for understanding relates between parameters of process and optimal manufacturing technology, for needing geometry of part, with lower material and time resources and stable quality (Turichin et. all).

On of main features of HSDLD technology is high productivity, which can attain 15 kg of metallic powder per hour: during growing process motion of the head relatively product occurs with a high speed. Increase of cladding head motion speed with respect to the product leads to development of active zone surface instabilities, causing the appearance of defects in the formation of products - quasi-periodic relief on the surface and interrupt the growth process. In the paper [9 P. 676] the stability of the process technology is shown. The condition of process stability is as follows:

$$2\frac{\sigma H^2}{\nu_0 b^3 L} < \frac{\partial j}{\partial z} \qquad (1)$$

where σ - the surface tension; H - depth of molten pool; ν0 - linear velocity of the laser beam over the surface grown item; b - half the width molten pool; ∂j / ∂z - the gradient of flux density in the gas-powder jet at the normal to surface of grown product. Figure 1 shows the stabilization process to the surface.

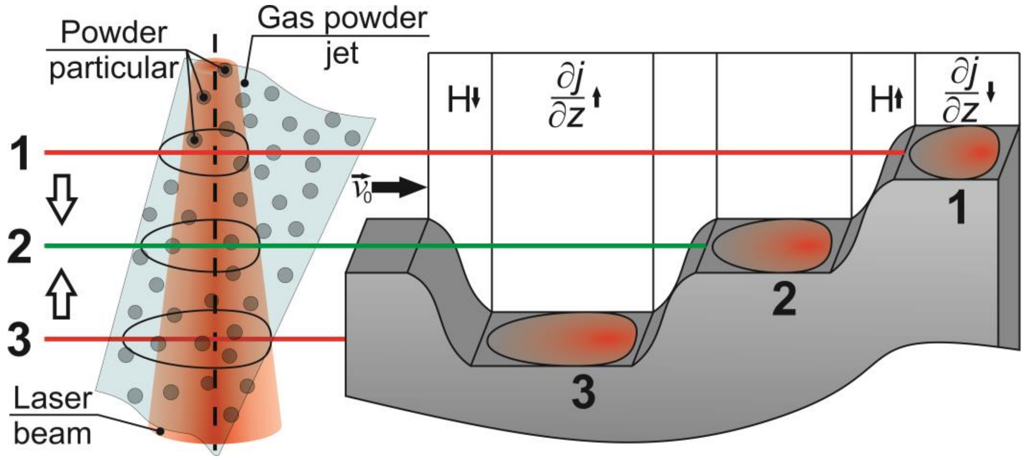


Fig. 1. Scheme of stabilization process.

It should be noted that the depth of molten bath in cases 1-3 are related as follows:

$$H_1 > H_2 > H_3 \tag{2}$$

Position 2 is level of stable formation of a surface, 1 and 3 of the acceptable process variations, respectively. When there is a change of the depth of molten pool (H) to H1 level length L and width b are increase. The same situation occurs, when there is a decrease of the depth the molten pool (H) to the H3 level – the length L and width b decrease. For stabilization of surface position there is necessary flux density decreases at the displacement to position 1, as the result the thickness of the deposited layer decreases. At the same flux density and the thickness of the deposited layer increase with the displacement to the position 3. Thus, the particle flux density determines the stability of the process, for the fulfillment of this condition is to have the focus gas-powder jet below the working area of deposition.

2.1. Equipment.

During last years, a range of direct laser deposition machines was developed and manufactured. All machines based on similar principles:

- Fanuc industrial robot and two-axis positioner are used as manipulators for deposition head and workpiece. In total providing eight axis of freedom for building complex geometry.
- IPG fiber laser with power from 500 up to 5000 W provides laser energy for heating and melting metal powder
- Hermetically closed chamber with controlled atmosphere of pure argon prevents workpiece from oxidation. Inner volume is optimized to reduce argon consumption for purging.
- Modular deposition head, which is equipped with interchangeable set of nozzles for different applications – including not only deposition but welding process also.

Usage of industrial robots brings new opportunities. They simplicity and wide range of models make possible to adapt machine to workpiece size. They make possible to produce parts of almost unlimited size. It was shown that parts of 1600 mm diameter and 150 kg weight is not the limit for this technology. With 3 kW fiber laser normal deposition rate with 2.5 mm thick wall is about 1.5 kg/h. So building 150 kg workpiece takes about 110-120 hours (taking into account idle transfers). When facing real production task industrial robots make it possible to adapt deposition machine for customer requirements. For example if typical workpiece size is small – reducing chamber size and robot reach brings reduction in production costs: argon consumption, maintenance and changeover times, footprint and machine price.

Eight degrees of freedom significantly increase the complexity of geometry in comparison with five-axis machines. It is possible to build ceiling slabs in hard-to-reach places. It is even possible to use 6-axis robot as workpiece manipulator with stationary or moving deposition head. In case of using gripper as robot EOAT fully automatic work flow can be realized, when robot changes substrates without operator's help.

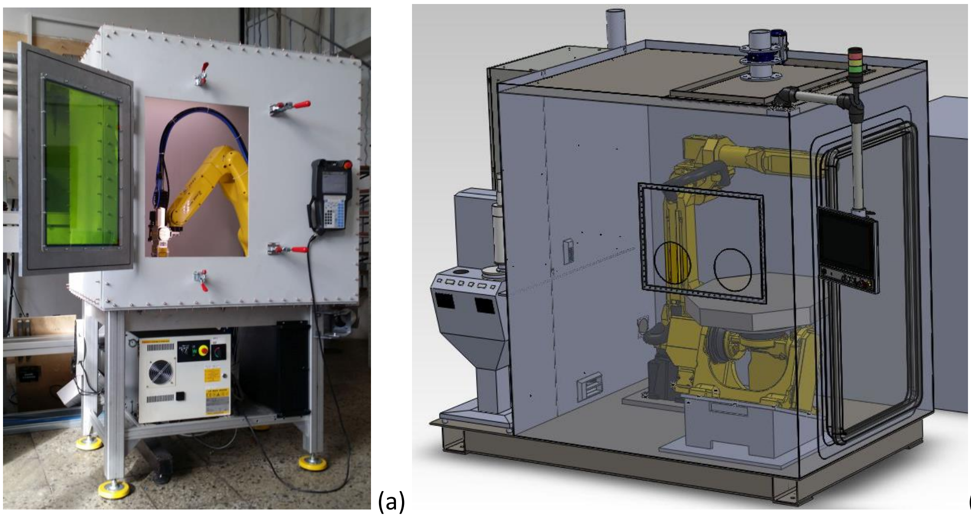
Range of direct laser metal deposition machines.

Size "S":

- Robot: Fanuc LR Mate 200iD/7L, reach 911 mm, repeatability 0.03 mm;
- Laser: IPG Photonics YLM-MM series, power from 500 up to 1500 W;
- Maximum part size: Ø300 mm, H=300 mm, 30 kg;
- Chamber volume: 1.4 m^3.

Size "L":

- Robot: Fanuc M20iA/20m, reach 1813 mm, repeatability 0.08 mm;
- Laser: IPG Photonics YLS series, power from 1500 up to 5000 W;
- Maximum part size: Ø1000 mm, H=600 mm, 250 kg;
- Chamber volume: 6 m^3.



(a) (b)

Fig. 2. Direct laser metal deposition machine, size "S"(a), size "L"(b).

Size “XL”:

- Robot: Fanuc M20iA/20m, reach 1813 mm, repeatability 0.08 mm;
- Laser: IPG Photonics YLS series, power from 1500 up to 5000 W;
- Maximum part size: Ø1600 mm, H=600 mm, 250 kg;
- Chamber volume: 25 m^3.

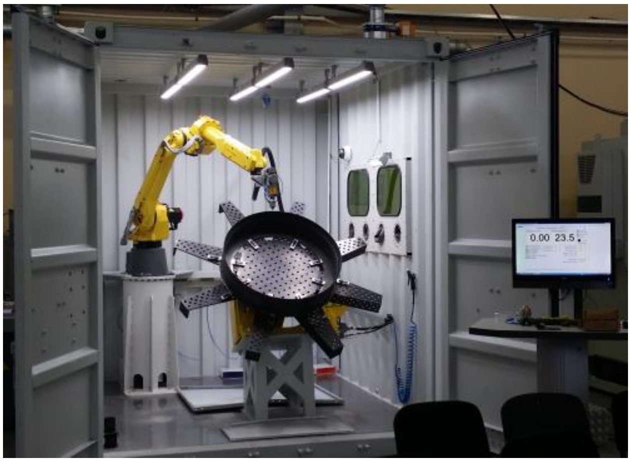


Fig. 3. Direct laser metal deposition machine, size “XL”.

2.2. Experimental results

As a result of the project products with different geometry and from the various alloys were manufactured using the lateral and coaxial nozzles. Using different gas-powder nozzles high process productivity was achieved. Lateral feed with scanning has productivity of manufacturing part blanks above 18 kg/h (thin wall 3 - 20 mm); lateral feed by focused gas-powder jet has productivity above 5 kg/h (wall 0.8 - 3 mm); coaxial feed by focused jet – productivity above 1 kg/h (wall 0,6 – 2 mm). Examples of deposited samples are shown on fig.4.

Fig. 4. Deposited samples.

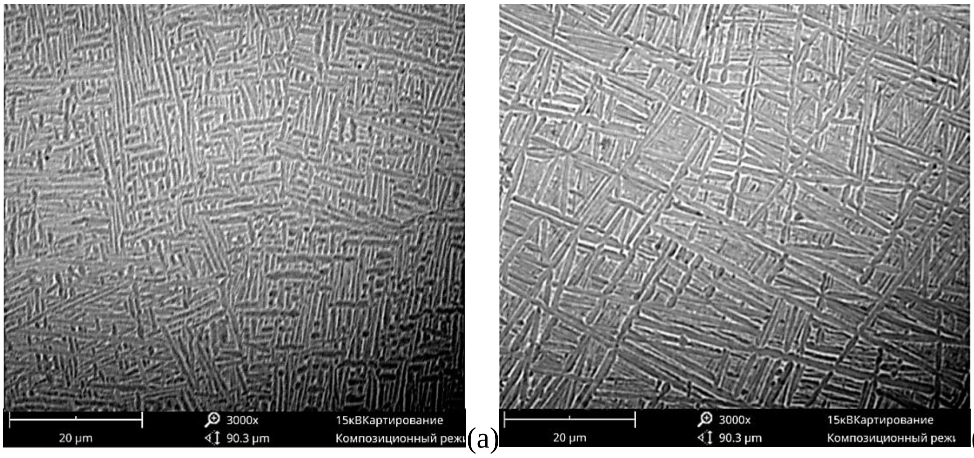
3. Materials, structure and properties research

Fractional composition of the powders used was varied in the range of 50-150 microns, the shape of the particles - spherical. The deviation from sphericity does not exceed 5%. Experimental studies were conducted on nickel-based alloys (Inconel 625, Inconel 718, GS6U, EI698P etc.), titanium (Grade 2, Grade 5, VT20 etc.).

Metallographic studies were carried out on microscope DMI 5000 (Leica) with software Tixomet. Researches of chemical compound and the distribution of chemical elements are made on scanning electron microscope Phenom ProX and Mira Tescan microscope using console Oxford INCA Wave 500. To determine the mechanical properties samples were tested on uniaxial tension, using universal testing machine Zwick/Roell Z250 Allround.

3.1. Ti-based alloys

Titanium alloys Ti-6Al-4V and Ti-6Al-1V-1Mo-2Zr grade are belong to the group α+β and near alpha alloys according. Principally these two groups of alloys are characterized by beta phase content, in near alpha alloys up to 6%, and in α+β up to 25% (Turichin et. all, 2016). The microstructure of deposited Ti-6Al-4V samples is consisting from lamellae α–phase in β-matrix. The microstructure of deposited Ti-6Al-1V-1Mo-2Zr samples is consisting from acicular α–phase colonies located in β-grains. The grain size does not exceed 100 µm. Size of α-phase is of the order of 15-40 µm.



(a) (b)

Fig. 5. Microstructure of DLD samples (a) Ti-6Al-4V (grade 5), (б) Ti-6Al-1V-1Mo-2Zr.

Table 1. Mechanical properties of Ti-6Al-1V-1Mo-2Zr alloy

Technology	Yield strength, MPa	Tensile strength, MPa	Elongation, %
Laser metal deposition	882	968	6,6
Cast+Heat Treatment	876	951	6,4

Table 2. Fatigue tests of ATi-6Al-1V-1Mo-2Zr alloy

№ Loading stages	№ sample	Frequency Hz	Tension MPa	Cycling	Test result
1	1	594	340	2x106	Not cracked
2	1	594	380	2x106	Not cracked
3	1	594	420	1,7x106	Cracked 14 mm from bottom

3.2. Ni-based alloys

3.2.1. EI698 (cast alloy)

The EI 698 alloy is nickel based heat-resistant cast alloys with an equiaxial type of structure. The content of the hardening γ'-phase, which determines the properties of the material, is 14-17% by volume. The microstructure of deposited EI 698 is cast. Depending from the cross section, a dendritic and cellular-dendritic structure is formed, the cell size does not exceed 10 μm.

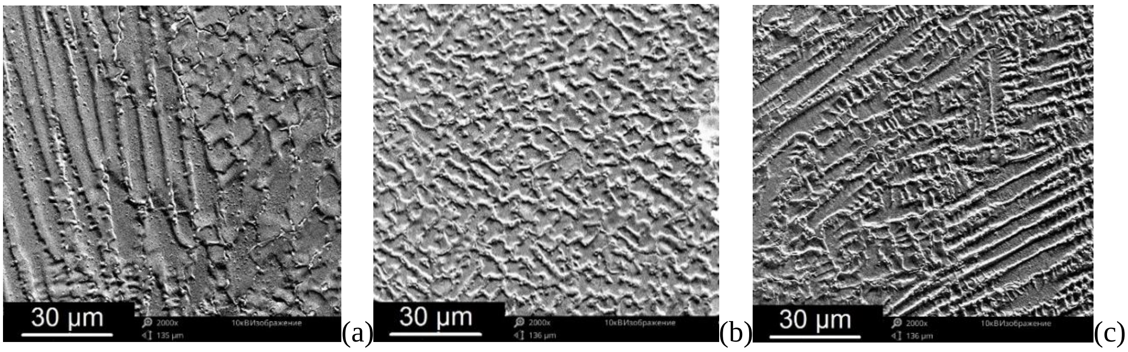


Fig. 6. Microstructure of EI698 DLD samples: (a) cross section, (b) top view, (c) longitudinal direction.

Table 3. Mechanical properties of nickel base EI 698 alloy

Technology	Yield strength, MPa	Tensile strength, MPa	Elongation, %
DLD	840	1030	18
Cast+ Hardening 1120ºC, 8 h, air; stress relieving 1000ºC, 4 hours, air; 750-775 ºC, 16-25 h, air	705	1150	16

3.2.2. ZHS6u (cast alloy)

The ZHS6u alloy is nickel based heat-resistant cast alloys with an equiaxial structure type. The content of the hardening γ'-phase, which determines the properties of the material, is 50-55% by volume. The microstructure of deposited ZHS6u alloy is cast. At using of DLD, the size of the structural components is much less than, for example, in casting (Klimova-Korsmik O.G. et. all, 2016). For comparison, the size of the cuboids of the γ'-phase in the cast samples is 500-1000 µm, in the deposited samples the size of the γ'-phase is 50-150 nm. Carbides are uniformly distributed throughout the cross section of the sample and their dimensions do not exceed 10 µm.

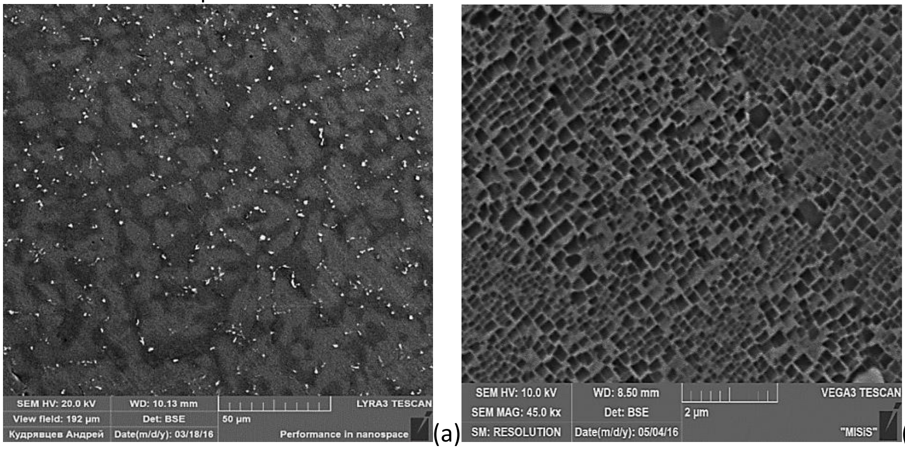


Fig. 7. Microstructure of ZHS6u DLD samples (a) x1500 (b) x10 000.

Table 4. Mechanical properties of nickel base ZHS6u alloy

Technology	Yield strength, MPa	Tensile strength, MPa	Elongation, %
DLD	1046	1350	11,5
Cast+ Heat Treatment	1075	1100	2,9

3.2.3. Inconel 625 (wrought alloy)

The Inconel 625 alloy is nickel based heat-resistant wrought alloy with an equiaxial structure type. The microstructure of deposited Inconel 625 alloy is cast (Turichin et. all, 2015). Carbide inclusions are located along the boundaries in the form of a grid. The dimensions of the dendrites in the longitudinal direction do not exceed 50 µm.

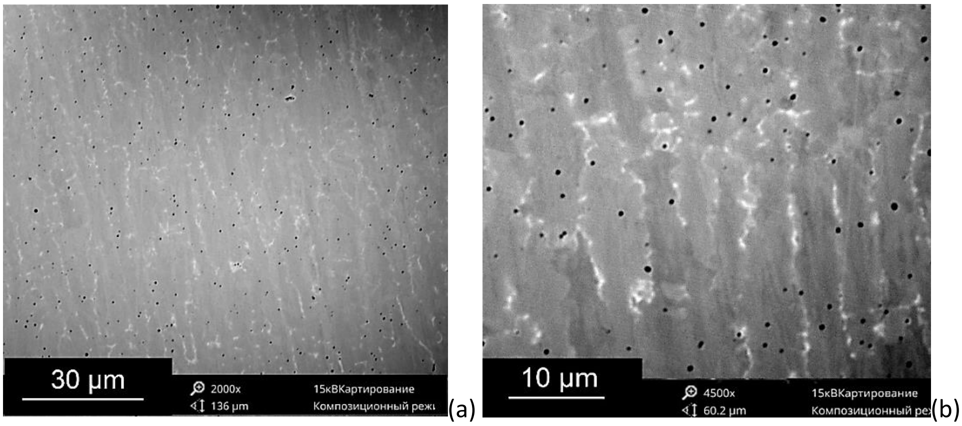


Fig. 8. Microstructure of Inconel 625 DLD samples (a) x2000 (b) x4500.

Table 5. Mechanical properties of Inconel 625 alloy.

Technology	Yield strength, MPa	Tensile strength, MPa	Elongation, %
DLD	488	865	27,7
Rolled	415	827	28

4. Conclusions

Direct laser metal deposition technology is a complex process with large number of important parameters. The main requirements are stability of process formation of grown details and heterophasic nature of the process. As the result high quality products with ultrafine structure could be achieved.

Furthermore, during last 3 years the first Russian equipment were manufactured, which realized direct laser metal deposition technology. High-speed direct laser deposition is:

- technology for manufacturing of details with complex form from powder materials using 3D models;
- potential using of different materials in a single part and obtaining details with gradient properties;
- Machines of various sizes;
- dimensions of details are almost unlimited.

The process productivity is 5-15 times higher in comparison with selective melting technologies. Mechanical properties of the obtained product at a level of hot rolled metal, there are no pores, cracks and lack of fusion.

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