

Additive techniques of manufacturing functional products from metal materials

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Abstract. 3D processes are one of the most innovative and perspective technologies for the production of machine parts. Currently, this technology is developing very quickly and is becoming more and more competitive for traditional methods of making prototypes and models, as well as for the production of functional products - semi-finished products or finished machine parts. It is used in many areas of life - from medicine and biomechanics, through such industries as: automotive, aviation, film production, to art, jewellery, furniture production and fashion. The paper presents the characteristics of 3D techniques focused on the production of machine parts from metal materials. Selected Laser Sintering (SLS), DMLS - Direct Metal Laser Sintering, SLM - Selective Laser Melting, Laser Cusing, Laser Engineering Net Shaping (LENS), Fused Deposition Modelling (FDM) and Electron Beam Melting (EBM) have been characterized. Metal materials used in the manufacture of products using additive techniques have been presented. The advantages and disadvantages of the presented technologies were highlighted and attention was paid to economic aspects.

1. Introduction

Additive Manufacturing (AM) is defined by the American Society for Testing and Materials (ASTM) as a process of joining materials to real objects, usually layer by layer, basing on 3D CAD data. In this technology, the material is added, not removed from the part being processed as is the case in traditional processing (machining). The author of work [1] has stated that 3D printing or Additive Manufacturing indicates the beginning of a third industrial revolution.

The first additive technique was Stereolithography (SL) developed by Charles Hull in 1984. Hull and 3D Systems Company which he had founded produced the first commercial 3D printers. The STL file format developed by them is still used in most programs for creating 3D models. Next, in 1998, Stratasys Company has developed the technique of depositing melted material (FDM). In this method, the deposited material (usually plastics) is pressed through a nozzle heated up to the temperature of its melting. The nozzle controls the material flow and it relocated automatically in accordance with the instruction of the CAD program. The model is generated layer by layer.

Nowadays, there are many highly developed AM techniques. According to [3], these processes can be classified as liquid based, solid based, and powder based (Figure 1). The processes considered are stereolithography (SL), Polyjet, fused deposition modeling (FDM), laminated object manufacturing (LOM), 3D printing (3DP), Prometal, selective laser sintering (SLS), laminated engineered net shaping (LENS), and electron beam melting (EBM).



It should be pointed out that additive manufacturing based on 3D print is one of the most innovative and promising technologies of manufacturing. Nowadays, the 3D print develops very quickly and becomes more and more competitive to the traditional methods of prototyping, modelling and production. It finds application in many fields – from medicine and biomechanics, through such branches as automotive, aviation, film production, to art, jewellery, furniture production and fashion [2-4]. 3D printing offers advantages at each stage of generating a product, from the initial conceptual project to the manufacture of final products.

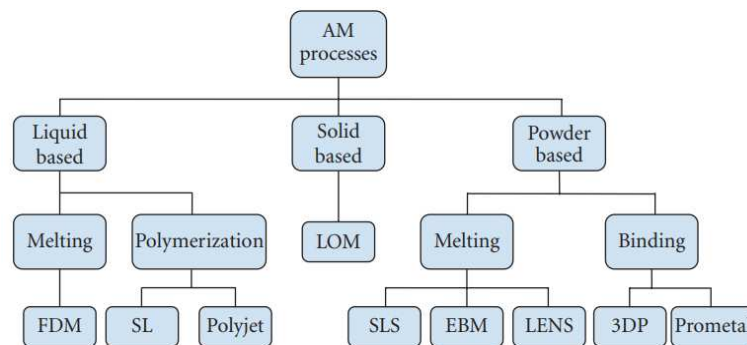


Figure 1. The classification of AM processes; adapted from [3, 6].

Additive manufacturing of metals is, in most cases, performed on a working platform where a layer of metallic powder is distributed and subsequently locally sintered with a laser beam. Model building layer by layer enables elements with complicated geometry to be 3D printed of metal without the necessity to use special tools. The printed parts are characterised by high accuracy, relatively good surface quality and mechanical properties. 3D print is more and more often used for production of ready-made elements and for making functional and durable products. In accordance with [5] five out of ten printed elements are ready made products.

This paper is focused on the characteristics of 3D techniques applied for the production of machine parts from metallic materials, including: Selected Laser Sintering (SLS), DMLS - Direct Metal Laser Sintering, SLM - Selective Laser Melting, Laser Cusing, Laser Engineering Net Shaping (LENS), Fused Deposition Modelling (FDM) and Electron Beam Melting (EBM).

2. Characterization of additive manufacturing techniques

2.1. Selective laser sintering (SLS) and selective laser melting (SLM)

Selective laser sintering is based on the principle of selective laminar melting of plastics and metal powders by means of a laser. The powder particles are joined together by initial melting, not by melting through [7]. Some metal powders must be covered with special substances which are a kind of bond melted by the laser beam and bonding the powder particles [8, 9]. The deposition of successive powder layers with a typical thickness of 20 -150 μm is realized using a powder deposition system [10]. Figure 2 shows a general scheme of functioning of the technology of selective laser sintering. In this technology, the most often used materials are plastics, among others polyamides and their mixtures with dyes, glass meal or aluminium meal and even an addition of carbon fibre.

The DMLS (Direct Metal Laser Sintering), SLM (Selective Laser Melting, Laser Cusing technologies are the reserved names of the same technology consisting in selective sintering and melting of powdered metals by means of laser. The application of the method allows for making uniform structured metal elements directly from the design made on a computer. The print is made due to the relatively high power of the laser which sinters the subsequent layers of the selected metal powder with high accuracy. The process is performed in a closed chamber with the use of nitrogen or argon. The device automatically deposits a new layer of the powder and, depending on the requirements (velocity, quality), is able to make a layer with the thickness of 0.01 – 0.08 mm [12].

Once the process of sintering a layer is completed, the platform on which the model is located, is lowered followed by the deposition of the next layer of the powder. The DMLS/SLM technology makes it possible to produce complex geometry parts made of material identical to that used in traditional production (e.g. in foundry) [13, 14]. The executed elements do not require additional machining and financial input prior to production. As a rule, the arm distributing the powder is provided with a blade at its end which cuts off the melting irregularities of the previous layer.

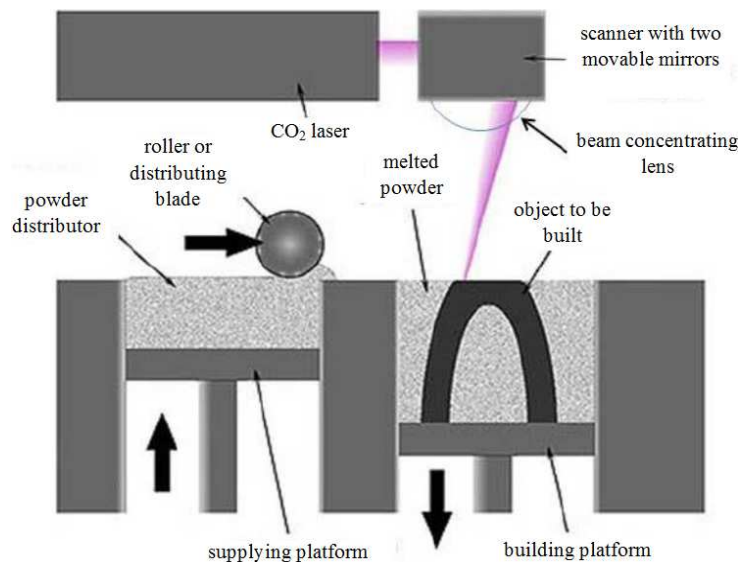


Figure 2. The scheme of SLS technology; adapted from [11].

The principle of this technique is shown in Figure 3. A significant limitation of the DMLS/SLM technology is the necessity to generate durable supporting structures. This is due to the significant temperature differences between the working chamber atmosphere and the liquid metal.

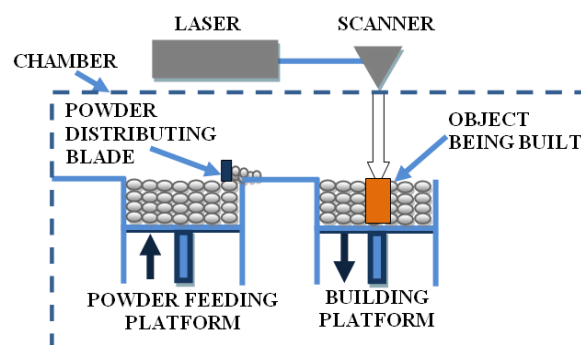


Figure 3. The scheme of the SLM/SLM technology.

After a part is made, it must be cut off the starting plate and the supports must be removed. The shape of the supports can be various and it is determined when designing the outprint. At that time, too, the number of the supports to be applied is determined. The DMLS/SLM technology is usually applied in creation of prototypes and in single production (large dimensioned elements) and in short series production – for small elements, mainly for the possibility of obtaining high quality and low price of the manufactured elements.

The major advantage of the technology is the possibility to make an element with the structure that cannot be made in any other way. It has to be pointed out, however, that an important inhibitor of the development of this technology is the patent race conducted by the biggest companies. An issue of

crucial importance in manufacturing parts by the DMLS/SLM technique is the process optimisation in respect of the quality of the executed parts, as well as their density and purity.

According to [15], the SLS/SLM technologies can be divided in term of the binding mechanism and the sort of the processed materials (Figure 4).

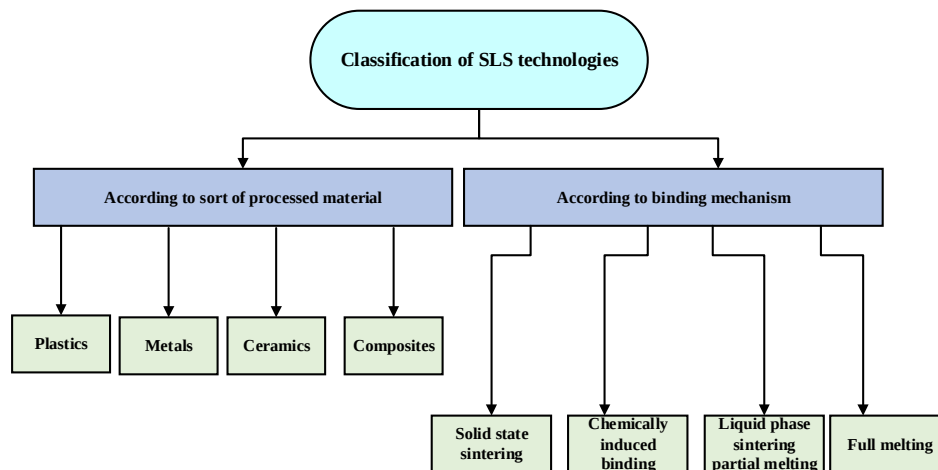


Figure 4. The classification of SLS/SLM/DMLS technology; adapted from [15].

2.2. Laser Engineering Net Shaping (LENS)

This method, known also as: Laser Cladding, Directed Energy Deposition and Laser Metal Deposition, consists in local supplying metal powder and laser sintering; due to that it can be applied both for making new parts and for regeneration of ones previously made by traditional techniques. In this technique, the laser melts the base material on which one or more metal powders are deposited by the nozzle (Figure 5).

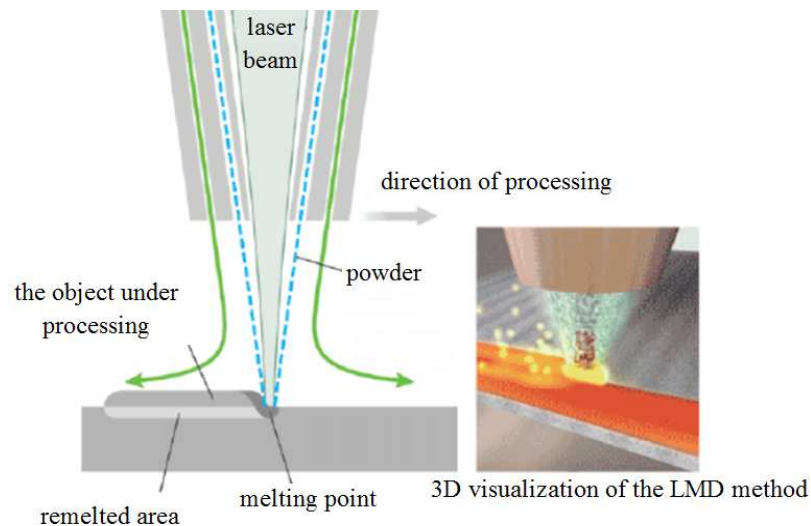


Figure 5. The scheme of the LENS technology [16].

The major advantage of the application of the LENS technique is the possibility of creating strong surfaces on soft metals, as well as creating layers which are resistant to the action of high temperatures, water or chemicals. Unfortunately, parts produced by the LENS technology are characterized by the occurrence of porosity and thus have unsatisfactory geometric accuracy, as well as high surface roughness [17-19]. Therefore, post-process machining is required for the surface quality improvement.

2.3. Electron Beam Melting (EBM)

In the EBM technique, building of the object is effected directly from the 3D CAD data by laminar deposition of powder on the lowering platform. The functioning principle of the Electron Beam Melting technology has been shown in Figure 6. Melting of the subsequent layers is effected by means of a focused beam of electrons in a chamber with high vacuum with a minimum presence of helium in order to prevent the electron beam dissipation. Due to the high density and structure purity, the technology is applied in production of implants containing porous structures. Such a structure cannot be made by machining.

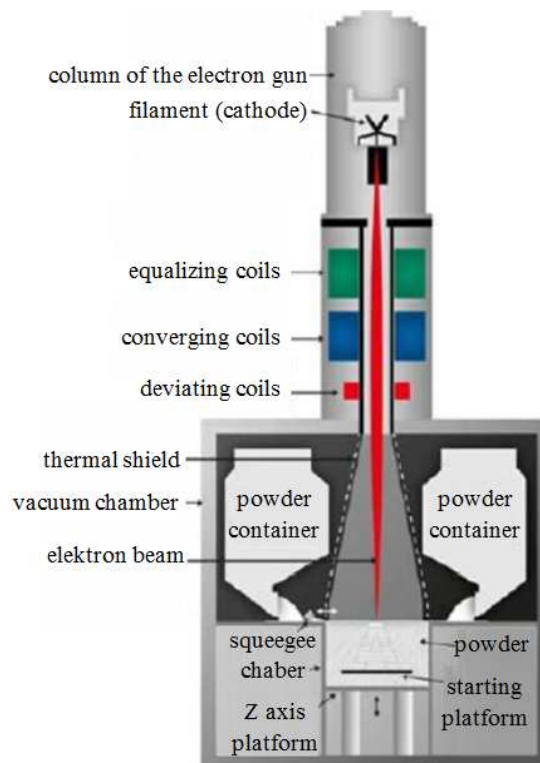


Figure 6. The scheme of the EBM technology [20].

The major advantage of this technique is the possibility of quick building of parts (even up to 60 cm³/h). The EBM method is 3 to 5 times quicker as compared to other additive technologies of manufacturing metal parts. Unlike the SMLS/SLM technology, the parts made by the EBM technology usually do not require heat treatment because the process itself is much quicker and, additionally, due to the insulating properties of vacuum, heat is arrested inside the built elements due to which the value of melting stresses is relatively small.

However, a significant limitation (similarly to the LENS technology) is low quality of the manufactured surfaces. Thus, finish cutting processes (e.g. turning, milling, grinding) are very often also required.

3. Metallic materials applied in additive manufacturing techniques

The advanced techniques of additive manufacturing with the use of metals are intended for application in the branches in which the most important aspects are mechanical strength, individualized designs and execution accuracy. Those are such branches as: stomatological branch, medical one, equipment of injection moulding machines, automotive branch, industrial equipment, aircraft and aerospace branch.

One of the materials used in additive manufacturing is martensitic steel, MS1. Its high mechanical strength and hardness make the alloy perfectly suitable for building elements of injection moulds. Due

to laminar manufacturing parts by the DMLS method, it is possible build forming inserts with cooling channels adapted to the part shape, i.e. with conformal channels. As result of soaking at the temperature of 490°C and free cooling, MS1 acquires high hardness at the level of 52-54 HRC and strength comparable to that of standard materials used in building injection moulds and casting ones.

A popular steel also used in the additive technologies is stainless steel, 316L. Due to its high corrosion resistance, this material is perfectly suitable for work in the environment of organic and inorganic acids, as well as for medical applications (e.g. surgical tools). The standard thickness of additively deposited layer for that steel is 20 µm, which ensures relatively high surface quality and minimum wall thickness of up to 0.4 mm. Due to the high value of the thermal conductance, the material is suitable in the DMLS process offering high dimensional accuracy of the parts being built. The 316L steel is processed in argon atmosphere due to which high chemical purity of the alloy is maintained [21]. Just after outprint, surface roughness at the level of $R_a = 13 \pm 5 \mu\text{m}$ and $R_z = 80 \pm 20 \mu\text{m}$. Parts made of the 316L alloy can work in the temperature range not exceeding 420°C because above that threshold secretion of chromium carbides takes place.

Another material used in the additive technologies is fine grained bronze based powder named Direct Metal 20 (DM20). Parts made of DM20 have good mechanical properties, high density and good surface quality. Typical applications are, first of all, prototypes of constructional elements and tools. Parts made of Direct Metal 20 have also good corrosion resistance [22].

Popular materials used in additive technologies are also considered as hard-to-machine, alloys of titanium, silumins and high temperature creep resistant nickel alloys.

The light Titanium alloy, Ti64 has perfect mechanical properties. Till not long ago, this alloy has been considered a strategic material in the aircraft, shipbuilding and aerospace industry and for military needs [23-25]. Its major advantages include: high corrosion resistance, biocompatibility, low weight and very good bio adhesive properties.

AlSi10Mg silumin is used in the DMLS technology and a typical alloy applied for casting, with very good casting properties. It is applied mainly in manufacturing thin-walled castings with complex geometry. The AlSi10Mg silumin offers good strength, hardness and dynamic properties and, consequently, is used in the production of parts subjected to high loads. Additively made parts can be machined, welded, polished, lacquered, etc.

Nickel-chromium alloys, Inconel 635 and Inconel 625 have high tensile strength and creep strength and stress resistance, as well as resistance to high temperatures and corrosion in various environments. Those materials are also suitable for elements with complex geometry. Printed models made of the Inconel 635 and Inconel 625 alloys achieve exploitation properties comparable to those of forged metal and exceed the utilization properties of cast parts. The elements can be machined, welded, polished and lacquered, both after outprint and after heat treatment.

4. Economic aspect of additive manufacturing

Relatively low productivity and very high price of the systems for mass production result in rather small popularity of the additive techniques in industry. Nevertheless, additive manufacturing shows important advantages: it reduces material demand and, first of all, allows for manufacturing elements with more complex shapes, which is important not only for aesthetic reasons, but for practical ones, too, for example, in designing light vehicles. It has to be kept in mind, however, that mass application of those technologies depends, first of all on economic aspects – as long as their price is not reduced and productivity improved – those technologies will not be widely applied in industry.

An advantage of the 3D print is low specific cost, among others, by material saving and easy forming of complex shaped elements. In accordance with investigation of [26], implementation of the SLM technology to series production can contribute to significant reduction of specific costs.

Consideration should also be given to the concept of substituting injection forming with 3D print presented by the authors of paper [27]. It should be pointed out that the major source of costs in injection forming is the cost of the mould. In the case analysed by the authors, the costs of the mould amounted to 8500\$. Due to that injection forming will be cost effective in the case of production of at

least 50 pieces. Introduction of any kind of corrections in the model will also be very expensive. Different relations occur in the case of 3D outprint where a part is generated directly from the CAD model thus eliminating the cost of mould modification. Due to that the manufacturing cost values do not depend on the number of the elements produced. It can also be expected that the costs of 3D print will drop, which will allow for the execution of even higher number of parts at reduced costs.

It should also be pointed out that additive manufacturing will be more and more important in providing spare parts to enterprises. This will allow for significant reduction of storage costs, time of waiting and cost of transport of the spare parts.

5. Conclusion

Additive manufacturing based on 3D print is one of the most innovative and promising technologies of manufacturing. At the moment, 3D print develops rapidly and is more and more competitive to the traditional methods of prototyping, modelling and production. This is due to the many advantages of the technology including, first of all low specific costs, but also the possibility of forming parts with very complex shapes made of hard-to-machine materials (e.g. titanium alloys, silumins or high temperature creep resistant nickel alloys).

Nevertheless, some limitations influence the relatively small popularity of those techniques in industry. Those limitations are, first of all, relatively low productivity, as well as very high price of the systems for mass production. A significant limitation is also moderate quality of the manufactured surface (mainly the condition of the geometrical structure of the surface), in some cases necessitating convectional finish machining (e.g. grinding). As result, this generates additional costs.

In connection with the above further development investigation is purposeful, aiming mainly at process innovations, as well as optimization of the process input parameters in respect of improvement of the technological and economical effects of manufacturing.

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