

ADDITIVE METAL PROCESSING TECHNOLOGIES - PROBLEMS AND WAYS OF LEVELING THE SURFACE DEFECTS

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Abstract

This work provides an overview of the technological features of additive technologies for manufacturing metal parts and products (3D printing metals). The nature and types of printing, perspectives, and opportunities for their development are indicated. The advantages and disadvantages of additive technologies are clarified. An analysis of the technological process parameters has been made, on the basis of which the main problems hindering its mass introduction in the industry have been identified. The main dependencies of the quality and properties of the manufactured parts on the process parameters are given, and ways of avoiding and eliminating the defects are presented.

Keywords: additive production, 3D printing, selective laser melting, laser sintering, DMLS, hardening, surface treatment

1. INTRODUCTION

The additive technology for the production of metal products (3D printing of metals - known as Additive Manufacturing Process, AMP) is a process of creating objects by superimposing thin layers based on digital technologies - a three-dimensional CAD model with specialized 3D printers for metal. After 2010, AMP technologies are in a phase of rapid growth (Zlenko, Popovich & Mutylna 2013, Kondratiev 2018, Laplume, Petersen & Pearce 2016). The turnover of the global ATM market is increasing on average by more than 27% per year (Chumakov 2014, Bogers, Hadar, & Bilberg 2016), and their prices are constantly decreasing (Laplume, Petersen & Pearce 2016, Bogers, Hadar, & Bilberg 2016, Freedman, DH 2012).

3D printing is a process, in which the part is created by introducing or bonding of additional material in which the part is generated by the introduction or coupling of the additional material. The advantage of this way of printing is that almost any possible shape can be created. The 3D printer is a type of industrial robot (Fig. 1.) Machines can cost from hundreds to millions of dollars and use a wide variety of printing technologies. (Kondratiev 2018, Laplume, Petersen & Pearce 2016, Chumakov 2014, Bogers, Hadar, & Bilberg 2016).



Fig. 1. Industrial 3D printer for the production of metal parts

Source: <https://www.engineering-review.bg/bg/aditivno-proizvodstvo-na-metalni-detaili/2/3664/>

3D printing is radically different from all other existing traditional methods of producing details. The most basic, differentiating principle for 3D printing is that it is an additive manufacturing process, used to make a three-dimensional object based on the addition of successive layers of material on top of each other. Unlike traditional production technologies, which are based on the principle of removing excess material (pressing, punching, cutting with removal of chip, drilling, grinding and subsequent treatments to achieve the desired shape and dimensions), the additive technologies are based on the principle of addition of material, in which the final product is created by superimposing different layers of material on top of each other, without form-forming processing by removing material, without tools and without the need for any component assemblage.

With traditional technologies, material losses can reach up to 90% of the original workpiece, and the final product is obtained by welding, soldering, gluing, or assembling the individual parts and components. At ATM the finished product is formed without unnecessary production waste, which leads to significant savings in materials, labor and energy. To avoid assembly requirements, components can be specially designed with complex geometry and complex functions. The ability to create three-dimensional solid objects with the help of digital control has recently significantly changed the industry and transformed a number of industrial sectors, medicine and education (Kondratiev 2018, Laplume, Petersen & Pearce 2016, Bogers, Hadar, & Bilberg 2016).

The economic efficiency of 3D technology consists in its quality, without waste and significant reduction of costs in serial and en masse production (Zlenko, Popovich & Mutylina 2013, Kondratiev 2018, Laplume, Petersen & Pearce 2016, Chumakov 2014, Bogers, Hadar, & Bilberg 2016, Freedman, DH 2012) and in her environmental friendliness (Zlenko, Popovich & Mutylina 2013, Kondratiev 2018, Laplume, Petersen & Pearce 2016).

The introduction of AMP in practice will significantly contribute to the creation of a "smart" economy and will facilitate the transition to the sixth technological regime (Kondratiev 2018, Laplume, Petersen & Pearce 2016, Bogers, Hadar, & Bilberg 2016). AMPs allow to reduce certain technological processes or to eliminate them, as well as to reduce the errors of the "human factor" in the production of metal products (Kondratiev 2018, Bogers, Hadar, & Bilberg 2016). 3D printing is now capable of producing extremely complex in shape and configuration parts, tools and fixtures that can withstand different operating conditions and which have led to a real revolution in manufacturing, energy and automotive. In many cases, especially when applied in small businesses, AMP flexibility is a crucial advantage. The high-quality printing of metal parts makes it possible not to wait for the necessary part from the factory, but to produce it on spot, for which is enough availability of the necessary drawings in electronic format.

In recent years, these technologies are increasingly used in various areas of industry - Fig.2. They are among the fastest growing industries in the world (Kondratiev 2018, Bogers, Hadar, & Bilberg 2016, Engineering-review 2016, Engineering-review 2017).

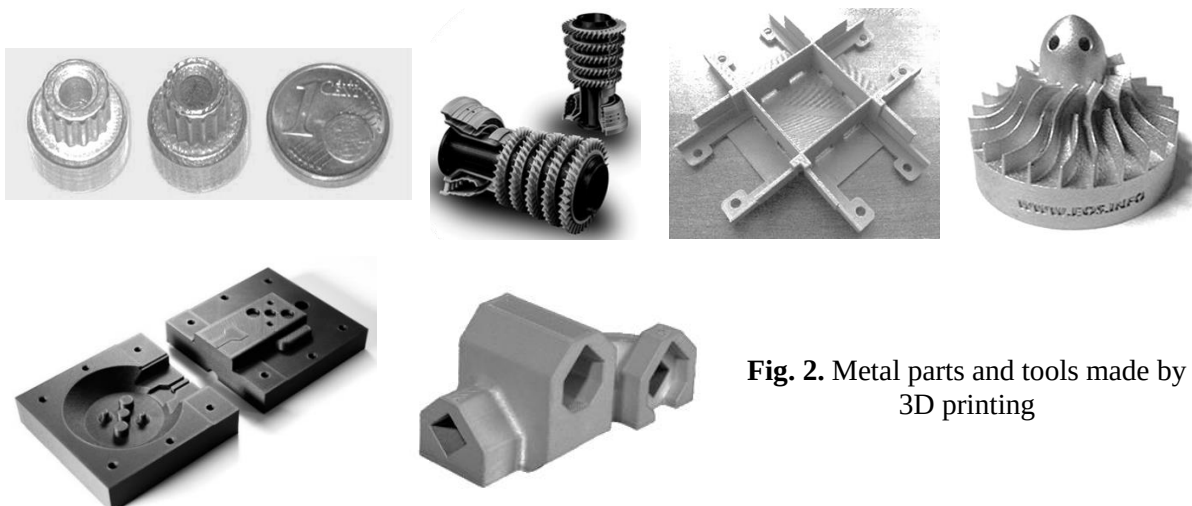


Fig. 2. Metal parts and tools made by 3D printing

The process of 3D printing of metals is directly related to the future of mankind and from a technological and social point of view, it is clear that very soon the removal of metal will not be the only metalworking process (Kondratiev 2018, Laplume, Petersen & Pearce 2016, Bogers, Hadar, & Bilberg 2016).

3D printing of finished metal products is also placed at the center of scientific research. The number of scientific publications dedicated to three-dimensional printing using metals is growing by 50% every year (Kondratiev 2018, Laplume, Petersen & Pearce 2016, Bogers, Hadar, & Bilberg 2016, Engineering-review 2016, Engineering-review 2017). However, in addition, AMP faces a number of unresolved issues that prevent the mass adoption of these unique technologies in production and repair activities. First of all, the speed of 3D printing is not very high so far, which makes it unsuitable for mass production, then the amount of metallic materials that can be used in three-dimensional printing is still quite limited (though gradually increasing). In addition, 3D printers are limited in the size of the goods they produce. 3D printing has not yet reached the engineering precision and precision of traditional technology. The main disadvantage hindering the mass spread of these intelligent technologies is the relatively high roughness, unevenness of the surface layer and the presence of pores.

In this regard, the objectives of this work are:

- to indicate the nature and types of printing, the available metal materials, the prospects and opportunities for their development;
- to clarify the advantages, disadvantages and limitations of using an AMP;
- to identify the main problems hindering its mass implementation in practice;
- to present strategies for control and ways to avoid and eliminate surface defects of metal products obtained by AMP.

2. ESSENCE AND TECHNOLOGICAL FEATURES

Charles W. Hull created the first working 3D printer in 1984. Over time, technology and machines (3D printers) are gradually evolving and improving, becoming more useful, applicable and more accessible, and since 2010 their entry into the single and serial production has been developing rapidly and their role in industrial metalworking has reached a significant scale. Many different 3D printing technologies already exist. Each of them is suitable for different applications and / or works with different materials. What they all have in common is that they are manufacturing processes in which products are built by adding layers of material instead of being cut from blocks of material (milling and turning).

The general principles of additive production are presented in (Kondratiev 2018, Bogers, Hadar, & Bilberg 2016, Engineering-review 2016, Engineering-review 2017), as well as in the standard BDS EN ISO 17296. 3D printing is a relatively simple, highly automated process involving several basic steps:

1. Create a computer-designed file that can be done using CAD software such as Solidworks, Autodesk Fusion, Onshape, or many others. The CAD file is exported as a STL file, the universal input file type for 3D printers. BDS EN ISO / ASTM 52915: 2016 establishes a new suitable format of the standard CAD file - AMF (additive manufacturing file format) for all additive manufacturing processes, which replaces the previous standard STL format created by Chuck Hall.
2. Orientation of the detail, selection the material and set the print parameters, after which the software automatically generates the "making" of the part, cuts the file into layers and determining the paths of the tools for each layer.
3. Start printing. The software automatically starts printing the part layer by layer. At the different technologies and materials, the thickness, pitch and printing time of each layer are controlled until the specified part size is reached.

Currently, there are many different methods and technologies for 3D printing of metals. Each of them is suitable for different applications and / or works with different materials. The main differences between them are based on the way the layers are arranged and the patterns are created. For the

implementation of these methods as a direct source of energy is mainly used a laser (Chumakov 2014, Engineering-review 2016, Engineering-review 2017, Kuznetsov et al 2015, Dikova, Panova & Simov 2011, Yasa & Kruth 2011, Averyanoiva, Bertrand & Verquin 2011).

The Dust bed technologies (Engineering-review 2016, Engineering-review 2017) and a direct processing of the powdery layers are known as laser melting systems under various trade names. Almost any system based on a powder bed, uses a method of deposition of metal powder, comprising a coating device for spreading the powder layer on the substrate and a reservoir for powder. The layers are usually 10 to 100 μm thick. The melting process is repeated section by section, layer by layer, until the last layer melts and the detail is complete. The only exception to this principle is the electron beam melting (EBM) process, which uses an electron beam under full vacuum.

The superimposition of the thin metal layers is most often performed by the following technological methods:

2.1. *Selective laser melting of metal (SLM), which is one of the most common industrial technologies for 3D printing* (Engineering-review 2016, Dikova, Panova & Simov 2011, Yasa & Kruth 2011, Averyanoiva, Bertrand & Verquin 2011, Popkova 2015) - Fig. 3.



Fig. 3. 3D printer for selective laser melting

Source: https://solidfill.com/news/metalni_chasti_za_audi_izraboteni_chrez_3D_printirane

A thin layer of powder is fed into the working chamber in the amount required for the first layer, and the material is deposited on a movable work platform. The powder is leveled with a special roller and the excess is removed. The camera of the 3D printer during operation is filled with inert gas - most often argon or nitrogen with low oxygen content. With the help of a powerful high-energy laser, the metal powder is glued together along the contour of the first layer. In the X and Y directions, special scanning mirrors guide the laser device. After finishing the current layer, a new layer of powder is automatically applied. These steps are performed until the subject is fully reproduced. The created model is then removed together with the platform and the excesses are cleaned. Both alloys and pure metal powders can be used. The range of materials available for this 3D printing method is much wider than with selective SLS laser sintering and DMLS direct laser sintering. The most preferred materials are stainless steel, alloys of nickel, chromium, titanium, cobalt and aluminum, but gold, platinum, tungsten and copper can also be used.

SLM produces metal parts with completely different microstructures than those of cast iron or forged steels. The unusual dislocation network, which is found in the one- and two-dimensional structures, is the result of the high temperature gradient and growth conditions that occur during SLM. This unusual dislocation network underlies the exceptional mechanical properties of the resulting material.

The resulting details are light, thanks to the ability to add internal cavities to the original 3D model. The method does not have an absolute lack of waste, but most of the material that was not involved in the direct construction of the product can be reused.

Selective laser melting of metal is designed for any production where the speed of reproduction of solid monolithic objects with complex geometry is important. The method is invaluable as it allows the production of parts with cavities in the walls, which makes it extremely suitable for the aerospace and automotive industries.

Of paramount importance for SLM-derived products are the characteristics of the powders used (Kuznetsov et al 2015, Dikova, Panova & Simov 2011, Yasa & Kruth 2011, Averyanoiva, Bertrand & Verquin 2011, Popkova 2015, Logacheva, Sentyurina & Logachev 2015).

2.2. *Direct Metal Laser Sintering (DMLS)* - Fig. 4, is a variant of laser sintering (SLS), which it works with metal - aluminum, stainless steel and other alloys (Engineering-review 2016, Popkova 2015, Logacheva, Sentyurina & Logachev 2015, Barucca et al. 2015). The technology involves the operation of a powerful laser that melts and merges powdered metal layer by layer to create the desired structure. The process is similar to welding with a very precise laser. The parts are printed in a closed chamber with an atmosphere of high argon content. A fiber laser with ytterbium is used, which is directed by means of dynamically moving mirrors. The laser gradually builds the model by layering by sintering, following the pre-set trajectory of the computer. The precisely tuned laser, the metal powder and the additive manufacturing process in combination allow great freedom in design. A key advantage of the technology is that it can be easily used to print complex closed models with various internal, components that are not otherwise available (fig.5). When built using DMLS technology, the metal parts are attached to a platform on which they are placed by supports. Once ready, they move to an intermediate zone, where they are separated from the platform by machining. Auxiliary supports are automatically generated by the Standard Template Library (STL) and are manually compiled into a 3D CAD file before being built. They are made of the same material as the rest of the structure.



Fig. 4. 3D printer for direct metal laser sintering

Source: <https://www.spacecad.bg/printeri-za-metal>



Fig. 5. Product demonstrating the advantages of three-dimensional printing in the production of complex parts

2.3. *Electron Beam Melting (EBM)*

Here, an electron beam is used as a source of energy instead of a laser (Engineering-review 2016). The electron beam melts the metal powder layer by layer under a high vacuum range and is extremely effective as it achieves complete melting of the powder. The EBM method is highly recommended and preferred because it can produce high-density metal parts, thus preserving the properties of the material.

2.4. *Binder jetting is a cost effective, low-energy method of fabricating parts out of powder.* In this process, a machine uses the same powder spreading methods as SLS, but uses a liquid binding agent to adhere the parts instead of a laser. After printing, these parts either need to be cured (plastic) or sintered (metal) to yield a full part.

The metallurgical bonding of the coating material to the base material and the absence of trimming are some of the characteristics of this process. The process differs from other welding techniques in that low heat output enters the substrate.

2.5. *ADAM (Atomic Diffusion Additive Manufacturing)* – Fig.6.

ADAM, or bound powder deposition, is a process at which the machine extrudes a thread consisting of metal powder, plastic binder - after printing, the binder dissolves, and the metal powder is sintered into the completed part.



Fig. 6. “Metal X” type system for connected dust deposition ADAM

Source: <https://markforged.com/metal-x/#system-overview>

2.6. *Powder adhesion* - Powder adhesion is not yet popular, but is a rapidly growing method in 3D printing. Because the process is productive, it has been adopted as a technology that is suitable for 3D printing in mass production.

2.7. *Laser Engineered Net Shaping (LENS)* - The powder material is fired directed into the spot of focus of the laser beam. This part of the material that falls into the focus spot is baked for a very short time and successively forms the layers of the object. Metal powder is used, which allows the production of alloys with various industrial applications.

The last step is the final process. It usually includes various technological operations, such as - cutting the part from the building board, annealing to remove internal stresses, grinding or sandblasting for smoothing surfaces, deposition of coatings, heat treatment for hardening and others. Often, post-processing can take up to 3 times longer time than printing the part. However, the cost and time for making the functional prototypes are many times lower than those for making the same with conventional cutting technology.

However, this step requires specific skills and materials. Because when an object is first printed, it often cannot be used until it has been heat-treated, ground, or polished so that it can be used as intended.

The most important element in using an AMP is the choice of material itself, as it will determine which printing method is most appropriate.

3. MATERIALS FOR 3D PRINTING OF METALS

3.1. Considerations when choosing a material

3D printing materials are often an integral part of the relevant technology. Any technology, whether modeling by DMLS, EBM, ADAM, or LENS, outperforms others in creating certain unique geometric shapes. Not all existing metallic materials can be used for the additive production of parts, but in most cases, and at the appropriate equipment, for each application can be created metal powder - a raw material for the production of the necessary products.

When choosing a material and technology for 3D printing, the requirements for dimensional accuracy, minimum execution time, and wall thickness of the structure must be taken into account and it must be ensured that the material can meet the relevant strength and the other requirements.

The efficiency and scale of the application of 3D technology in industry largely depends on the development of new compositions of materials that ensure the formation of strong and durable parts for any type of industry. How strong the product will be and how fast it will be made depends on the chemical composition of the material used for printing. The ability of the material to function in the desired application depends in part on the design of the workpiece.

The tensile strength of the material are among the most fundamental properties, which are often used as reference points when deciding on the suitability of a material. Today, 3D printing has advanced to the point where it is able to provide the same tensile strength as traditional metallic materials made by conventional technologies.

3.2. Materials for additive production of metals.

Until recently, the powders for AMP represented for a very small share of the powder metal market. Over time, however, the growing popularity of 3D printing has significantly increased the need for special powder metal mixtures.

The variety of available materials for additive production of metals is constantly expanding, and a number of manufacturers of AMP machines offer their own-patented materials. Research institutes, universities and manufacturers of AMP systems are already developing and offering special materials customized to the needs of customer applications. Nowadays, the joint efforts to follow the quality measures further accelerate the development activity and the production of metal alloys.

The most commonly used metals for 3D printing and alloys are stainless steel type 17-4PH, 316L and others, tool steel, invar, inconel, titanium alloys, aluminum - AlSi12, nickel- cobalt- chromium and copper alloys, as well as gold, platinum, tungsten and copper.

For example, 316L, created by Desktop Metal (<https://markforged.com/>) is austenitic steel with corrosion resistance and improved mechanical properties at extreme temperatures and is suitable for salty seawater, food industry and pharmaceutical production, including engine parts, laboratory equipment, pulp and paper production, medical articles etc.

The chemical composition of some of the most commonly used steels is as follows (Engineering-review 2016, Engineering-review 2017, Kuznetsov et al 2015, www.realizer.com, Logacheva, Sentyurina & Logachev 2015, Barucca et al. 2015, Amon et al. 1998):

316l	-	Fe base, Ni - 10-14 %, Mo 2-3%, Mn 2 %, C 0,030%;
15-5PH	-	Fe base, Cr 13-15, Ni - 3,5-5,5 % , Cu 2,5-4,5 % , Mo 2-3%, Mn 1 %, C 0,07%;
17-4PH	-	Fe base, Cr 15-17, Ni - 3-5 % , Cu 3-5 % , C 0,07%;
2709	-	Fe base, Ni - 18-19 %, Mo 4,7-5,2%, Co 8,5-9,5 % C 0,03%;

H13	-	Fe base, Cr 4,7-5,5, Mo 1,1-1,75%, C 0,32-0,45% Si 0,8-1,25% V 0,8-1,25%;
INVAR 36	-	Fe base, Ni - 35-37 %, C 0,1.

Immediately after their manufacture, the printed metal parts and castings have a similar density and strength. After heat treatment, the 3D metal parts printed with this technology are comparable to traditional parts in terms of porosity and strength characteristics.

For the production of quality products, the metal powders used must have a homogeneous chemical composition, a spherical particle shape and a narrow particle size distribution. Such powders have a low coefficient of friction between the particles and good flowability, high bulk density and density after shaking. The presence of internal pores and oxide layers is highly undesirable. The oxide film on the surface of the dust particles reduces the wettability of the particles and leads to the formation of a pores.

Currently, the following standards have been developed for some of the most commonly mixtures used for AMP:

- ASTM F2924:2014 - For additive production with titanium alloy with 6% aluminum and 4% vanadium (Ti-6Al-4V) by the so-called. "Powder-based soldering" with an electron beam or laser.

- ASTM F3055:2014a – For additive production processes by soldering a nickel alloy powder base UNS N07718 with an electron beam or laser. It is an alloy of nickel and chromium, with added amounts of iron, niobium and molybdenum. The products made with this material are subjected to further processing by metal cutting, electroerosion, etc. machines to achieve the required surface quality and dimensions.

- ASTM F3056:2014e1 - An alloy of nickel, chromium and molybdenum UNS N06625, which is used for the production of products with certain mechanical properties resembling forged products, and is used in extreme temperature conditions such as jet engines.

According to some authors (Engineering-review 2016, Logacheva, Sentyurina & Logachev 2015, Amon et al. 1998). AMP can also be used as a tool for designing materials, for control the microstructure to achieve certain mechanical properties.

Although titanium, aluminum alloys and stainless chromium-nickel and cobalt steels and alloys are already being successfully printed, there is still a long way to go until the printing of metallic materials becomes widespread.

4. MAIN PARAMETERS OF TECHNOLOGICAL PROCESSES IN AMP

The accuracy of printed metal products is influenced by many factors from the very beginning of the process and manufacturing technology - to the final processing and its end. The setting of the 3D printing mode is controlled by nearly than 100 parameters, and to achieve sustainable quality of the details, prior training of the operator is required. In addition, each manufacturer of AMP equipment offers a specific set of materials and detailed instructions for adjusting the parameters of the machine for each of the materials. The inclusion in the list of materials is preceded by long-term work on defining optimal parameters of modes. In the course of this work the optimal interrelation of such parameters as laser power, speed, and trajectory of scanning of the laser beam is determined, energy distribution in the laser spot, fractional and chemical composition of the powder, the scanning step of the laser in the X-Y plane, the construction step, the distance between the scanning paths, the thickness of the powder material layer, the platform preheating, the type of shielding gas and the temperature of melting the material (Popkova 2015, Logacheva, Sentyurina & Logachev 2015, Dikova, Ts 2017). The higher the scanning speed, the higher is the productivity of the machine and the lower is the surface roughness. In addition, greater is the likelihood of pore formation. Of particular importance is the coordination of the scanning step, material properties and other parameters to minimize the porosity and oxide inclusions in the internal structure of the constructed part.

The resolution of the printer determines how thin each layer can be from the detail of the subject. Usually one layer is about 100 µm, but some printers can achieve a layer of up to 16 µm.

With different technologies and materials, the thickness of each layer and the surface are controlled, while the dimensions are controlled by the printing time.

The materials in the technological systems for AMP are determined and selected according to the specific technology. Each 3D printing technology transforms the material through externally applied heat (lasers and other types of directed energy). The chemical, optical, mechanical, thermal or electrical characteristics of materials determine their behavior under certain conditions. As quantitative indicators, these properties can help in assessing the benefits of one material over another for a particular application.

5. ADVANTAGES

3D printing of metal parts not only replaces CNC machining or casting process, it is the best way to produce parts and assemblies with complex shapes that cannot be created in the traditional way (Engineering-review 2016, Popkova 2015, Logacheva, Sentyurina & Logachev 2015, Amon et al. 1998). Moreover, with a single process and on a single machine with high repeatability and high accuracy. The advantages of AMP derive from its high flexibility - the product is produced directly based on a CAD model, and this allows through this process to produce almost any geometry that can be designed. The use of additive technologies potentially gives a number of advantages over traditional production processes and forming technologies, such as casting, pressing, CNC machining, (Kondratiev 2018, Laplume, Petersen & Pearce 2016, Bogers, Hadar, & Bilberg 2016, Engineering-review 2016, Kuznetsov et al 2015, Popkova 2015, Logacheva, Sentyurina & Logachev 2015, Barucca et al. 2015), while allowing manufacturers to consolidate in one process different production operations without the need for tooling.

The main ones are:

- The standard programs of the CAD system can be used by anyone (if they has the necessary qualifications) and anywhere in the world for the design of goods and their production, using appropriate 3D printers. Each product can be personalized according to the requirements of the end user, as three-dimensional printing allows the production of small batches of low-cost goods, which is impossible in the traditional production process.
- Three-dimensional printing allows parts to be produced with any complexity, while reducing production time, combining several machining and assembly operations.
- The traditional treatment process generates a significant amount of waste materials, while additive technologies generate minimal waste, and the design can optimizes the product so that it is less material-intensive and at the same time lighter and stronger.
- The production process can be decentralized and carried out close to end users, which allows to reduce the delivery time, transport costs and the number of intermediate services and thus to minimize risks.
- The main advantage of additive processes is the possibility for direct production of assemblies and parts - without the need for technical preparation, production of tooling, without expensive and time-consuming technological processes such as CNC machining, erosion, casting and molding.
- One of the biggest advantages of 3D printing is to quickly gain an idea of to possible design errors and whether the design is suitable for the desired application. This allows for faster business feedback while saves time and money.
- 3D printing has a price advantage over casting and the use of metalworking machines in the production of small series or models with a unique design.
- With regard to agricultural engineering, during harvest, it is possible to restore the performance of a tractor or combine in just a few hours.
- The production of metal parts by 3D printing allows the creation of complex details without the design limitations inherent in traditional production methods.

- 3D metal printers offer a drastic shortening of the "design - technical preparation - production" cycle, even within one working day.
- Another advantage of the additive method is that the same machine can produce many radically different products, and it is possible to produce increasingly complex shapes and structures that have not been cost-effective so far. In addition, additive manufacturing allows companies to optimize the use of materials, allowing less and less losses in the production process.
- Another advantage is the unusual dislocation network obtained with the SLM technology with 316L stainless steel, which is the basis of the exceptional mechanical properties of the metal (Engineering-review 2016). The ability to produce complex metal parts with exceptional mechanical properties that cannot be achieved by conventional means is one of the main advantages of AMP.

6. DISADVANTAGES. OPPORTUNITIES FOR OVERCOMING AND ELIMINATION

Along with their numerous and indisputable advantages, modern additive technologies have a number of disadvantages that limit their wide application.

- First of all, the speed of 3D printing is not very high so far, which is why additive metal production as a process is not yet suitable for mass production of millions of identical simple parts. Currently, three-dimensional printing technology is mainly used in the production of goods of small size. They are made of a single material that does not involve interacting parts, intended mainly in the manufacture and repair of machinery and equipment.
- There are currently relatively small amounts of raw materials that can be used in 3D printing, as well as a limited set of protective coatings.
- 3D printing has not yet reached the engineering precision of traditional technology.
- The production of quality metal parts with 3D printing requires well-trained engineers who know the principles of both mechanical processing and the mechanical and thermal characteristics of metal powders and metals into which they are converted, as well as the laser technologies.
- Fractures and cracks in ATM printed parts. They are due to three main factors: internal stress exceeding the limit strength of the material; concentrators of mechanical stress in the model; fatigue at long-term cyclic temperature and mechanical loads.
- The main disadvantage that prevents the widespread use of these intelligent technologies is the relatively high roughness and unevenness of the surface layer and the presence of pores. The most dangerous defects of AMP-synthesized parts are related to density disturbances, such as cracks, gas pores and pore accumulations caused by shrinkage of materials during cooling. In addition, in the details it is possible to form a stress - deformation state, which occurs during the crystallization of metals. According to the data of almost all authors, the surface of the samples obtained by AMP is rougher and traces of the layer-by-layer elaboration of the models are clearly visible on it. The roughest is the surface of the products produced by SLM technologies (Kuznetsov et al 2015, www.realizer.com, , Averyanoiva, Bertrand & Verquin 2011, Popkova 2015, Logacheva, Sentyurina & Logachev 2015, Aloshin et al. 2016, Dzhendov, Pavlova & Simov 2014, Dikova,Ts 2017), whose values are most often between 15 and 40µm. In addition, on the layers, drops of molten metal and parts of the support columns can be seen. Moreover, the details obtained by SLM technology have different roughness in the vertical, horizontal and inclined sections, which is associated with the layer-by-layer application of the powder material and the formation of steps (degrees), which are more pronounced on inclined surfaces.

The surface of the DMLS-printed parts has an average roughness Ra of approximately 7-10 µm. The increased surface roughness of the part reduces its technological and operational characteristics. In most cases, special full or local processing is required to refine the roughness to the required value.

7. OPPORTUNITIES FOR IMPROVING THE SURFACE QUALITY AFTER ATM

In order to achieve the necessary specifications or to improve the properties of the manufactured parts, such as surface quality, geometric accuracy and mechanical properties, additional processing is often required after the AMP.

Even 3D metal printers with the lowest capabilities and prices can be used to create, for example, instrumental and technological equipment, but the surfaces of finished products need post-processing to observe their requirements. Some physical characteristics can be improved by finishing operations at the end of the AMP process chain (Engineering-review 2016, Engineering-review 2017, Popkova 2015, Logacheva, Sentyurina & Logachev 2015, Aloschin et al. 2016). Most often, operations such as filling the pores and sandblasting the surface are required, and in many cases heat treatment, grinding, polishing, etc. are required. Through various polishing methods, the average roughness Ra can be reduced to 0.8-3.5 μm . Suitable for single production of parts that require specific surface quality is manual polishing.

However, after performing these operations, the accuracy of the dimensions of the product decreases. The external dimensions of the structure can be compensated by readjusting the process modes, but the additional processing increases the production time and the cost of the products, which significantly reduces the efficiency of the AMP.

The high roughness and the impossibility for good cleaning and shaping of surface defects are the most serious obstacle for the mass application of this extremely promising technology for the manufacture of metal parts and all-metal structures.

At present, there is no effective way to reduce surface roughness and porosity. Various methods are offered, such as mechanical surface treatments, special pressing (Popkova 2015, Logacheva, Sentyurina & Logachev 2015), etc. , but all of them envisage leaving of allowances for further processing and use of special technological regimes for the different materials and shapes of the products. Yasa E. and Kruth J. (Yasa & Kruth 2011) have proposed a method for minimizing porosity, according to which each layer is treated twice with a laser. As a result, the porosity is reduced by an order of magnitude, but the production time of the part is almost doubled. Internal surfaces, such as grooves, can be polished by abrasive flow treatment (sandblasting, magnetic abrasive, shot blasting, etc.). Other possible finishing processes are electrogrinding, electrochemical and electroerosive grinding and polishing, etc.

A way to prevent breakage and cracks is heat treatment, after which the porosity of the 3D printed metal parts decreases. However, heat treatment, on the one hand, increases the time and cost of production and on the other - hides the risk of distortion and deterioration of the shape and size of the part. The increased surface roughness must also be taken into account, which, when making an all-metal structure, must be removed by subsequent surface treatment. To avoid the deformation, AMP-produced parts can undergo a stress-relieving process that returns the metal to a hardened state. The conditions for carrying out these processes depend mainly on the alloy used, but are most often carried out at about 900-1065 °C for a time of 1 to 2 hours (Engineering-review 2016, Aloschin et al. 2016, Dzhendov, Pavlova & Simov 2014). Cooling takes place at room temperature. Secondary heat treatments such as hot isostatic pressing, hardening in solid solution and disperse hardening (Engineering-review 2016) can make printed parts stronger, harder and with characteristics close to forged metals. These procedures have repeatedly proven to increase the density of the material after processing, but significantly increase the time and cost of the products.

The reduction of defects in the surface layer (roughness and pores) is also possible by using the method of electrospray deposition (ESD), whose main advantages are high adhesion of the formed coatings, the possibility for local surface treatment, easy and affordable technology and equipment, low energy consumption, high environmental friendliness of the process (Gitlevich et al. 1985), the possibility to attach of ESD application module to the 3D printer and use the same file to build the part, for applied of coatings. ESD is one of the well-known and proven methods of surface hardening, largely devoid of many of the disadvantages inherent in other existing methods. Improving the quality of surfaces obtained by AMT can be achieved during reaction electrospray treatment at the expense of three rapidly occurring phenomena: plasma smoothing of the protrusions as a result of the electrospray discharges, filling of the

cavities with melt, which is formed during the rapid local melting of the layering electrode in the conditions of the pulsed electrospark discharge, and local synthesis of wear-resistant phases during the chemical interaction of the melt with the substrate. The efficiency and scale of the application of ESD in the AMP industry largely depends on the development of new compositions of electrode materials and improving the parameters of the devices (Gitlevich et al. 1985, Nikolenko & Verkhoturov 2005, Ivanov, Verkhoturov & Konevtsov 2017). The solution to this problem requires the selection of <electrode-substrate> pairs, in which the local melting of the electrode forms a liquid melt capable of filling cavities and interacting with the chemical elements contained in the substrate, as well as the selection of appropriate parameters of the electric discharges. One of the possible ways to increase the efficiency of ESD and the wear resistance of electrospark coatings (EC) is the creation of nanocrystalline and amorphous structures in them. Advances in science and technology in the field of materials science have made it possible to use modern materials in electrospark processing, which according to a number of authors (Loginov et al. 2016, Levashov et al. 2008, Kudryashov et al. 2018, Zaitsev et al. 2017, Milligan, Heard & Brochu 2010, Hinnert et al. 2017, Cadney et al. 2009, Heard & Brochu 2010, Brochu & Portillo 2013) contributes to increasing the wear resistance of work surfaces. A fundamentally new approach to the production of suitable electrodes was discovered with the development of self-propagating high-temperature synthesis (SHS) technology (Levashov et al. 2011, Loginov et al. 2016, Levashov et al. 2008, Kudryashov et al. 2018). The nanomodified SHS-electrode materials ensured the creation of new reinforcing multifunctional protective layers on the treated surfaces with nanocrystalline and / or amorphous phases, with higher physical, mechanical and tribotechnical properties. Depending on the composition of the electrodes, it is possible to obtain layers characterized by high wear resistance, heat and corrosion resistance, low coefficient of friction, etc. (Loginov et al. 2016, Mukanov et al. 2019, Enrique et al. 2019). The use of nanostructured and amorphous layering electrodes of Al, Al-Si, Al + Ni and others made it possible with minimal technical effort and cost to reduce surface defects and roughness, while increasing hardness and wear resistance, to reduce production and maintenance costs and to increase the quality of manufactured products.

The strengths and weaknesses of AMP technologies are considered through the methods of "SWOT-analysis" - Table 1. From the data presented in Table 1 it is established that the advantages (strengths) of ATM technologies are much more and more significant than the disadvantages. They open up extremely wide opportunities for industry and humanity. Their widespread implementation in practice can lead to a new industrial revolution not only in production but also in many other spheres of human existence. However, the mass adoption of these "smart" technologies is hampered by their existing shortcomings (weaknesses), especially surface defects, and surface roughness. Table 2 gives existing at this stage opportunities to reduce surface defects. An indicative assessment of the degree of applicability of the individual activities was performed.

The analysis of the obtained data shows that at the present stage the electrospark treatment is outlined as the most suitable option for most cases and especially for the surfaces of the movable and contact joints of the parts.

Although for the time being the production of finished metal products is only peripherally affected by new technologies, with the improvement of 3D printers and elimination of shortcomings, this technology will find wide application in the production of computers, electronics and electrical equipment, mechanical engineering in all its subsectors, household and will have a strong impact on the automotive industry and transport engineering. The additive industry, which produces finished goods, leads to the improvement of the technological and production process, influencing the production costs, to the improvement of the product and the marketing of new and different in their consumer qualities goods and shortening of operations, performed by manufacturers. The widespread use of new technologies can change the layout and organization of production of manufacturing industry around the world and over time to obliterate the difference between goods and services.

Table 1. SWOT analysis of AMP technologies

Advantages	Disadvantages
<u>Technological</u> Without prior preparation of production; All operations are on one machine only; Without instrumental and technological equipment; Absence or reduction of assembly and installation; No waste; Lightweight construction; Possibility to make internal cavities and openings; Production of small batches of low cost goods; Combining and replacing several machining and assembly operations into one; creates a target product with a minimum of intermediate goods; Possibility to produce products that cannot be produced by conventional technologies; The production process can be decentralized; Production of strategic products; Wide range of products; Individual work with clients;	Difficult to make large details; Insufficient amount of materials; Slower production than conventional technologies in the simplest details; Presence of pores and high roughness; Lower accuracy than conventional technologies; Need for finish processing;
<u>Constructive</u> The best way to produce parts and assembled assemblies with complex shapes; Uniqueness and high flexibility; Response to any change in consumer needs; Generation of minimal waste; The design can optimize the product so that it is less material-intensive and at the same time lighter and stronger; Possibility for direct production of units and details - without the need for technical preparation; Drastic shortening of the cycle "design - technical preparation - production"; The same machine can produce many radically different products;	Need for qualified staff
<u>Product quality</u> Reducing the influence of the subjective factor; Achieving good quality indicators; Builds complex geometric shapes that cannot be produced by other processes.	Presence of pores and high roughness; Lower accuracy than precision mechanical operations
<u>Economic advantages</u> Savings of machines, tools, materials, jobs; Low costs, low energy and material consumption; High efficiency, low cost;	Higher price for the simplest details; Lower performance in large series
<u>Innovative advantages</u> Unsuspected possibilities for creating the most complex in shape parts and products that cannot be produced by convention technologies; Opportunities for creating fundamentally new constructions;	
<u>Opportunities</u> Finding new technologies for surface treatment and filling of pores and cracks	<u>Threats</u> Competition, Time and money

Table 2. Assessment of the possibilities for reduction ('treatment') of pores and roughness

	Opportunities	Compatibility with available assets (materials, machinery and equipment)	Compliance with criteria, time and price requirements	Compliance with strengths, technological criteria	Risks	Ease of implementation	Sum of points
1	Changing the Processing Modes	compatible -4	little increases the production time - 4	incomplete removal -4	incomplete removal - 3	5	20
2	Re-pass with the laser beam without adding material	compatible -5	increases the production time -2	incomplete removal -4	incomplete removal -3	5	19
2	Selection of suitable materials	reconcilable -4	5	incomplete removal -3	incomplete removal -3	4	19
3	Additional processing with metal removal	incompatible -2	need of allowance- 3	5	change the size and shape -2	3	14
4	Additional heat treatment	incompatible - 3	need of additional surface treatment - 4	incomplete removal of Ra - 4	incomplete removal , deformation -3	3	17
4	Additional surface treatment	incompatible -3	incomplete removal of the pores, need of allowance -3	incomplete removal of pores -3	change the size - 4	3	15
5	Reaction electrospark surface treatment	reconcilable -3	little increases the production time -4	4	5	5	21

LEGEND: 1-lowest, 5- highest

CONCLUSIONS

1. Different technological printing methods have specific advantages that are commensurate with the needs of the different possibilities for application and choice of material.
2. The choice of material and technology for 3D printing depends on the requirements for the final product. The most commonly used for 3D printing metals and alloys are stainless steel, type 17-4PH, 316L, etc., tool steel, invar, inconel, titanium and titanium alloys, aluminum - AlSi12, nickel, cobalt-chromium and copper alloys, also so gold, platinum, tungsten and copper.
3. The analysis of the technological features and possibilities, the types, essence, advantages and disadvantages of the additive technologies (3D printing) of metals and the available metal materials shows the potential of this technology.
4. At this stage, there is no effective way to reduce surface roughness and porosity.
5. The performed SWOT analysis shows the predominant strengths of AMP technologies.
6. The presented ways and guidelines for reducing the defects of the surface layer of the products obtained by AMP, including ESD, allow to overcome the challenges of traditional production and to create conditions for the production of otherwise impossible to manufacture with traditional technologies.
7. Based on the methods of SWOT-analysis, technology for reaction electrospark surface modification is presented, as one of the most promising, light, economical and affordable ways to simultaneously

fill surface pores and cracks, reduce roughness and increase surface hardness and wear resistance, products obtained by AMP.

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