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Chapter

Plasma Metal Deposition for Metallic Materials

Enrique Ariza Galván, Isabel Montealegre Meléndez, Cristina Arévalo Mora, Eva María Pérez Soriano, Erich Neubauer and Michael Kitzmantel

Abstract

Plasma metal deposition (PMD®) is a promising and economical direct energy deposition technique for metal additive manufacturing based on plasma as an energy source. This process allows the use of powder, wire, or both combined as feedstock material to create near-net-shape large size components (i.e., >1 m) with high-deposition rates (i.e., 10 kg/h). Among the already PMD® processed materials stand out high-temperature resistance nickel-based alloys, diverse steels and stainless steels commonly used in the industry, titanium alloys for the aerospace field, and lightweight alloys. Furthermore, the use of powder as feedstock also allows to produce metal matrix composites reinforced with a wide range of materials. This chapter presents the characteristics of the PMD® technology, the welding parameters affecting additive manufacturing, examples of different fabricated materials, as well as the challenges and developments of the rising PMD® technology.

Keywords: additive manufacturing, plasma metal deposition

1. Introduction

Additive layer manufacturing (ALM) is an emerging manufacturing process that produces parts close to their final shape or ready to use. It is getting a rising interest in the present and future production technologies due to the open range of opportunities. ALM uses an energy source to melt or sinter material, depositing it layer by layer.

There is a wide variety of classifications of the different variants of the ALM process. One of the most popular is considering the energy source to perform the specimens. Hence, depending on the energy source, the ALM technologies can be divided into plasma-based (Gas Tungsten Arc Welding, GTAW; Gas Metal Arc Welding, GMAW; Plasma Arc Welding, PAW; Wire Arc Additive Manufacturing, WAAM), laser-based (Selective Laser Sintering, SLS), or electron beam-based systems (Electron Beam Welding, EBW; Wire Electron Beam Welding, WEBW) [1, 2].

The main advantage of the plasma-based techniques over the laser-based or the electron beam-based ones is the cost of the equipment. Moreover, in this last group, there is a necessity to work in a vacuum chamber, where the manufacturing atmosphere has to be clean of fumes and particles; otherwise, these could divert the electron beam. A disadvantage of the plasma-based techniques is the low resolution of the final parts produced; with the other techniques, it is possible to control the energy supplied and to have a smaller welding pool that allows a better geometric resolution.

Figure 1a presents an example of the devices employed to develop plasma metal deposition (PMD) parts. Moreover, **Figure 1b** shows a typical specimen manufactured *via* ALM, which is employed by the aerospace industry. There is a schematic representation of the arrangement of the layers in **Figure 1c**.

Moreover, building up parts with different materials is possible due to the development in powder metallurgy, whose advances have made it possible to produce powders of any material. Additive manufacturing (AM) is not only fed by powder, but also with wire shape material, which has the advantage of introducing the material directly into the heat source, although it has the disadvantage of being limited by commercially available materials. In this regard, advances in the field of the raw materials for AM might contribute to developing new material combinations with outstanding properties and complex geometries.

In line, another named classification can be considered according to disposing of the raw material. The material can be injected or introduced directly into the energy source, blown-powder/wire-feed techniques (Direct Metal Deposition, DMD) [3–5], or disposed on a bed or platform in powder shape (Laser Powder Bed Fusion, LPBF) [6–8]. Such powder-bed based ALM equipment is typically limited in manufacturing large parts due to the size of their building platforms. However, DMD processes are suitable for large-scale parts. Both being close to the final geometry and working with any type of material, AM processes are a point of interest due to the significant reduction of energy, saving time in post-production processes, and saving raw material in the manufacturing of a product.

One big advantage is the possibility of building pieces close to the final geometry even with complex shapes. Thanks to the advances in computer science, additive manufacturing is helped by computer-aided design (CAD) programs to produce any part, even with a difficult geometry [9].

The technology described in this chapter, known as plasma metal deposition, belongs to the plasma-based processes, similar to PAW but with the additional advantage of using not only a wire as feedstock, but also powder, or a combination of both. The equipment has been developed at RHP-Technology GmbH (Seibersdorf, Austria), and this system can produce parts with various metallic materials, as well as metal matrix composites (MMCs), or gradient material structures.

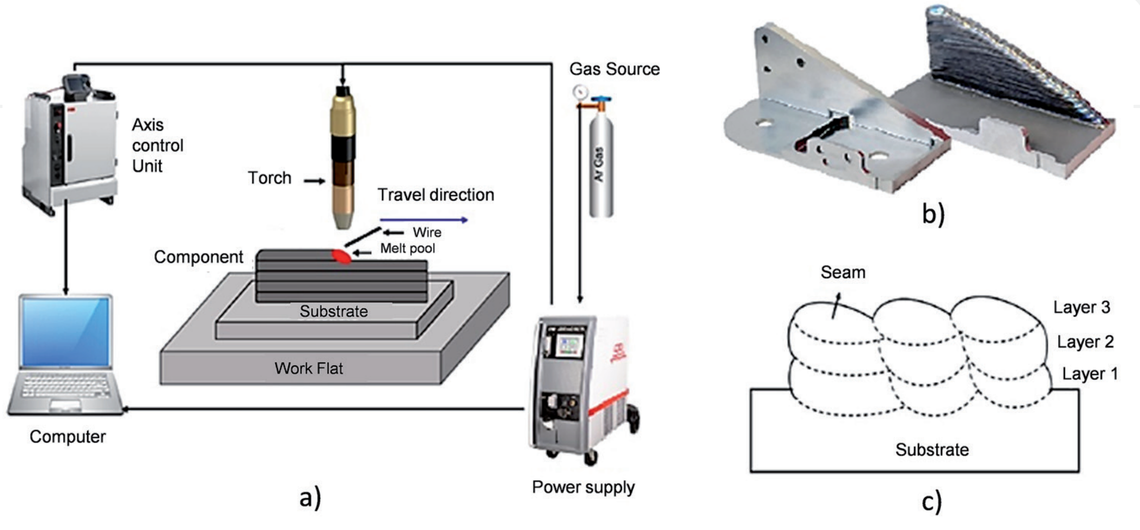

Figure 1.
a) Schematic of the PMD system, b) photograph of the sample as build vs. sample after post-processing, c) schematic of a cross section of the sample.

2. Plasma metal deposition

The PMD process is based on a torch where the plasma is produced for melting or sintering materials that are injected in powder shape or introduced as wire directly in the plasma focus (**Figure 2**) [10–12]. The gas used for producing the plasma is argon (pilot gas). It is introduced between the electrode and the copper torch. Due to a difference of potential of 20 V, the gas gets ionized, and a high-temperature plasma plume is created.

This plasma plume creates electrical contact between the electrode and the workpiece to ignite the main arc. Around the main plasma arc, an inert gas stream (shielding gas) is injected to protect locally the welding area from oxidizing during the manufacturing process or from other external agents entering the welding. The plasma torch is actively cooled with water through internal ducts, which prevents the torch and its components from being damaged due to high temperatures.

The PMD process can supply a DC mode, where the electrons flow from the electrode to the substrate, and AC mode, which alternates the flow direction of electrons. The AC mode is needed for manufacturing materials with high-oxidation surface alloys such as aluminum or magnesium. When the electrons go from the workpiece to the electrode, they are used for breaking the oxide layer and later on the flow changes to melt the material below.

The powder feedstock is injected with the help of a metric wheel feeder and pressurized argon (powder gas) through pipes directly into the plasma focus, where a welding pool of molten material is produced.

In the case of using wire feedstock, two wires are driven into the plasma focus with feeder wheels. Before introducing them into the plasma focus, the wires pass through a wire heater system that can be activated, to preheat them in advance and use less energy from the plasma to melt them. The heater works by inducing a current through both wires warming them. As it can be seen in **Figure 3**, the wire feeder is set up on a specific holder where the XYZ position of the wires can be adjusted, as well as the relative angle of the wires to the weld pool.

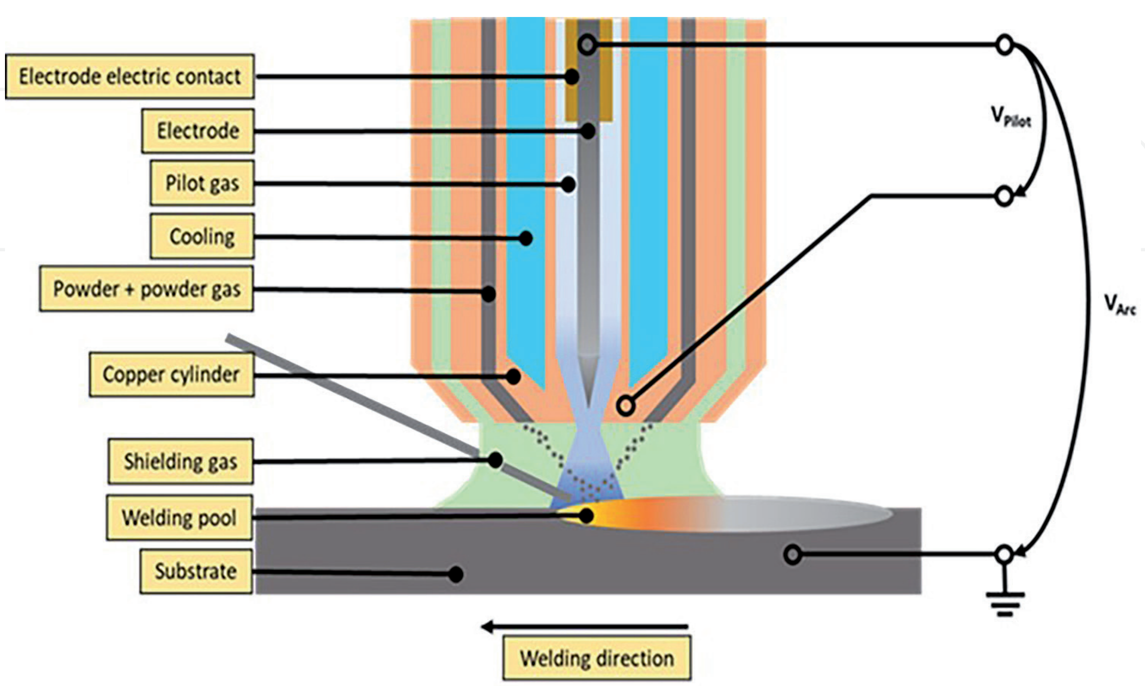

Figure 2.
PMD torch scheme.

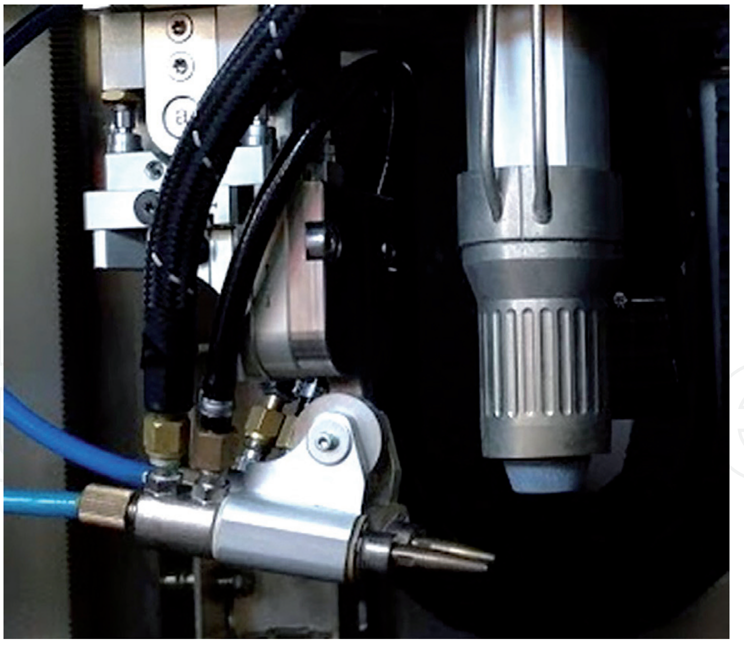

Figure 3.
Image of the hot-wire wire feeder next to the PMD torch.

The plasma torch is fixed to a gantry system that allows its movement in three dimensions over a working table (X-Y-Z axes) (**Figure 4**). This working table, at the same time, is chilled to avoid damaging the mechanical components of the equipment. The size of the gantry system and the working table will determine the maximum size of the produced part, being possible the manufacturing of large-size components. Thus, this technique offers more advantages regarding greater flexibility of specimen size, in comparison with the LPBF technique.

Furthermore, a turning/tilting table is available for producing revolution components or parts with high complexity where a 5-axis system is needed: for example, on high-overhang angle parts, cantilevers, or the edges of flange-kind components.

Figure 4.
Picture of PMD machine.

Moreover, the torch and wire feeder system are installed on another turning axis that eases the direction formed between the plasma focus and the wires following the toolpath. Also, by turning 180°C the torch leads to two different welding configurations, which can be used by adding the wires in front or after the weld pool.

In particular, and in accordance with the previously commented, the PMD device in RHP-Technology GmbH facilities has a working volume of 2000 mm × 1000 mm × 600 mm. In this respect, that allows the manufacturing of large-size components. On the contrary, in powder-bed systems where the part size depends on the platform in which the powder is disposed of and on the load that it can hold, the size of the specimens is limited to the axis geometry.

The plasma torch could be installed on any mechanical axis. The installation of a PMD torch on a robotic arm is the most effective way for repairing parts with complex geometry. Advantages include the possibility of repairing large pieces with localized defects or even improving the properties of the surface by cladding a material with greater hardness.

The welding and axis systems are located inside a welding chamber that enables the manufacturing of components in a protective gas atmosphere during the whole welding process, not only locally in the surroundings of the welding pool, but also giving general protection to the part during the cooling. This fact is of high importance when the used raw material has high oxidation sensitivity, for example, titanium alloys.

The chamber is filled with inert gas, usually argon. Through pipes with multiple diffusers on the floor of the equipment, it is sought to have a laminar flow of inert gas in order to achieve the evacuation of oxygen from the bottom to the top. Its effect is very important to avoid undesired secondary reactions during manufacturing. Sensors placed along the height of the machine measure the oxygen content at any moment, while the filling of the chamber allows having a precise amount of oxygen inside. In this regard, there is a guaranty of the quality protection of the manufactured specimens.

In the case of the welding gases used, generally, the main plasma is created by ionizing argon gas as explained above, but to increase the energy input in aluminum alloys, mixtures of argon-helium can be employed. The shielding gas that locally protects the welding pool can influence the mechanical properties and welding conditions of some materials; for example, for some steel alloys, the use of argon-carbon dioxide mixture is recommendable [13–16].

Figure 5.
Image of the PMD weld pool by monitoring welding cameras.

One of the most important aspects to control the welding process is the weld pool. The geometry, viscosity of the deposited melted material, and the time the deposited material is in the liquid phase give an idea of the penetration and dilution with the substrate or layers below, and the surface quality of the weld seam. Monitoring the weld pool during the complete additive manufacturing process is of interest; therefore, two welding cameras are installed on the PMD equipment next to the plasma torch to control in real-time and record the behavior of the welding process at any moment (**Figure 5**).

During the deposition, the layer height can be not homogeneous due to the geometry of the workpiece itself. In order to make corrections to the workpiece during the welding process, the equipment consists of a system called "automatic height control". The PMD system keeps the welding current constant during the process to always maintain the same value, the voltage between the electrode and the part varies. This variation is directly linked with the distance between torch and component. Using this voltage variation and coupling it with the material feeding system, more material can be added instantaneously on the areas where the workpiece layers are lower and the other way around when the layers are higher than initially designed.

Every welding parameter is logged and, together with the welding process videos, allows the identification of possible building mistakes or pores if found on a post-processing analysis.

3. Material feedstock

In PMD, different kinds of feedstock can be used as powder, wire, or both at the same time. In the case of powder feedstock, since the powder is directly injected into the welding pool, the process is not as limited as selective laser melting (SLM) or other powder-bed fusion techniques. In these processes, the powder size range has a direct impact on the final quality of the produced specimens.

There are specific powders that can be employed in PMD, as spherical gas atomized powders, irregularly rounded powders, and sharp edge powders typical of ceramics feedstock. On this subject, there is a great range of raw powders that could be combined promoting the development of a wide variety of specimens. Moreover, powders produced experimentally as water atomized are also suitable, and even the shape and range size are in this case irregular (**Figure 6**).

Introducing wire feedstock in the welding process increases the deposition rate significantly versus the use of powder. Furthermore, powders are linked to an overspray that does not occur when a wire is used. Different ranges of wire diameters can

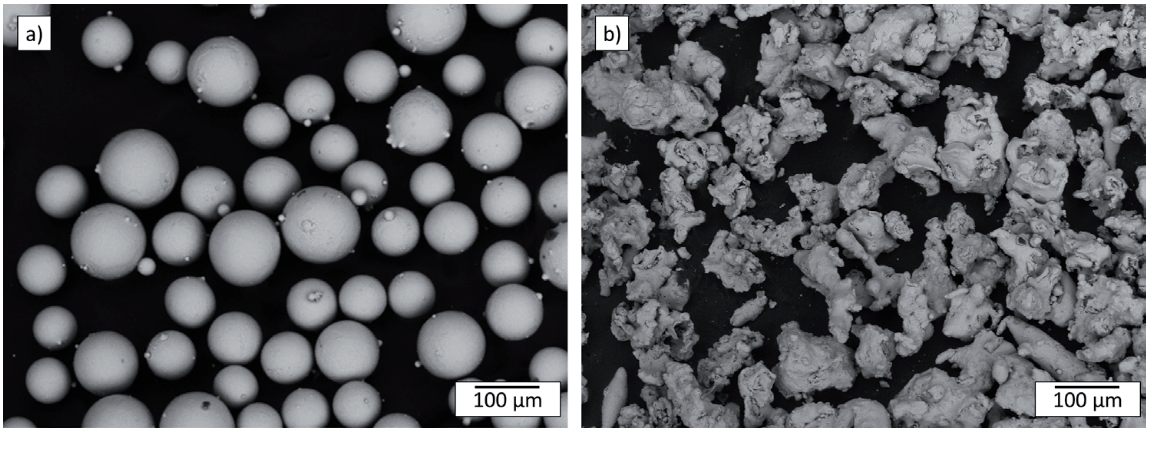

Figure 6.
Image of two different powders used in PMD: a) spherical plasma atomized powder, commercially available and b) irregular water atomized powder, experimentally manufactured [17].

be used from 0.6 to 3 mm. There are pure alloyed wires, filled wires, and rods that are suitable for the PMD process. In particular, some wire manufactures are introducing on their catalog wires specifically for additive manufacturing where the surface roughness of the wire is controlled and cleaned, with a minimized impurity content.

As commented previously, the use of wire feedstock facilitates a high deposition rate (~10 kg/h). Although not every alloy is available in a wire shape, powder metallurgy advances have made it possible to have commercially available powders of any alloy. Moreover, if an alloy is not available in powder shape, PMD enables the manufacturing of components by *in situ* alloying from elemental powders.

4. Plasma metal deposition limitations

In this subsection, some limitations of the PMD technique are reported. In order to be objective and concise, all of these limitations are briefly described comparing it with other AM techniques commented above.

4.1 Surface roughness

In contrast to Laser Powder Bed Fusion, where the component surface has a high resolution and exalted detail part can be manufactured, PMD components have a higher roughness due to the layer height (~1–3 mm), and the high deposition rate used could derive to metal droplets on the surface. These effects could affect the final behavior of the specimens fabricated.

PMD produces near-to-net-shape components that need to be post-machined at least on the functional areas. The post-machined process is also compromised with the droplets on the surface, which might contain a high-impurity content and be able to damage the cutting tools. However, despite this fact, the process is still economically beneficial because of the high raw material saved, and the manufacturing time reduction.

4.2 Shadowing effect

If wire feedstock is used, the position and the angle of how the wire is introduced into the plasma focus have a high impact on the final component geometry. This problem does not occur when powder blown is used where the powder is directly injected through the plasma torch and deposited on the weld pool from above (**Figure 7**).

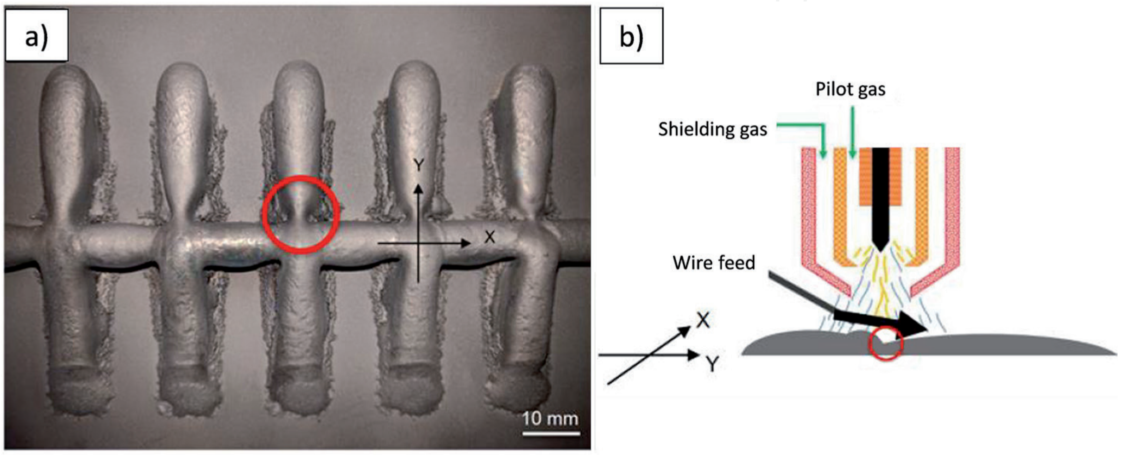

Figure 7.
Shadowing effect: a) caption of a shadowing effect mistake on a crossing points deposition and b) scheme of the shadowing effect.

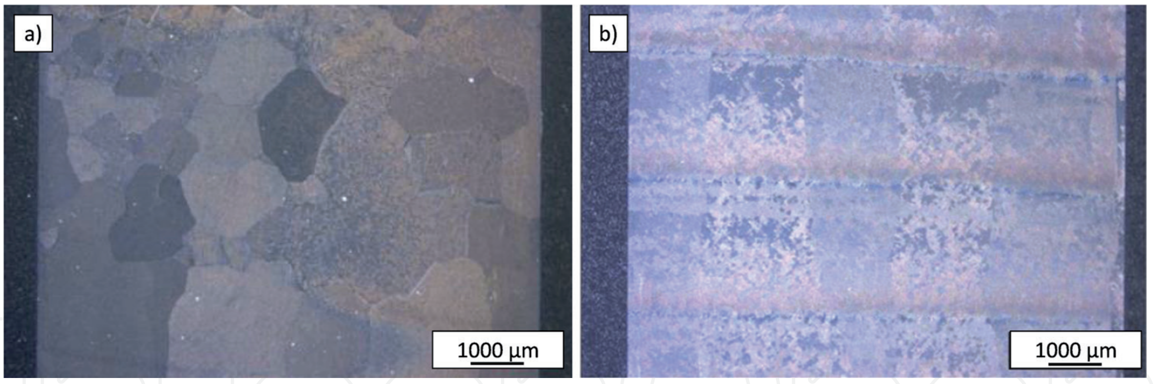

Figure 8.
Light microscope images from Ti6Al4V PMD manufactured sample, grain size detail: a) grain cross section, b) grain's length section.

4.3 Thermal cycle and grain size

The high energy input and thermal cycle from the layer-by-layer building up process provoke material mechanical stress that can induce cracks and deformation on the component. The substrate where the material is deposited is also suffering deformation and needs to be clamped. The stress on the substrate can produce that the deposited material gets detached.

Furthermore, the thermal cycles induce columnar big grains in the metallic matrix growing in the direction to the coolest area of the component that usually coincides with the vertical direction (**Figure 8**).

Incompatibility between the cladding material and the piece may appear as another disadvantage. Due to the high energy input of the PMD process, the geometry of the part can suffer distortions.

5. Results

In this section, several images of the produced specimens *via* PMD are presented classified according to the raw material employed, the kind of materials, also the processing parameters, as well as some of their properties.

5.1 Steels

The number of applications for steel is as numerous as the steel types available. Stainless steel, carbon steel, high-hardness steels, high-impact steels, etc., are feasible to be manufactured with PMD, as seen in **Figure 9** [18–20].

Also, reparations of broken tools or cladding with materials that give an added value to the existing component are possible with PMD.

In addition, when repairing some steels, it is necessary to preheat the piece before adding material; this can be previously done with the same plasma torch locally in the area that needs to be repaired, without adding material.

5.2 Nickel alloys

Nickel alloys are of high interest in the industry [20–22]. Their high corrosion resistance, high-temperature resistance, or as in the case of the alloy Invar 36 that suffers no deformation on a temperature range from −100 to 200°C, which make these alloys suitable for numerous high-performance applications.

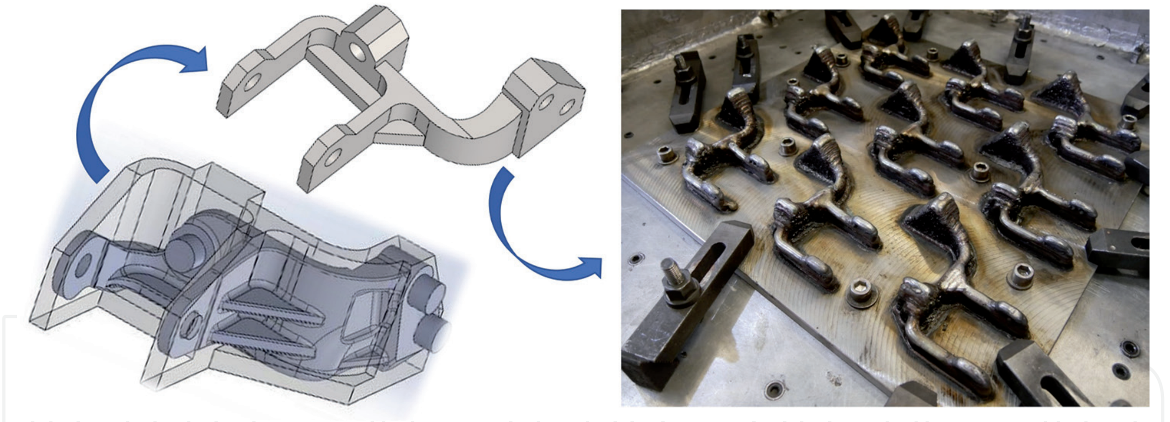

Figure 9.
Steel 17-4PH gearbox bracket. On the left, design adaption for PMD manufacturing from the casting model. On the right, gearbox bracket on a PMD production.

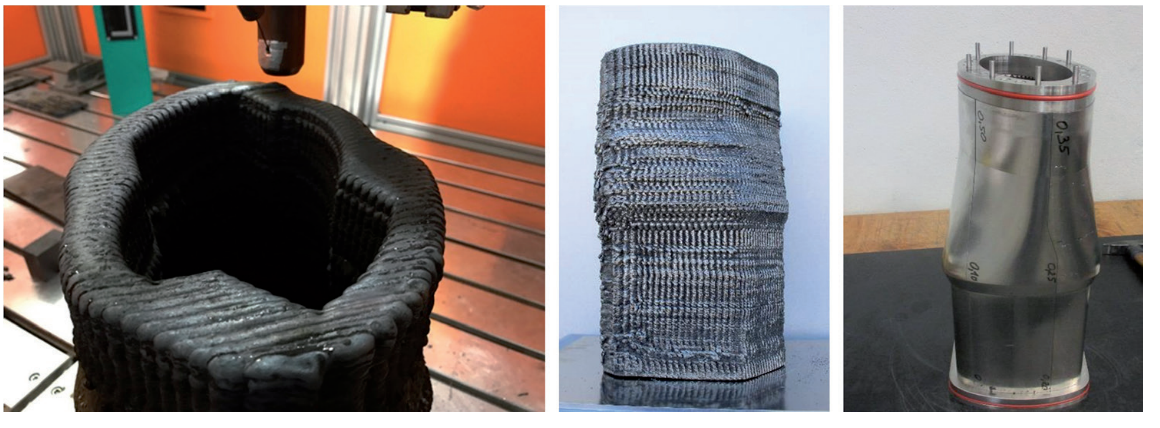

Figure 10.
Nickel alloy Invar 36 CFC tooling PMD manufactured. From left to right, PMD manufacturing, tooling as-deposited, and tooling as-milled.

Moreover, the nickel-based alloys have a high cost related to the raw material, and this cost is drastically reduced by using an additive manufacturing technique as PMD where near-net shape components are built, and the buy-to-fly ratio is significantly shortened (**Figure 10**).

5.3 Titanium alloys

The low density and high specific stiffness in titanium alloys as Ti6Al4V make the technique of interest for aeronautical and space applications [12, 23] **Figure 11** illustrates one example of fabrication with this material.

To avoid oxidation on titanium alloys, these materials need to be PMD manufactured under a protective atmosphere.

5.4 Aluminum alloys

Aluminum alloys have the characteristic that their oxides have a much higher melting temperature than the not oxidized material. When using a fixed current value to deposit aluminum, the oxide layer will not melt; therefore, the material will not deposit if the current is low. On the other hand, if the current applied is high, the material will overheat, and the weld pool cannot be controlled.

AC current is used to weld aluminum because its positive half cycle provides a “cleaning” action by breaking the oxide layer, and its negative half cycle provides

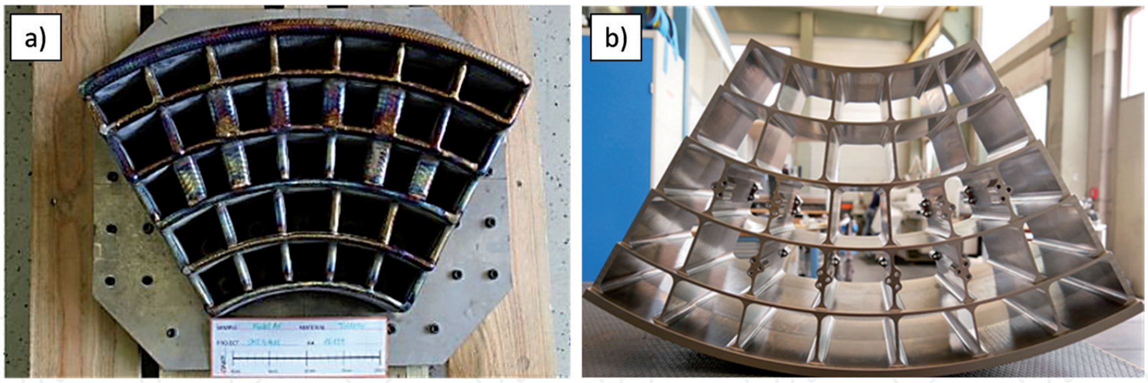

Figure 11.
Ti6Al4V optical bench demonstrator manufactured under the European Space Agency (ESA) activity SME4ALM: a) component as-deposited, b) component after post-process milling.

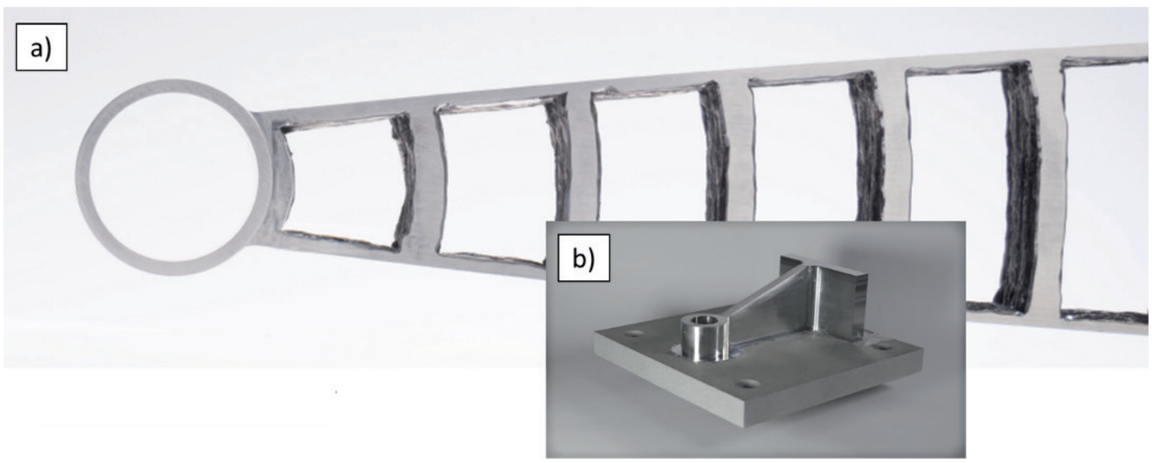

Figure 12.
Two examples of PMD manufactured aluminum alloys components: a) lightweight arm from AlMg5Cr, b) bearing bracket made of AW 5356.

energy input directly on the metal matrix that allows penetration and dilution of the deposited material. The time the positive and the negative half cycle are activated is controlled by the welding parameters known as frequency [Hz] and balance [%]. Two examples of PMD manufactured aluminum are shown in **Figure 12**.

5.5 Magnesium alloys

In addition for the aluminum alloys described above, magnesium alloys' oxides have a higher melting temperature than the matrix material; thus, AC current is needed for PMD deposition (see **Figure 13**) [24].

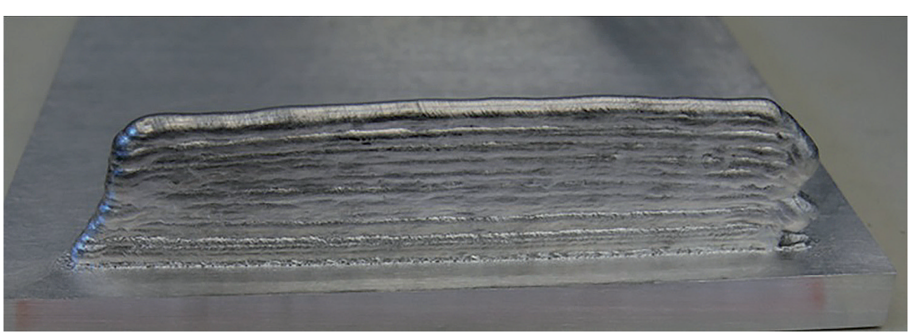

Figure 13.
PMD AZ91 magnesium alloy test specimen.

Furthermore, an extra risk appears if fine magnesium powder is used due to its high flammability and spontaneous firing.

5.6 On-going studies

This manufacturing technique is currently being developed for the processing of composite materials, in particular titanium-matrix composites, using powder material with reinforcement ceramic particles, mainly TiC and B_4C.

There is also work going on producing intermetallic, mixing the elemental component wires, since intermetallic ones do not still exist in the market.

6. Conclusions

To sum up, the PMD additive manufacturing process is an interesting and innovative technology that allows the following (**Figure 14**).

- Manufacturing large-size components: The size limitation is given by the structure where the torch is held.
- High deposition rate: Using welding wires of high diameters combined with the high energy input of the plasma allows the deposition of a considerable amount of material per hour.
- Flexibility: The possibility of using wire feedstock, as well as powder, as starting material gives to the user a large field of possibilities where *in situ* alloying, metal matrix ceramic composites, multi-material components, etc. are possible to manufacture.
- Scalability: The PMD equipment is set up as modular, and the equipment can be enlarged easily depending on the application requirements.
- Economically friendly: building near-net-shape components reduces the manufacturing times and material costs, especially on high-price alloys.

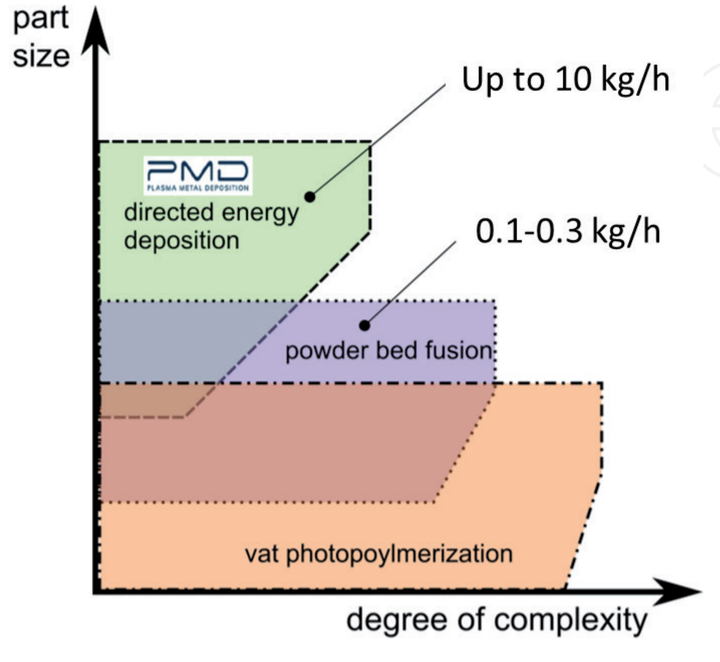

Figure 14.
Scheme of the application range of PMD vs. other additive manufacturing processes.

Conflict of interest

The authors declare no conflict of interest.

Notes/Thanks/Other declarations.

The authors warmly thank the European Space Agency (ESA), who fund the AZ91PMD (n°4,000,122,896/18/NL/BJ/gp) and SME4ALM (n°4,000,121,981/17/NL/BJ/gp) activities; and the European Commission (Horizon 2020) who fund the SUPREME (grant n° 768,612) project, within some of the presented components were carried out.

Author details

Enrique Ariza Galván[1], Isabel Montealegre Meléndez[2]*, Cristina Arévalo Mora[2], Eva María Pérez Soriano[2], Erich Neubauer[1] and Michael Kitzmantel[1]

1 RHP-Technology GmbH, Seibersdorf, Austria

2 Universidad de Sevilla, Seville, Spain

*Address all correspondence to: imontealegre@us.es

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