Chapter 8

# Powder Application in Additive Manufacturing of Metallic Parts

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Additional information is available at the end of the chapter

http://dx.doi.org/10.5772/66874

**Abstract**

This chapter is going to give up-to-date overview of development in the field of additive manufacturing (AM) of metallic components. There will be briefly mentioned input materials and specific requirement for the input materials (powders and wires). General technology process overview will be presented here, and selective laser melting (SLM) technology and beam melting technologies will be described. Advantages of 3D printing technology will be explained in terms of special designs; special properties and generally multifunctional components of production possibilities will be shown. Postprinting procedures leading to improvement of mechanical properties of printed components like thermal or thermomechanical treatment will also be mentioned here.

**Keywords:** additive manufacturing, 3D printing, laser sintering, beam sintering

## 1. Introduction

Additive manufacturing (AM), sometimes called as 3D printing, is a process that is used to manufacture complex 3D products. In additive manufacturing, an object is created by deposition of several layers over each other by computer-controlled deposition process. The objects produced can be of virtually any shape. The components are created by additive manufacturing techniques on the basis of computer 3D models. Great attention has been given to this subject recently since it offers new opportunities in factories of the future.

Additive manufacturing may be a more appropriate term to use rather than 3D printing because it includes all processes that are "additive." The term "3D printing" applies more specifically to additive manufacturing processes that use a printer-like head for deposition of the material (e.g., material jetting), and 3D printing is now only one of the processes that is part of the additive manufacturing universe. Technical articles and standards generally use the term "additive manufacturing" to emphasize this broader meaning.

Additive manufacturing applications appear to be almost unlimited. Early use of 3D printing in the form of rapid prototyping was focused on preproduction models. However, additive manufacturing is now being used to fabricate high-tech industrial (aerospace, medical/dental, automotive, and electronic) and consumer (home, fashion, and entertainment) products, and today's materials include not only polymers but also metals and ceramics. This chapter is going to deal with powder-based additive manufacturing. In the initial part, a brief overview of powders for additive manufacturing preparation and subsequently additive manufacturing techniques is presented.

## 2. Preparation of input materials for additive manufacturing

There is a wide range of additive manufacturing technologies that are going to be described later in this chapter. Depending on the technology considered, an appropriate input material should be used. Generally spoken there are two basic groups of input materials: powders and wires. Wire-feed processes such as laser metal deposition (LMD) and electron beam additive manufacturing (EBAM) are typical by higher deposition rates [1] with lower shape detail accuracy in comparison to powder-bed or powder-directed energy deposition processes. Considering pricing of these two branches of the input materials, wires are significantly cheaper in comparison to powders, and also the offer of the feedstock alloys available in the form of wires is significantly wider. However, the powder-based technologies can use special materials not available in the bulk form. This fact together with higher part geometrical accuracy leads to a wide application range of powder-based processes. Further, we are going to deal mainly with powder-related additive manufacturing.

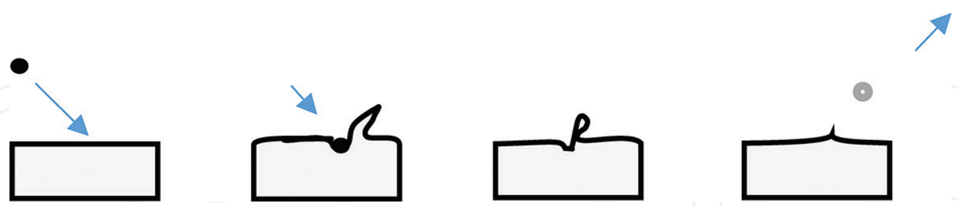

**Figure 1.** Water atomization principle [2].

The powders are prepared by atomization that can be done by several processes such as water atomization or gas atomization. While the water atomization, shown in **Figure 1**, leads to average particle size from 42 up to 120μm [1], the gas atomization leads to a finer particle sizes, and thus gas atomization is presently preferred for powder production and will be shown more in detail. The problem on powder productions is very wide, exceeding the scope of the current chapter, and thus a very brief overview of this field is provided here.

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### 2.1. The gas atomization process

The gas atomization process is the most common process to produce spherical metal powders for additive manufacturing. In cases when highly reactive materials, such as Al, Ti, or Mg, are atomized, protective gases or vacuum shall be applied.

The initial step of the gas atomization process is molten metal pouring from a tundish through a nozzle. The liquid metal is subsequently subjected to jets of neutral gas (nitrogen or argon). The gas jets divide liquid metal into tiny droplets and contribute to droplets cooling down that continue as they fall within the atomization tower. Powders are finally accumulated on the atomization tower bottom [2].

Two main configurations of twin-fluid atomizers are distinguished within molten metal atomization. The first kind is called the confined or close-coupled atomizer, and the second kind is called the free-fall atomizer. Both concepts are illustrated in **Figure 2** [3].

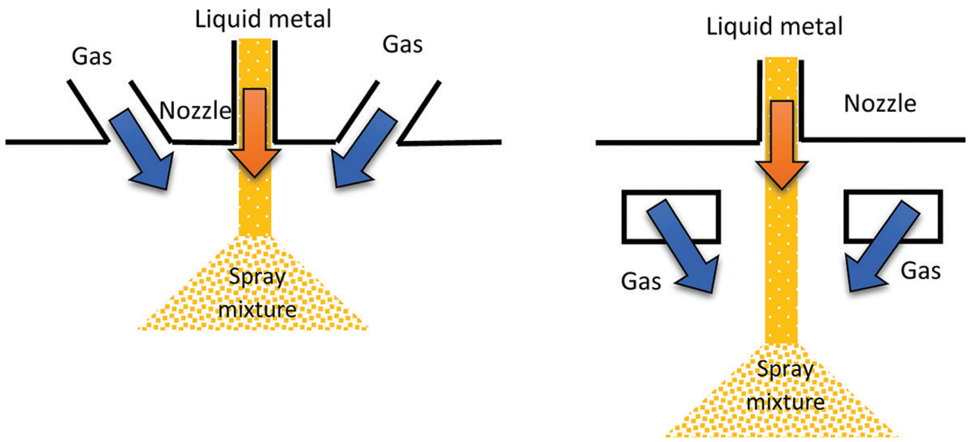


**Figure 2.** Principle configurations of gas atomization: left (close-coupled atomizer (confined)) and right (free-fall atomizer).

In the case of the close-coupled gas atomizer, the gas flow surrounds instantly the liquid metal pouring from the reservoir nozzle. In the case of free-fall atomizer, there is some gap between the nozzle outlet and gas jets. This fundamental difference between the atomizers leads to advantage of the higher cooling rates for the close-coupled atomizer and thus higher efficiency in comparison to the free-fall atomizer. However, the free-fall atomizer exhibits significantly lower susceptibility to freezing than the close-coupled atomizer. The freezing issue comes from very small distance between the liquid metal outlet nozzle and cooling gas that leads to very intensive cooling and thus problems with freezing at process early stage, when the nozzle is not sufficiently heated. Once the nozzle is heated up by flowing liquid metal, the problem with freezing is minimized. Additional advantage of free-fall atomizers over close-coupled ones is possibility of gas jet adjustment in the course of the process. By controlled scanning and oscillating of the gas cooling jets, running atomization process can be adjusted at any moment, and therefore desired powder size and distribution can be better achieved. Close-coupled atomizer offers process adjustment by modification of the cooling gas pressure only that allows much lower process modification versatility in comparison to free-fall atomizer [3–5].

### 2.2. Special atomization processes

In the case of special material atomization, appropriate approaches shall be employed such as:

- Vacuum inert melting (VIM) where the melting takes place in a vacuum chamber. This process is recommended for super alloys in order to avoid the melt contamination by oxygen for highly reactive materials such as Ti and Al.
- Plasma atomization and spheroidization consist of in-flight heating and melting thanks to a plasma torch of feed material followed by cooling and solidification under controlled conditions. Depending on processes, the raw material can be particles as well as bar or wire feedstock. Plasma atomization can be used in particular to spheroid refractory metals such as Mo alloys, W, and WC.
- Centrifugal atomization, also known as plasma-rotating electrode process, consists in melting with a plasma torch where the end of a bar feedstock is rotating at high speed and thus ejecting centrifugally the molten droplets of metal.
- Powder blending and mechanical alloying, to produce metal matrix composites (MMCs).

### 2.3. Metal powder characteristics for additive manufacturing

Key metal powder characteristics for additive manufacturing are chemical composition, powder size distribution (PSD), morphology, and physical properties.

Additional points are important to consider when selecting metal powders for additive manufacturing processes such as storage and aging of powders; reusability of powder after additive manufacturing cycles; and health, safety, and environmental issues [2].

Regarding the chemical composition, it is important to take into account interstitials, such as oxygen, nitrogen, carbon, and sulfur, as they may affect significantly material properties depending on alloys. With the gas atomization process, all powder particles have the same chemical composition, but finer particles tend to have higher oxygen content due to the higher specific surface.

The chemical composition will influence in particular melting temperature, mechanical properties, weldability, and thermal properties (thermal conductivity, heat capacity, etc.). The chemical composition can also evolve slightly after multiple uses in additive manufacturing machines.

Depending on additive manufacturing technology and equipment, two main types of particle size distributions are considered:

- Powders usually below 50 μm for most powder-bed systems. In this case, finer powder particles below 10 or 20 μm shall be avoided, as they are detrimental to the powder flowability.

- Powder between 50 and 100–150 μm for electron beam melting (EBM) and LMD technologies.

The recommended particle morphology for additive manufacturing is spherical shape because it is beneficial for powder flowability and also to help forming uniform powder layers in powder bed systems.

The powder morphology can be observed by scanning electron microscope (SEM) (**Figure 3**). Typical defects to be controlled and minimized are:

- Irregular powder shapes such as elongated particles.
- Satellites which are small powder grains stuck on the surface of bigger grains.
- Hollow powder particles, with open or closed porosity.

Porosity content can be evaluated either by SEM observation or by helium pycnometer. The presence of excessive amounts of large pores or pores with entrapped gas can negatively affect material properties.

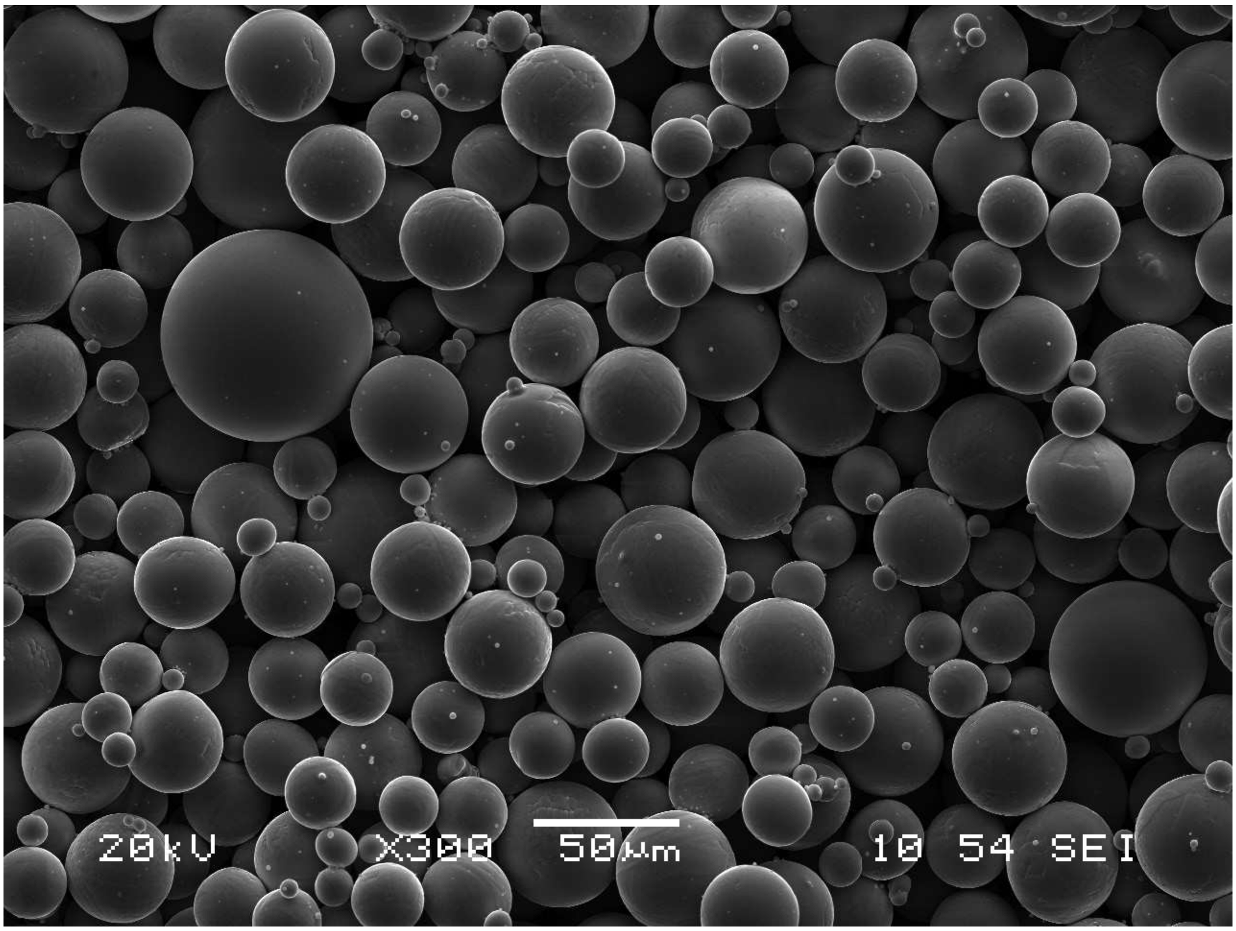


**Figure 3.** Example of atomized globular Ti-powder (inert gas atomizer).

## 3. Most common processes of metal additive manufacturing

Additive manufacturing is a very dynamic field with very wide range of new procedures being developed, so this chapter gives an overview of mostly used ones.

### 3.1. Powder-bed fusion processes

Powder-bed fusion (PBF) processes were among the first commercialized AM processes. Developed at the University of Texas at Austin, USA, selective laser sintering (SLS) was the first commercialized PBF process. All other PBF processes modify this basic approach in one or more ways to enhance machine productivity, to enable different materials to be processed, and/or to avoid specific patented features.

In the case of the powder-bed process, the product is created stepwise by thin powder layer sintering deposited subsequently over each other until the desired shape is achieved. The power source for powder-bed fusion processes can be laser or electron beam that melt and fuse metal particles together. Vacuum is required in the case of electron beam melting (EBM) processes or in case of highly reactive metal processing (titanium, magnesium, etc.). The input powder material is located in the container from which it is fed into processing zone where it is subsequently fused. The powder that is brought to the process zone is in the form of thin layer of thickness about 0.1 mm. There are various processes assuring even thickness of powder layers such as roller- or blade-based ones. In order to maintain constant distance between the power source and processed object, the bed is lowered with each new layer. The unfused residual powder remains on the powder bed and can be recycled for further use [6].

#### *3.1.1. Electron beam melting (EBM)*

In the EBM process, fully dense metal components are built up, layer by layer of metal powder, melted by a powerful electron beam in high vacuum. Full melting of metal powder is required in each deposited layer.

The power source of the EBM machine is high power electron beam. The beam has to have sufficient energy in order to achieve desired melting capacity and productivity. The beam is computer controlled by electromagnetic coils that can scan the beam over the process area providing desired melted layer shape [7], as can be seen in **Figure 4**. Advanced electron beam machines allow several melt pools to be maintained simultaneously—multibeam technology.

Electron beam melting is distinguished by its superior refining capacity and offers a high degree of flexibility of the heat source. Thus, it is ideal for remelting and refining of metals and alloys under high vacuum. Thanks to specific properties of this process, the main application is in the field of high-temperature resistant and reactive metals such as, e.g., titanium, zirconium, and tungsten. The EMB is widely used for ultrapure sputtering target material production and for titanium waste recycling. This solid free-form fabrication technique produces fully dense metal parts with characteristics of target material [4, 8].

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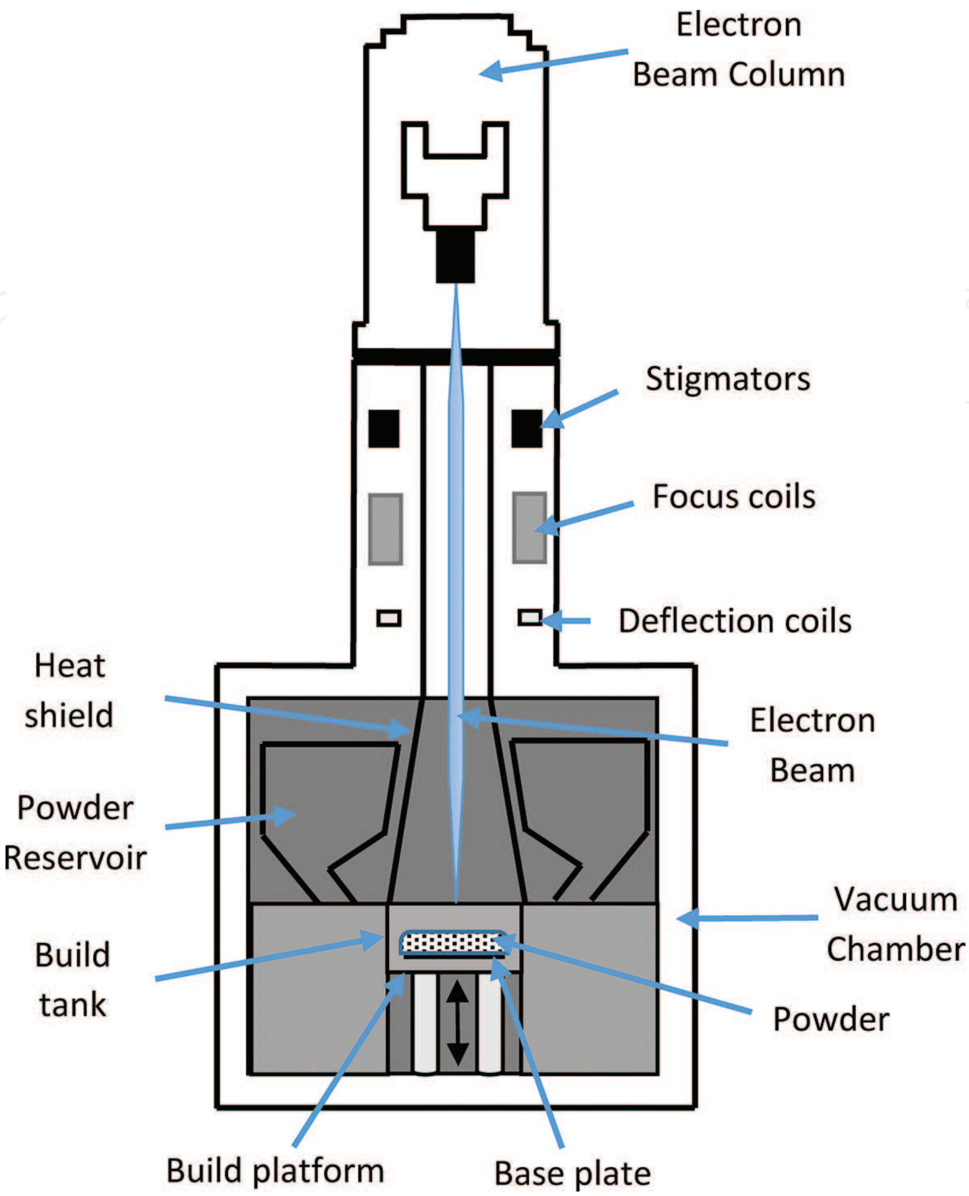


**Figure 4.** Electron beam additive system scheme.

The EBM process takes place in vacuum and at high temperature, resulting in stress-relieved components with material properties better than cast and comparable to wrought material. Very complex shapes can be achieved by EBM technology as can be seen in **Figure 5**.

The electron beam guns are very powerful heat sources that can achieve melting and even evaporation temperatures of most of the materials of interest. Computer control of the beam by electromagnetic coils enables fast scanning with very high accuracy. The EBM yields very good power transfer efficiency, depending on the material of interest reaching 50–80%. Thanks to high power density of the electron beam of about 100 W/cm$^2$, only shallow melt zone is achieved that has beneficial effect on the produced component from microstructure point of view. The process is run under high vacuum up to 0.001 Pa that leads to effective melt

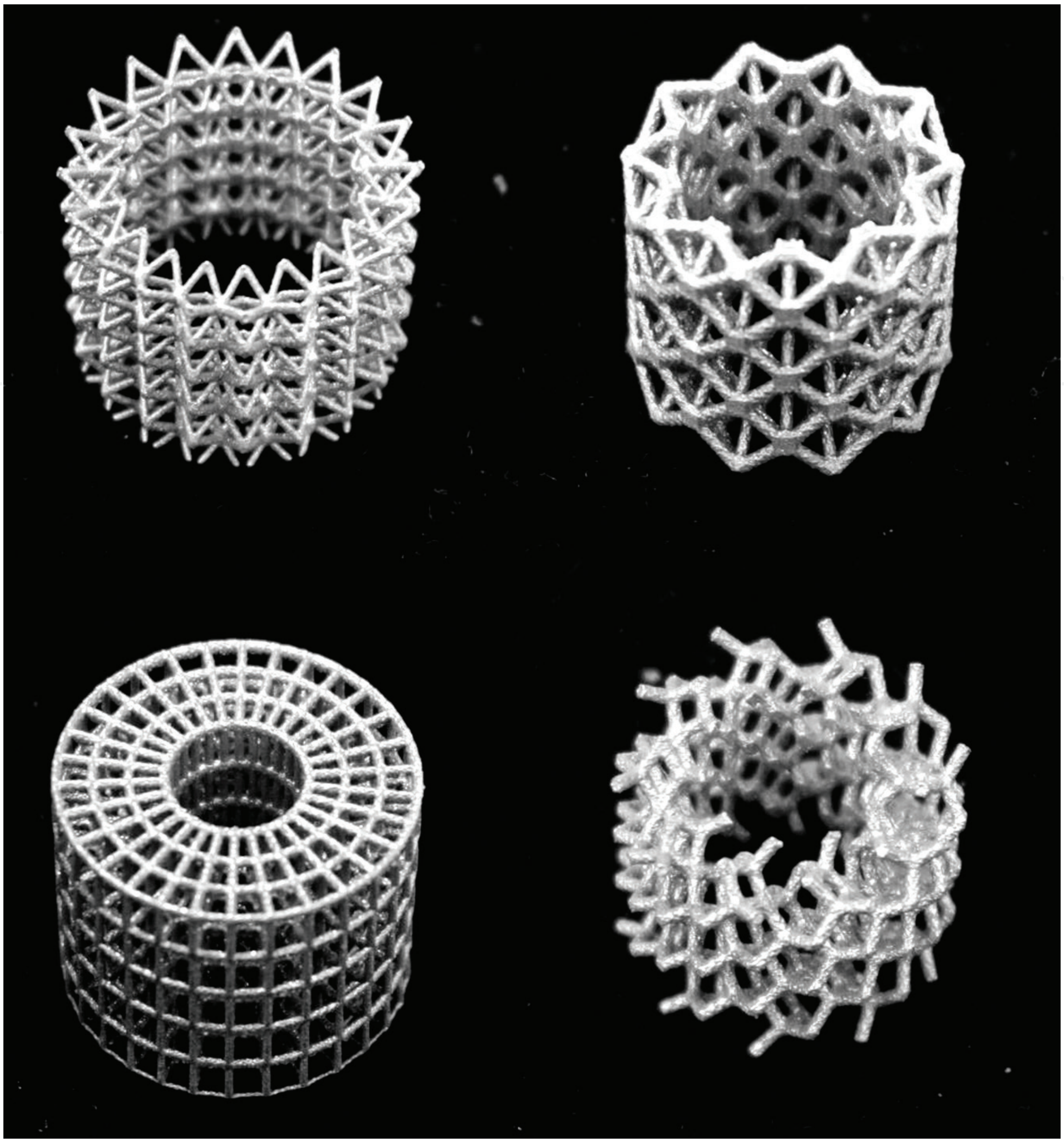

**Figure 5.** Examples of printed complex structures.

degassing providing high purity materials. Negative side of this effect is loss of certain alloying elements that has to be considered if special complex alloys are being processed [4, 9].

### *3.1.2. Direct metal laser sintering (DMLS)*

Direct metal laser sintering (DMLS) is another technique from the field of additive manufacturing. The energy source here is laser beam that is computer controlled so it can scan across the applied powder layer in order to sinter shape according to CAD model into a solid component. The process is also, as in the case of EBM, incremental sintering of thin layers step by step, with typical layer thickness of 20–100μm, until full 3D object is created. Depending on the shape, complexity and component stability on the worktable, special supports might be necessary for successful component production. During the process preparation, also

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appropriate component orientation has to be decided taking into consideration potential properties variations due to various heating conditions at different component spots and reheating of some parts more than the others. DMLS provides very complex shapes with very high accuracy, good surface, and excellent mechanical properties [10, 11]. Scheme of DMLS system is depicted in **Figure 6**.

Direct metal laser sintering (DMLS) is gradually gaining the position of a production method for rapid as well as a precise production of fully functional prototype parts or final products for various applications. Prototypes made using this technology are good for parts that cannot be easily die-casted or machined. The process produces highly durable but still fine components that are used in many industries, including aerospace, automotive, electronic or packaging industries, and medicine. A wide range of applications is gained in the production of molds and dies for plastic, ceramic, or metal products. With constantly increasing speed of devices and a permanently growing number of materials, the range of applications of this technology is higher as well. Material selection for DMLS process is very wide, from light alloys and steels to high alloyed super alloys and composites. The choice of material depends upon the end use of your application and requirements for strength, durability, sterilizability, weight, thermal properties, and corrosion resistance. DMLS is carried out for a wide range of materials among which aluminum, cobalt, chrome, nickel alloys, stainless steels, titanium alloys, and copper alloys are the most commonly offered.

The technology direct metal laser sintering has several modifications depending on the applied energy resulting either in complete local powder melting creating molten pool of metal, selective laser melting (SLM), or only local melting of single-grain parts, selective laser sintering (SLS). The SLM process yields fully dense components with mechanical properties comparable to bulk material; however, it is more difficult to control in comparison to SLS. The SLS-produced parts may require some additional treatment in order to reach better mechanical properties. Due to significantly higher energy input in the case of SLM and resulting

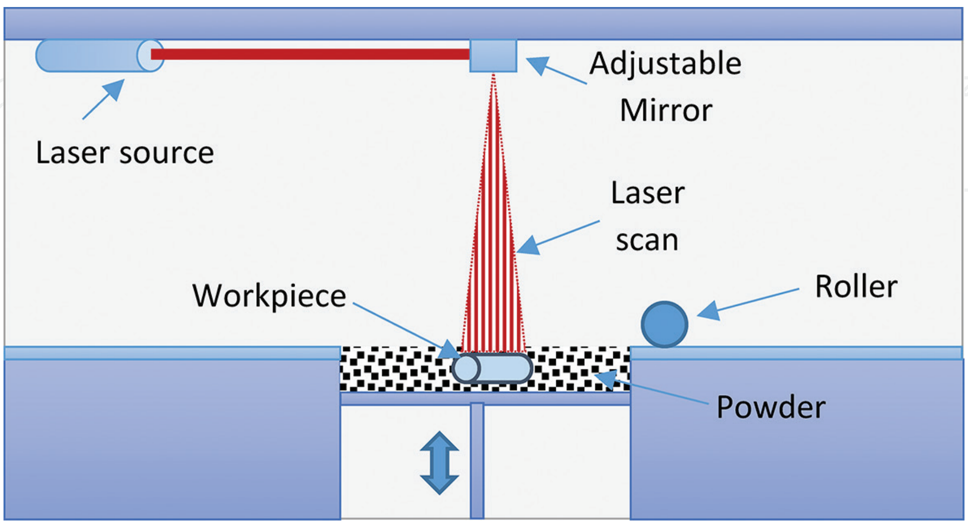


**Figure 6.** Schematic diagram of direct metal laser sintering process [11].

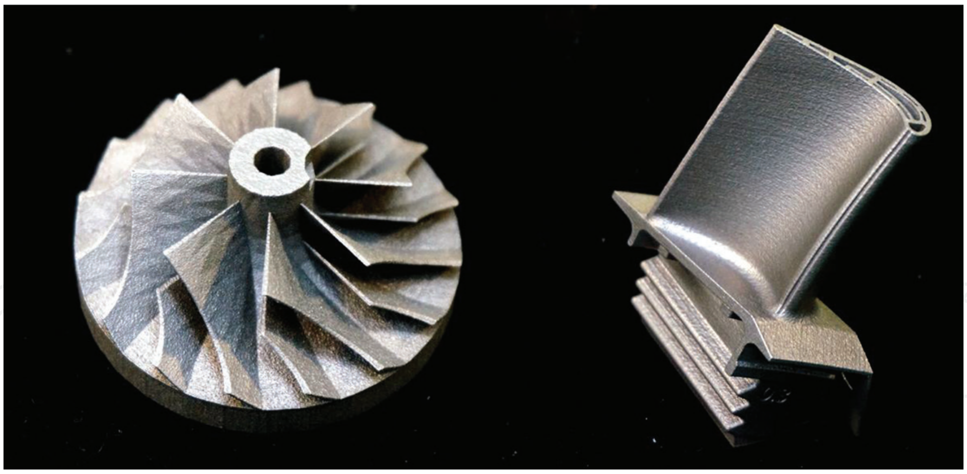

**Figure 7.** Examples of components produced by SLM.

complete powder melting, problems with residual stresses and geometry deformation may appear [12]. Examples of Ti alloy components produced by DMLS can be seen in **Figure 7**.

### 3.2. Blown powder processes

Processes using powder-bed fusion are still limited by the size of the built table and chamber. A process known as blown powder (BP) additive manufacturing can deliver some higher freedom in achieved geometry of manufactured parts. This method is available for many years. Its main difference to currently developed powder-bed methods is there is no need of powder supply in the form of layer by layer with subsequent sintering or melting. BP processes are using an additive material powder that is blown into the processing zone, where it meets with laser or plasma beam that melts the particle surface or whole particles and they are subsequently deposited on the substrate. The substrate can be present in a kind of form such as initial component layer, preprepared workpiece, or repaired serviced component. These principles were applied in many process developments [13].

#### *3.2.1. Direct laser deposition (DLD)*

The laser deposition processes are widely known under various names originating from manufactures or research institutes where they were developed. Probably, the most widely known are laser metal deposition (LMD), direct metal deposition (DMD), direct laser deposition (DLD), laser-engineered net shaping (LENS), laser cladding, laser deposition welding, and powder fusion welding [14].

In the case of laser deposition technology, the metal powder is introduced into focused beam of high power laser. The gas in the processing zone is strictly a controller to maintain repeatable stable process conditions. Molten base material is attained at localized area by focused laser beam, and additive powder is blown into this pool where it melts and subsequently solidifies creating deposition volume. Typical deposition thickness is ranging from 0.1 to 1 mm. The process is computer controlled in order to maintain constant distance between the nozzle, laser beam source, and deposited surface. By movement of the laser beam with nozzle over the component/base plate movement, desired component geometry can be attained. More advanced systems offer possibility of closed-loop system for dimension control achieving very accurate geometry. Due to higher deposition, layer thickness components with lower surface variety can be attained; however, the build-up rate is significantly higher in comparison to powder-bed-based processes. These systems are quite versatile, and another possibility that is available is also the use of multimaterial deposition providing possibility to adjust local chemical composition of the component to desired properties at the specific component locations according to service loading conditions. DLD process can be used for many applications ranging from a new component production to repairs or rebuilds of broken parts, as it is explained in more details later. An example of the application is for steam turbine blade service life extension by coating of steam turbine blade edges by Stellite-6 that increases wear resistance to cavitation. Another field of applications can be reducing component costs by saving expensive special materials that can be applied on the functional surface only, while the rest of the component can be made of some low-cost material [14–17].

DLD process allows deposition of a wide range of materials such as titanium, nickel, various steels, and among others also Stellite. The microstructure of deposited material is comparable to as-welded microstructure that provide usually rather worse mechanical properties, and thus subsequent thermal processing is desirable [18]. Scheme of DLD can be seen in **Figure 8**.

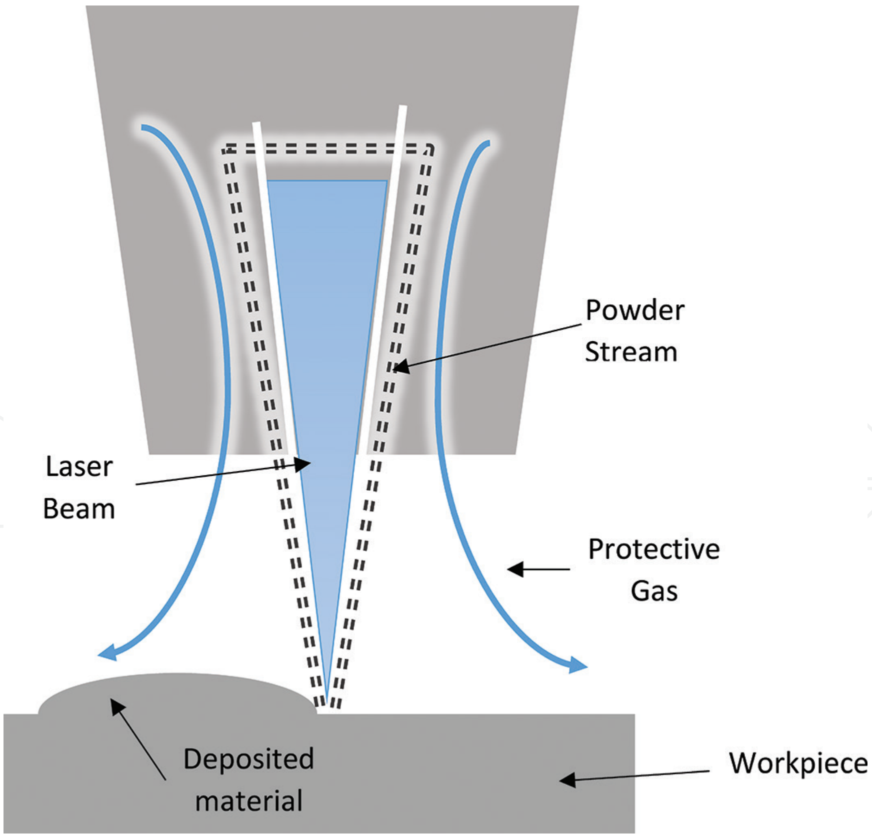


**Figure 8.** Laser metal deposition scheme [14].

There are basically three main applications of DLD processes [16]:

- Laser repair technology (LRT).
- Laser cladding technology (LCT).
- Laser free-form manufacturing technology (LFMT).

The laser repair technology is applied in cases when some parts of expensive constructions are worn or partly broken due to service loadings. The component replacement would be too expensive in these applications, and thus local repair can significantly increase the service life and thus safe substantial financial expenses. Typical examples of such repairs can be dies for close die forging, steam turbine rotors after smaller accidents, and mill or compressor components [16]. Examples of repaired parts by LRT are shown in **Figures 9** and **10**.

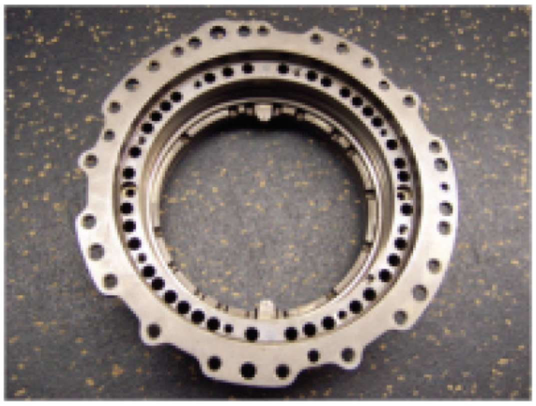

**Figure 9.** Laser repair technology of Titanium bearing housing [17].

**Figure 10.** Laser repair technology of Inconel 718 compressor seal [17].

Laser cladding technology is in contrary to LRT applying thinner layers that are mainly reconstructing worn surface, and thus smaller material volumes are deposited during this process [16]. Typical applications are bearings, seals, coupler surfaces, or shaft repairs, as shown in **Figure 11**.

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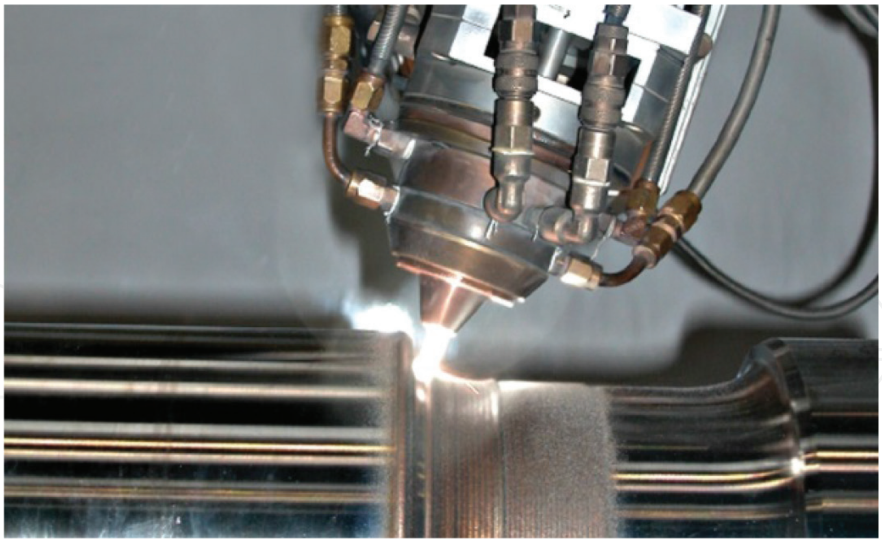

**Figure 11.** Laser cladding technology of wear-resistant material on shaft surface [18].

Creation of completely new components is done with the use of laser free-form manufacturing technology. This technology allows complete buildup of complex-shaped parts—free forms based on 3D computer model. This technology is applicable in prototyping or production of unique special components. The result of LFMT is almost 100% dense material with properties comparable with wrought material. Typical minimum wall thicknesses of free forms are of 1.5 mm [19]. Examples of these process products can be seen **Figure 12**.

**Figure 12.** Examples of parts produced by free-form technology [18].

## 4. Postprocessing technologies for additive manufactured parts

Although it is usually referred to additive manufactured parts, they are net shaped; some postprocessing is necessary in most cases of AM components. There are two basic reasons for subsequent processing of AM parts: geometry and properties. During AM processes there is always present partial or complete local volume melting followed by subsequent rapid cooling due to high metal conductivity of a large volume of surrounding bulk material in relation to melt size. These results in many cases in properties that are significantly lower than those achievable for bulk materials. Therefore, subsequent thermal or thermomechanical treatment provides significant improvement of mechanical properties. Additionally, it removes some residual stresses after AM.

The surface of AM components is generally uneven with visible layers or places where supporting structures were attached in the course of AM. Geometry itself can be slightly distorted by thermal stresses present during AM. Therefore, in many cases some additional processing either from dimensions or surface point of view to be applied to AM products is necessary. In cases where surface has some special function (decorative, sliding, etc.), blasting, grinding, and polishing can be applied for final-state surface achievement. In cases of high precision parts, machining is unavoidable in order to achieve desired geometrical tolerances.

The surface after AM can be uneven, and due to thermal stresses during AM, some small geometry distortions have to be expected.

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