Chapter 1
Introduction to Additive Manufacturing

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1.1 What is Additive Manufacturing

Modern markets place increasingly stringent requirements on development and production processes. Besides the requirements to improve product quality and the level of flexibility in development and production, additional requirements are being imposed to reduce costs, and in particular to shorten development and production times. A new trend that is increasingly visible in certain segments of the markets is the abandonment of mass production in favour of small-scale, and very often individual (personalized) production.

In order to meet such market demands, modern additive manufacturing processes have been developed and applied since the second half of the 1980s. The main feature of these processes is the addition of material, usually layer by layer, until the entire product is made. Such production principle makes it possible to create a complex product geometry that would be very difficult or impossible to make with other, traditional manufacturing processes. An additional feature of additive processes is manufacturing of products directly from 3D CAD model without the need for additional tools or fixtures.

Historically, modern additive manufacturing processes have undergone several stages with regard to their application and thus terminology has changed. Initially, these procedures were mainly used for rapid prototyping (RP). The term "rapid" should be understood conditionally, because the manufacturing time it takes to

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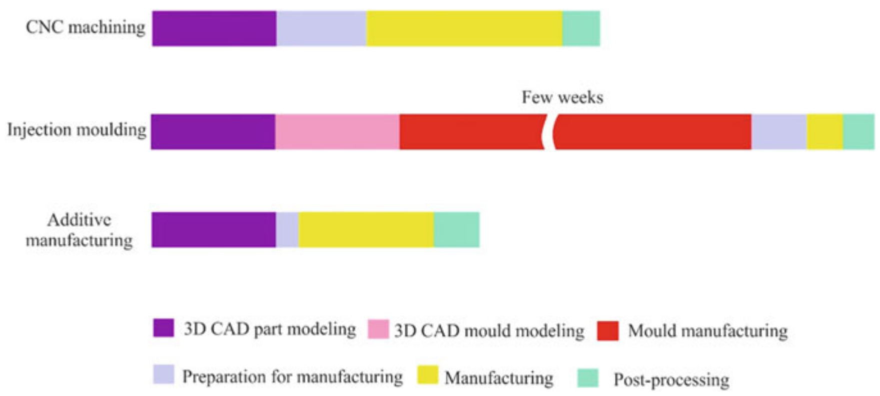

Fig. 1.1 Comparison of production time between classic processing (CNC milling) and AM (PolyJet process) (*Source* Ana Pilipović)

produce (prototypes) depends on the size of the product and on the thickness of the layers of which the product consists. Generally, the time can vary from a few mintus to a few days for production. This in itself is not fast, but when compared to conventional prototyping or conventional manufacturing, there is certainly a time reserve (Fig. 1.1).

The next step in the application of additive procedures is the rapid production of entire tools and moulds or their key elements (Rapid Tooling—RT). It is an application of additive manufacturing processes for the production of polymer, ceramic or metal tools and moulds which, due to the principle of layered building, make it possible to significantly reduce the production time of the most geometrically demanding parts of tools and moulds. When it comes to moulds for injection moulding of polymers, RT processes allow the creation of optimized tempering channels that ideally follow the shape of the mould cavity (Conformal Cooling), which can significantly shorten injection moulding cycle times and increase product quality.

Further development of materials used in additive manufacturing processes has led to the direct production of small batch or single finished products (Rapid Manufacturing—RM). These are procedures that allow manufacturing without the need for additional tools, so in the case of single production or small-scale production, they often present the only reasonable solution.

Additive processes can be divided by four main factors: the type of material, the energy source, the layer formation process, and the shape of the final product. These factors have an impact on the quality of surface finish, dimensional accuracy, mechanical properties, and time and cost of overall production.

After many years of vigorous development and extended application of RP/RT/RM processes, in 2009 an international commission ASTM International Committee F42 was established for additive manufacturing processes, and its first task was to terminologically define these procedures. As the term rapid in the use of additive processes has a relative meaning, the term additive manufacturing (AM) was defined as an umbrella term. The International Commission ASTM International Committee F42 defines additive manufacturing as the process of connecting materials when making objects directly from 3D computer models, usually layer by layer, which is in contrast to the subtractive mode of production.

1.2 Why Do We Need Additive Manufacturing

Additive manufacturing can shorten the time and cost it takes to make a new product from initial concept to production. Additive processes can help identify underlying errors on products that are expensive to correct in the later stages of their production. These processes enable the production of products of complex shapes directly from computer data in a very short time using the most automated processes. Assemblies can be made as one component or from two or more materials in one cycle. As a rule, these are the processes in which a product is built by stacking layers on top of one another, that is, an additive (generative) creation of a product.

Following categories can be strongly influenced by application of AM in product development and production processes:

1. Product Development
   - more iterations in product development are enabled and potential errors and difficulties are easier to spot
   - assemblies and connection points on the product can be checked in advance
   - the strength and durability of the product can be checked in advance
   - planning for product development and production is facilitated
   - product development time is shortened, and prototyping can be a powerful tool in concurrent engineering.
2. Product Quality
   - potential difficulties can be eliminated at the product, tool and mould development stage
   - it is easier to perceive a physical prototype than a blueprint or a computer model.
3. Production
   - it is possible to plan and eliminate potential errors on the elements of the production system
   - it is possible to anticipate possible mould problems in advance and optimize the design of tools and moulds
   - tool and mould elements can have improved thermal properties
   - tool and mould element manufacturing processes allow for uniform tempering (tempering channels can follow product contours).

4. Company's Position on the Market

   – the time from idea to product launch can be shorter and more reliable
   – market research using trusted product copies is much more credible
   – marketing materials for product promotion can be prepared in advance.

Another area for products made by additive manufacturing processes is during product development, primarily to improve the quality of communication between teams of professionals involved in development and to communicate with the market. Special prototypes can be used to analyze compliance with the prescribed standards (national and international) for products, product certification is possible, etc. The role of prototypes is also very important in the early detection of errors and omissions during product development.

Environmental requirements are becoming increasingly stringent today, so when developing a product, it is necessary to take into account the possibilities of its recycling and/or disposal. The use of models and prototypes also plays an important role in this segment. For example, using appropriate models, it is possible to analyze the disassembly of a complicated product or examine the ecological packaging of such a product, all at a very early stage in product development.

The existence of a large number of very rigid product design rules confirms the general opinion that in the classical process of product development and production, tool and mould production phases are the greatest limitation. Additive manufacturing processes, on the other hand, do not require the development and production of tools and moulds, and they provide almost limitless possibilities when it comes to the complexity of product geometry. By eliminating the need to make tools and moulds and the limitations imposed by design rules for classic processing operations, the only constraint in the development of new products becomes the designer's creativity.

Additive manufacturing processes can also be a solution to current trends of mass adaptation to market demands. Production batches are decreasing as new products appear on the market. Many customers want distinctive products that are intended only for them and no one else (product personalization). Additive manufacturing processes are precisely the ones which allow for a more cost-effective approach in cases of production of custom-made products. Since additive processes do not require the manufacture of tools and moulds, large-scale production is not required to depreciate the cost of making tools and moulds. On the other hand, the application of additive processes for direct production must satisfy production requirements such as quality control, traceability and repeatability of quality which is receiving increasing attention in order to bring the quality of products made by additive processes closer to those produced by conventional production processes.

While classic manufacturing processes result in components made from one type of material (with the exception of multi-component injection moulding), some additive processes allow the mixing and grading of materials in a large number of combinations. This leads to completely new opportunities and challenges for designers. The potential applications of Functionally Graded Materials (FGMs) begin with a simple example of a single material creation but with controlled porosity (for example, from

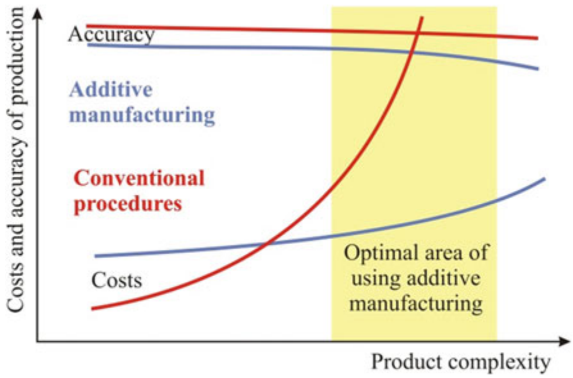

Fig. 1.2 Justification of the application of additive manufacturing (Courtesy of Pero Raos)

a hollow and softer core to a compact and hard surface), or products from two or more different materials. One of the current limitations in this area is the fact that modern CAD modelling programs do not support the development of products made of non-homogeneous materials.

However, products made by additive processes are not cheap. Their price is influenced by: the time of manufacture, the cost of the machine itself and subsequent maintenance, the work of the operator—during the manufacture, post-processing and cleaning, the price of materials and the price of materials for the supporting structure. Sometimes it is difficult to decide when to apply additive manufacturing and how many products to make to maximize their benefits (Fig. 1.2). Based on the cost of development and the accuracy of development and production as a benchmark, it can be concluded that there is an optimal area of application of additive manufacturing. Specifically, as the complexity (geometric and functional) of the future product increases, the costs of development and production with the conventional approach increase exponentially. The most demanding geometric shapes can be made by Additive manufacturing processes, without significantly increasing the cost of production. Therefore, it can be concluded that the justification for using additive manufacturing processes increases with the complexity of the product.

1.3 Additive Manufacturing Classification

Classification of additive manufacturing processes can be made upon several categories. There are a number of additive manufacturing processes which have some similarities in the process, material, machine type, surface finish, geometrical shape, required post-processing, etc. For many years, the additive manufacturing industry lacked categories for grouping AM technologies, which made it challenging educationally and when communicating information in both technical and non-technical settings. These categories enable one to discuss a category of machines, rather than needing to explain an extensive list of commercial variations of a process methodology.

According to the *International Standardisation Organisation* (ISO) and *American Society for Testing and Materials* (ASTM) in ISO/ASTM 52,900, additive manufacturing can be divided in 7 categories (Fig. 1.3).

The processes are classified as follows:

1. Material extrusion (MEX)—an additive manufacturing process in which material is selectively dispensed through a nozzle or orifice
2. Vat photopolymerization (VPP)—an additive manufacturing process in which liquid photopolymer in a vat is selectively cured by light-activated polymerization
3. Material jetting (MJT)—an additive manufacturing process in which droplets of build material are selectively deposited (example materials include photopolymer and wax)
4. Sheet lamination (SHL)—an additive manufacturing process in which sheets of material are bonded to form an object
5. Powder bed fusion (PBF)—an additive manufacturing process in which thermal energy selectively fuses regions of a powder bed
6. Directed energy deposition (DED)—an additive manufacturing process in which focused thermal energy is used to fuse materials by melting as they are being deposited. Focused thermal energy means that an energy source (e.g., laser, electron beam, or plasma arc) is focused to melt the materials being deposited
7. Binder jetting (BJT)—an additive manufacturing process in which a liquid bonding agent is selectively deposited to join powder materials.

In these 7 categories, commonly comercial used additive manufacturing processes are:

1. Material extrusion (MEX): Fused Deposition Modeling/Fused Filament Fabrication (FDM/FFF)

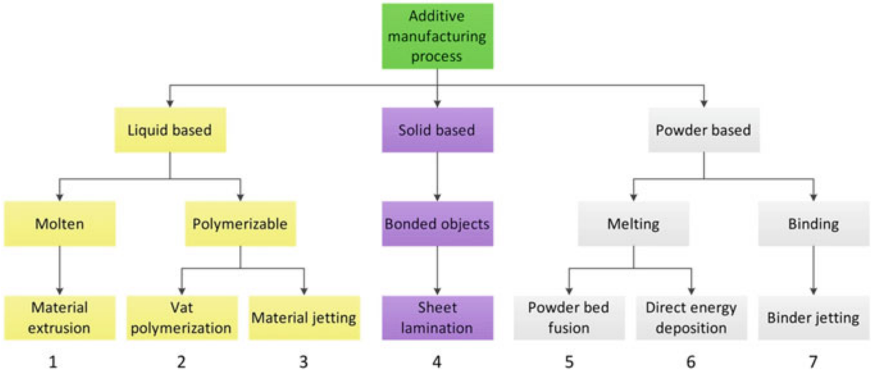

Fig. 1.3 Classification of additive manufacturing according to ISO/ASTM 52,900 (ISO/ASTM)

2. Vat photopolymerization (VPP): Stereolithography (VPP-UVL/P—SLA), Digital Light Processing (VPP-UVM/P—DLP), Continuous Liquid Interface Production (CLIP), Daylight Polymer Printing (DPP)
3. Material jetting (MJT): PolyJet, Drop On Demand (DOD), NanoParticle Jetting (NPJ)
4. Sheet lamination (SHL): Laminated Object Manufacturing (LOM), Selective Lamination Composite Object Manufacturing (SLCOM)
5. Powder bed fusion (PBF): Selective Laser Sintering (PBF-LB/P, SLS), Selective Laser Melting (PBF-LB/M, SLM), Electron Beam Melting (PBF-EB/M, EBM), Multi Jet Fusion (PBF-IrL/P, MJF), Selective Heat Sintering (SHS), High-Speed Sintering (HSS), Selective Mask Sintering (SMS), Selective Inhibition Sintering (SIS)
6. Direct energy deposition (DED): Laser Engineered Net Shaping (LENS), Aerosol Jet, Electron Beam Additive Manufacturing (EBAM), Laser Deposition Welding (LDW) and Hybrid Manufacturing
7. Binder jetting (BJT): 3D Printing (3DP)/ColourJet Printing (CPJ).

1.4 Vat Photopolymerization—VPP

Acrylate-based photopolymers are the first and most used resins developed for vat polymerization (VPP). Later were developed vinyl-ether and epoxy resins. All materials in vat polymerization are subjected to photopolymerization. The strategy behind the 3D photopolymerization is based on using monomers/oligomers in a liquid state that can be cured/photopolymerized upon exposure to light source of specific wavelength and form thermosets. A photoinitiator (with relatively high absorption coefficient) is required to convert photolytic energy into the reactive species (radical or cation) which can drive the chain growth via radical or cationic mechanism. The acrylates use a free-radical method, and epoxies and vinyl ethers use cationic method for polymerization. The polymerization can be shown schematically in 3 steps (Fig. 1.4).

Use of (meth)acrylate-based resins has proved effective in 3D photopolymerization, but they have certain disadvantages:

– These resins tend to undergo shrinkage during the polymerization. Pure (meth)acrylate resins tend to gel at low conversions depending on the functionality of the monomer used. This phenomenon would normally result in a very limited flow of the remaining uncured resin. Further photopolymerization above this conversion would lead to an increase in shrinkage stress with each newly formed bond. Depending on the molecular structure of the monomer/oligomer, the amount of shrinkage varies. Shrinkage and associated stress might result in curling and deformation during the layer-by-layer VPP
– Most of the (meth)acrylate-based photocurable resins contain multifunctional monomers which experience autoacceleration in the early phase of the chain growth (free radical) polymerization due to the fact that termination reactions are mobility restricted. The high kinetic chain length would result in the formation

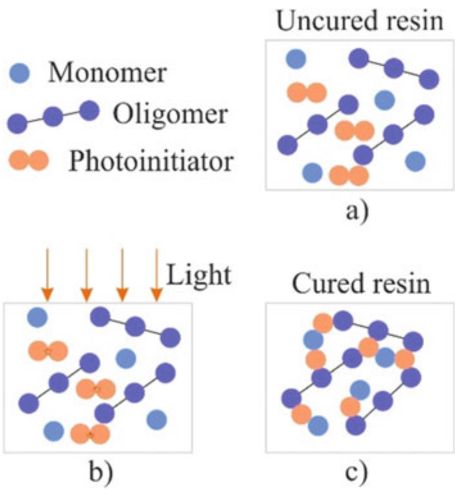

Fig. 1.4 Polymerization process (*Source* Ana Pilipović)

of networks with low uniformity and high brittleness, which is less efficient in dissipating stress, and therefore, cracks might propagate more readily.
– oxygen inhibition in the open vat.

Strategies to reduce the shrinkage are:

– the use of high molecular weight oligomeric acrylates (with less reactive group concentration) can reduce the shrinkage percentage; however, heating is required (during the 3D process) to reduce the high viscosity of these resins.
– the use of a radical step growth mechanism as an alternative to the chain growth polymerization.

To reduce brittleness:

– the use of chain transfer agents in regulating photocurable resins showed the ability to tune the cross-linking density, average kinetic chain length, and distribution of crosslinks alongside the backbone.

To lessen the oxygen inhibition:

– use of additives - but for resins containing both (meth)acrylate and epoxy might result in discolouration of the cured material.

The interest in using epoxide and vinyl ether monomers originates from their low volumetric shrinkage (~3%) that occurs during photopolymerization.

1.4.1 Stereolithography—VPP-UVL/P (SLA)

In the late 1970s and early 1980s, the concept of rapid prototype production began, based on the selective crosslinking of a photopolymer surface layer and the production of three-dimensional objects with consecutive layers. The process was called stereolithography, and in 1987 began the production of the first stereolithographic machines, i.e. the first machines in the field of additive manufacturing.

The principle of stereolithography is that the photopolymer solidifies when exposed to a light source. The build platform is located only one layer of thickness below the top of the liquid polymer surface. Helium cadmium (He-Cd) or argon (Ar) laser generates and focuses UV light and scans the polymer layer above the curing substrate. This step starts with the bottom section of the product. The build platform is then lowered down by the thickness of the next layer. The sweeper is used to avoid air bubbles in the product. As the product is being made in a liquid, it is necessary to secure its position by means of a support structure that is removed after the process is completed. The process is repeated until the final production of the whole product. The product is removed from the liquid polymer, and the excess polymer is washed in the solvent to obtain a so-called green phase. Subsequent curing takes place for a minimum of one hour. This step is necessary because some fluid can retain in layers.

Stereolithography process is shown in Fig. 1.5.

Recently, the production of multicolour products has become increasingly interesting to more users (e.g. in medicine). Therefore, a modified stereolithography procedure has been developed that enables the production of (for now) two-coloured products. The process consists of two steps. In the first step, a transparent photopolymer that forms the exterior of the product hardens, and in a second step a photopolymer mixed with pigments that forms the interior of the product. After the first step, the build platform on which the product is built is raised above the level

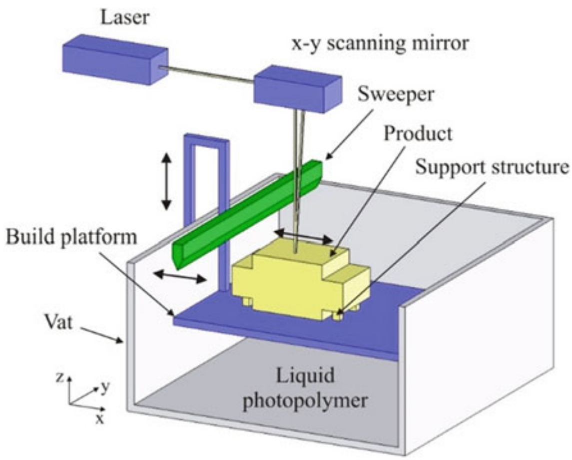

Fig. 1.5 Stereolithography (VPP-UVL/P) (*Source* Ana Pilipović)

of the photopolymer and the excess transparent photopolymer is removed. Subsequently, a coloured photopolymer is supplied to the production chamber using a special system. The laser outlines the required outlines on the coloured photopolymer and, after curing, the non-solidified photopolymer is removed and a transparent photopolymer is supplied. The substrate is lowered by one layer thickness compared to the position at the beginning of the previous step and the process is repeated.

The advantages of the VPP-UVL/P process are: combination of speed, precision (0.04 mm) and finish quality, very fine details (high resolution), machines produce very thin layers of 0.05 mm to 0.15 mm thickness, high productivity and production of transparent products.

The disadvantages of the VPP-UVL/P process are: high cost of materials, use of support structure, materials must be properly stored to prevent premature polymerization, possibility of using a narrow group of materials (photopolymers only), shrinkage of polymers after curing causes warpage and curling of the product, the product can be quite brittle, liquid material can be trapped in closed surfaces of the products, special space is required for the device because photopolymers develop harmful gases, post-processing like cross-linking of photopolymers and removal of the supporting structure is required, expensive laser maintenance.

Stereolithography products are used as prototypes, functional products, tooling models, injection moulding models, investment casting and sand casting models.

The following materials are used in stereolithography: poly(methyl methacrylate), epoxy resin, as well as materials having properties similar to polyethylene, polypropylene, polyamide 66, acrylonitrile/butadiene/styrene, polycarbonate and poly(butylene terephthalate). It is also possible to use a nanocomposites, as well as to use photopolymers (acrylic or epoxy resins) filled with metal or ceramic powder or particles. However, when using such composite materials of metal and ceramics, the removal of the polymeric binder at temperatures from 400 to 500 °C and final sintering of the filler particles at a temperature of about 1200 °C or higher is required after the stereolithography process. Figure 1.6a shows some products made using

a) b)

Fig. 1.6 Products made by the VPP-UVL/P process: **a** transparent Accura Phoenix **b** the bridge (Photo by Ana Pilipović) stereolithography. Figure 1.6b shows a large structure where it is particularly difficult to optimally remove the supporting structure.

1.4.2 Vat Photopolymerisation Digital Light Processing—VPP-UVM/P (DLP)

In the process of curing a photosensitive acrylic resin using a digitally processed light signal, the projected image from the VPP-UVM/P light source represents a cross-section of the product that cures in the polymer resin. Visible light is projected below the build surface. The device illuminates the entire layer at once, reducing the total cycle time (10 to 15 s depending on the polymer).

The projector is located under the build platform. The resin is contained in a glass-enclosed chamber that covers the projector. The first layer of the product is made on the bottom surface of the resin, which cures by the light projected from the projector. The build platform raises by the thickness of the new layer and the process starts from the beginning (Fig. 1.7).

During the process, millions of digital mirrors (1280 × 1024 pixels resolution) housed in a digital projector housing generate an image mask of each layer. Mirrors direct light through a mask that transmits some of the light at precisely defined locations, thereby achieving a controlled cure of the acrylic photopolymer. Thereby

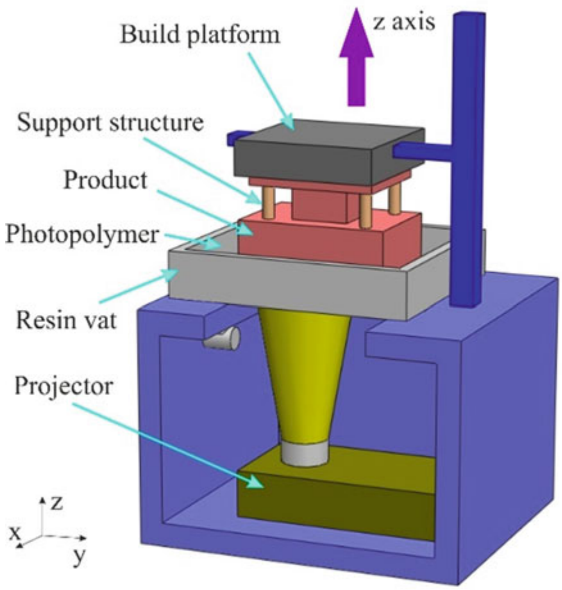

Fig. 1.7 Digital light processing (VPP-UVM/P) (*Source* Ana Pilipović)

a) b)

Fig. 1.8 Application of the VPP-UVM/P: **a** in dentistry, **b** for jewellery (Photo by Ana Pilipović)

the entire layer is simultaneously exposed to light and the curing is achieved in one step.

The advantages of the process are: quick and easy material change, the ability to apply a large amount of photosensitive materials (epoxy and acrylic resin, nano-composites, ceramic composites, photopolymer with wax content), as well as biocompatible materials.

The disadvantages of the process are: given the small size of the chamber, the process is only suitable for small-scale products and support structure is required.

The most common application of the procedure is in dentistry, medicine and jewellery (Fig. 1.8).

1.5 Material Jetting (MJT)

In material jetting (MJT) the liquid material is solidified through a process of photopolymerization. This is the same mechanism that is used in vat polymerization. Similarly to VPP-UVL/P, material jetted parts have homogeneous mechanical and thermal properties, but unlike VPP-UVL/P they do not require additional post-curing to achieve their optimal properties, due to the very small layer height used (16–32 μm). The materials used in MJT are thermoset photopolymers (acrylics) that come in a liquid form. Materials can be fully transparent and mimic ABS and rubber. Because material is sensitive to light, properties of the products can change over time.

1.5.1 PolyJet

PolyJet technology (Fig. 1.9) was developed in 2000, combining the good sides of stereolithography (VPP-UVL/P) and 3D printing.

The multi-nozzle printing head moves back and forth along y-axis and applies prints a layer of photosensitive polymeric material onto a 16 μm thick substrate, which is approximately 1/5 the thickness of the stereolithographic layer. Each layer of photosensitive polymer hardens under UV light, immediately after application, forming a fully cured product, without the need for subsequent curing. Liquid resin is heated to 30–70 °C to achieve optimal viscosity for printing. Two different materials are used: one for the model and the other for the support structure, i.e. half of the nozzles apply the material to the model and the other half to the support structure. After the first layer is completed, the build platform is lowered by the thickness of the next layer and the print head begins to create the next layer. After the product is made, the support structure (gel material) is easily removed with water at a pressure of 40 bar or manually, which depends on the shape, i.e. geometry of the product. Thin-walled and small products are cleaned at lower pressures and robust ones at high pressures, thus shortening the cleaning time.

The low layer thickness ensures the fabrication of a product with a very smooth surface, which requires no further processing. Finished products can be treated with particle jet, polished, sanded, painted, etc. Prototypes can be used as models for the production of silicone moulds for resin infusion process using a special combustion chamber.

The advantages of the process are: high quality (due to the very thin layer the products are very precise and have a very smooth finish), the ability to produce small details and thin walls, application in offices (there is no contact with the resin, the support structure is removed by water), the process is fast, no subsequent curing is required, it is possible to use different materials that provide different geometry, mechanical properties and colour. The great advantage of the PolyJet technology is, as with stereolithography, the production of transparent products.

The process is used in automotive, electronics, toy, footwear, consumer goods and jewellery industries.

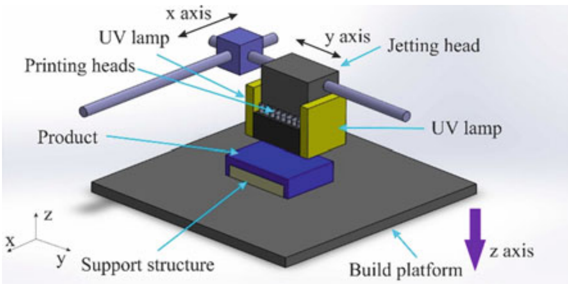

Fig. 1.9 PolyJet (*Source* Ana Pilipović)

Fig. 1.10 Product made with digital materials (Courtesy of Stratasys)

A newer version of the process, *PolyJet Matrix*, allows the mixing of materials and printing any two available materials (Digital Materials) simultaneously to achieve the target properties of the finished product (e.g. strength, elongation, hardness) (Fig. 1.10). Digital materials are designed in the computer, and it is possible to make products by combining different materials (e.g. rigid and flexible). The disadvantage of such a technology is the high cost of the printer. The building materials and support materials are separately supplied to synchronized printing heads. Each of the heads has 96 nozzles, through which the materials are injected into the workspace.

The advantages of the *PolyJet Matrix* technology over comparable technologies are: the possibility of making composite products with properties comparable to real products, a wide variety of black and white materials as well as coloured materials is possible, which enhances the visualization potential of the product. Also, there is no need for assembling of individual elements of the prototype set, and the technology is particularly suitable for developing injection moulded products and moulds for multi-component injection moulding.

The materials used in the PolyJet process are listed below.

FullCure photopolymer acrylic materials allow 3D models to be produced with high precision and fine detail. The variety of resins in the FullCure material palette offers the properties of transparency, colour, opacity, flexibility and rigidity. There are *FullCure 720, VeroBlue, VeroWhite, VeroGray, VeroBlack, VeroClear, Rigur, DurusWhite, TangoPlus, TangoBlackPlus, TangoGray*, and *TangoBlack* materials.

FullCure 720 is a transparent acrylic photopolymer suitable for rigid models. Advantages of the material include no post-treatment required, ultimate elongation of 20%, good flexural toughness, and the ability to machine, drill and chrome.

Vero materials are opaque coloured materials that allow fine detailing and reduce the need for colouring. They have excellent flexural strength and flexural modulus. VeroBlack is a material with a high flexural modulus and high moisture resistance, making it suitable for many applications. Opaque black allows for electronics use. *VeroGray* has excellent dimensional accuracy, low water absorption, high flexural strength (95 MPa) and flexural modulus. It is used in the automotive industry, for toy manufacturing, in medicine, electronics, etc.

DurusWhite is a material that has properties similar to polypropylene and possesses good flexibility, strength and toughness.

Tango materials have excellent ultimate elongation > 50%), flexibility and elasticity. There are *TangoBlack*, which provides maximum elasticity with a hardness of 61 Shore, *TangoGray*, which is a little stiffer (75 Shore), and *TangoPlus* with ultimate elongation of 218%.

Using the *PolyJet* technology, it is possible to make a product made of a material resistant to temperatures up to 80° C, which is called *ABS Like*, i.e. it has properties similar to ABS. It is often used to manufacture injection moulds (Fig. 1.11) that can withstand batches of up to 100 pieces.

More recently, coloured materials *VeroCyan*, *VeroMagenta* and *VeroYellow* have appeared on the market, which can also be combined with *Tango* materials to produce a flexible, coloured product (Fig. 1.12).

In PolyJet it is possible to make products with a glossy and matte finish. In the glossy setting, support material is added only when it is structurally required (i.e. for overhangs). Surfaces not in direct contact with support will have a glossy finish, while supported areas will be matte. The glossy should be used when a smooth shiny

Fig. 1.11 Injection mould made by PolyJet Matrix (Courtesy of Stratasys)

Fig. 1.12 Product made with digital materials: combination of Vero and Tango materials (Courtesy of Stratasys)

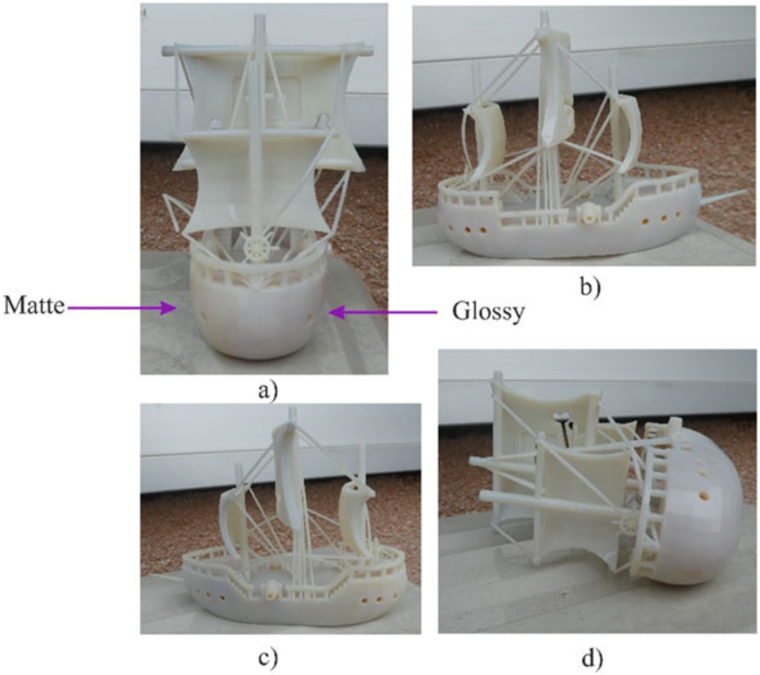

Fig. 1.13 A part printed in: **a** half glossy, half matte, showing the difference in surface finish, **b** glossy surface, **c** matte surface, **d** orientation during production (Photo by Ana Pilipović)

surface is desired. The cost of printing glossy is lower, as less material is used. The drawbacks of using this setting are the non-uniform finish of the printed parts and the slight rounding of the sharp edges and corners on the top, glossy surfaces. In the matte setting, a thin layer of support material is added around all the whole part, regardless of orientation or structural requirements. This way all surfaces have a matte finish. The matte should be used when accuracy and uniform surface finish are a requirement. The cost of the matte setting is slightly higher, as more materials are used and additional post-processing time is required. Notably, parts printed in the matte setting also have a relatively lower surface hardness (Fig. 1.13).

1.6 Binder Jetting (BJT)

Binder jetting (BJT) is process in which polymer, metal and sand products are commonly made. Metal-based binder jetting parts have relatively good mechanical properties thanks to the infiltration or sintering processes. They are also more cost-effective than PBF-LB/M (SLM) metal parts but have poorer mechanical properties because the grains of materials do not entirely fuse together. Compared to Laser

Beam Powder Bed Fusion (PBF-LB) in the BJT method parts are printed without heat so there is no differential cooling and therefore no warping and good dimensional accuracy. However, there are potential shrinkage issues during the infiltration or sintering processes. These are hard to predict and can cause parts to shrink by 0.8–2% of the part's total size.

Post-processing is often required to make the part stronger and give the binder-material better mechanical and structural properties. Some materials, like sand, require no additional processing. After printing, the parts are in a green, or unfinished, state and require additional post processing before they are ready to use. Often an infiltrate substance is added to improve the mechanical properties of the parts. The infiltrate substance is usually epoxy (in case of polymers), a cyanoacrylate adhesive (in case of ceramics) or bronze (in the case of metals). Another strategy is to put the product, in its green state, inside an oven to achieve a sintering of the grains of matter.

The build material is in powder form and binder is usually in liquid form. For build material it can be used metals (stainless steel, tool steel, steel/bronze, tungsten/bronze, cobalt chrome, copper, Inconel (nickel-chrome), titanium), sand, ceramics and polymers (PMMA). There are various types of binder materials, each suited for a specific application, like furan binder (for sand casting applications), phenolic binder (for sand moulds and cores), silicate binder (environmentally-friendly, for sand moulds and cores) and aqueous-based binder (for metals).

The binder, in the first place must be printable. An ideal binder would have low viscosity which allows the stream of individual droplet beads to form and then break off from the nozzles rapidly. Also, binder must have stability against the large shear stress induced by printing. Additional criteria include good powder interaction, clean burn out characteristics, long shelf life, and acceptable environmental risk.

1.6.1 3D Printing 3DP

3D printing got its name because of its similarity to ink-jet printing. In 3D printing (Fig. 1.14), binder or glue is ejected instead of ink. The build platform is positioned at a height necessary to place the powder layer on the substrate to the desired thickness. Typically, approximately 30% more powder per layer is applied to ensure good powder coverage on the build platform. The powder layer is selectively scanned by a 3D printer head that releases liquid binder and causes the powder particles/layers to adhere to each other. The nozzle head scans the powder to the desired cross-sectional shape. This starts with the lower cross section. The build platform is lowered for the thickness of the new layer. The new layer is scanned, adapting to the shape of the next upper section and adhering to the previous layer. The process is repeated until the top layer is made. Production time depends on the height of the product. After fabrication, the product is left in the powder chamber for some time to reach the required strength, then removed and the excess powder is removed with air. A subsequent tempering

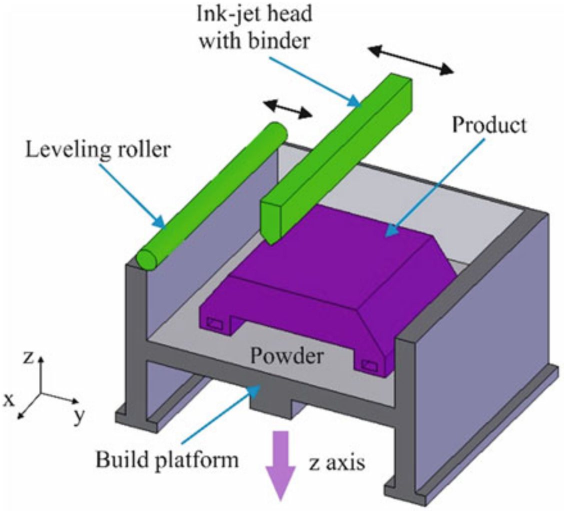

Fig. 1.14 3D printing process (*Source* Ana Pilipović)

process (10 min at 95 °C) and infiltration of wax, epoxy or cyanoacrylate is applied to harden the product.

An important advantage of 3D printing is the ability to create coloured products. Similar to 2D printing, the computer converts RGB colours (red, green, blue) to CMYK colours (cyan, magenta, yellow and black). Applying these four inks, the printer combines several dots into each printed pixel to produce a thousand colours. The same principle applies to 3D printing, that is, the binder can be ejected from a multi-nozzle head, with different materials, i.e. colours, in each nozzle (Fig. 1.15).

The result is almost complete density products that can be further processed or polished if necessary.

Fig. 1.15 Product with multiple colour combination (Photo by Ana Pilipović)

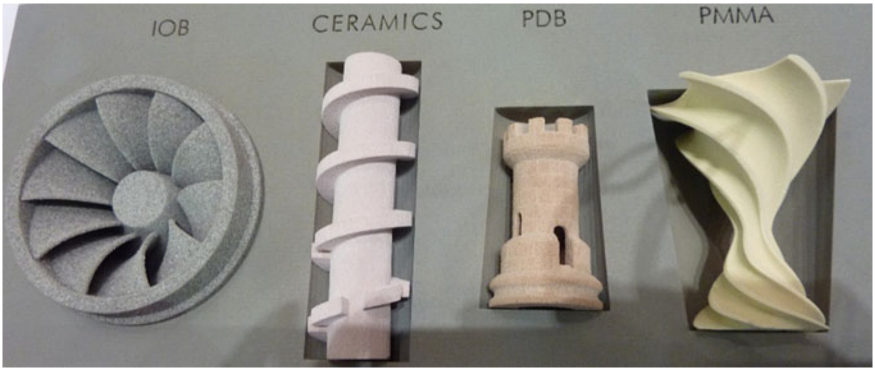

Fig. 1.16 Different materials for 3DP (Photo by Ana Pilipović)

Advantages of 3D printing process are: high speed of machine operation, possibility of usage of machines in offices (non-toxic materials), high precision of the printer, good dimensional tolerances of the products, possibility of printing of coloured materials, possibility of making very thin layers, low cost, no use of support structure is required, it does not require high energy for manufacturing, already used material can be reused.

The disadvantages of the process are: limited product dimensions, limited number of materials used and production speeds, poorer accuracy compared to other processes for large-sized products, high roughness, which requires additional machining, it takes some time to clean the product, products are after manufacturing fragile so they need to be further hardened with cyanoacrylate or epoxy adhesives.

Polymer materials used in 3D printing are: poly(methyl methacrylate) (Fig. 1.16), epoxy resin, and high strength and flexible polyurethane that is resistant to impact loads. Composite materials can also be used, especially for products with small details. The material consists of polymers with several additives that increase the surface finish quality, resolution, toughness and strength of the product. Such materials can be printed in different colours and is an ideal choice for delicate and thin-walled products, coloured products, accurate detailing and for the fabrication of products requiring high strength.

Fine casting materials are used to produce products that can be dipped in wax. The material consists of a mixture of cellulose, special fibres and other additives that allow the dimensions of the product to be accurate while increasing the absorption of wax and reducing the residue during the combustion process.

Direct casting material is used to make sand moulds (Fig. 1.17) for non-ferrous materials, as well as to make moulds into which metal can be directly casted, which is faster and less expensive compared to conventional metal casting processes. This material is a mixture of sand, gypsum and other additives that together result in high strength moulds with a good finish. The materials withstand the temperatures required for polymer casting.

Fig. 1.17 Sand moulds made with binder jetting (Photo by Ana Pilipović)

The elastomeric material allows the elastic parts of the product to be made. The material consists of a mixture of cellulose, special fibres and other additives that allow for the production of precision elastic parts.

Metal matrix composites are formed by infiltrating bronze into stainless steel. They have very good mechanical properties and are low in cost. They are used for construction products. Nickel has excellent chemical resistance and is used at elevated temperatures.

Loading new material into a 3D printer is a quick and easy process. All unused materials are recyclable, reducing the cost of the product.

3D printing can successfully produce prototypes, products, moulds and tools of very complex shapes. It was the first time that a mould of ceramic powders was made. When making moulds and tools made of metal powders, significant savings are achieved on production time and the cost of expensive post-processing.

1.7 Powder Bed Fusion Technologies (PBF)

1.7.1 Introduction to Powder Bed Fusion Technologies

Nowadays the additive manufacturing market offers a wide variety of AM technologies based on both metal and polymeric powders. These technologies evolve quite fast bringing new features and specs that make them more reliable, faster and more accurate. Hence, we can find more industrial applications of additive manufacturing, not only for rapid prototyping and design validation but also for final-use parts and industrial productions.

Powder based additive manufacturing is a technique of layer by layer manufacturing where an energy source is applied to melt or sinter metal, polymer and ceramic based materials.

Technologies reviewed in this book are the following:

- PBF-EB/M (Electron Beam Powder Bed Fusion of Metals) (or EBM—Electron Beam Melting)
- PBF-LB/M (Laser Beam Powder Bed Fusion of Metals) (or SLM—Selective Laser Melting)
- PBF-LP/P (Laser Beam Powder Bed Fusion of Polymers) (or SLS—Selective Laser Sintering)
- PBF-IrL/P (Powder Bed Fusion of Polymers with Infrared Light) (or MJF—Multi Jet Fusion).

Powder Bed Fusion Principles

Powder bed technologies use fine particles of different nature (metallic, ceramic or polymeric) as feedstock, we can find that depending on the am technique, they are provided with different power sources which aim is to consolidate the material creating 3D printed parts from fine powder layer by layer.

These AM technologies allows the production of very complex geometries using a heat source to fuse the powder particles layer by layer transforming the feedstock into solid parts.

Normally the PBF technologies work under a protected atmosphere so that the feedstock is processed in the right conditions avoiding oxidation during the process and therefore making possible that the powder can be used again after each build. Altough AM scenario is continuously evolving and different groundbreaking energy sources are being launched, PBF technologies use the following standard energy sources so as to selectively sinter the powders (Table 1.1).

Powder Bed technologies provide us with certain design freedom that varies depending on the technology and the materials to be processed, as general benefit of AM in comparison with traditional methods, we can create very complex geometries,

Table 1.1 Type of power source depending on PBF technology

	PBF-EB/M (EBM)	PBF-LB/M (SLM)	MBJT	PBF-IrL/P (MJF)	PBF-LB/P (SLS)
Power source	Electron beam gun	Laser beam (Fiber)	UV light source + furnace	UV light source	Laser beam (CO2)

inner channels and connections thanks to this design freedom that AM brings. Nevertheless, as in any process, AM technologies present also some kind of limitations that are gathered afterwards.

As a general overview of PBF technologies, they are all provided with powder tanks/deposits where the fine particles are picked up and delivered every layer by a raking system designed specifically for each process. Machines are also provided with a build platform that moves down as well as an energy source that sometimes is a punctual beam and sometimes heating lamps made up of UV bulbs. Although there are some "closed software" machines, we can normally adjust a wide variety of parameters within the process that enable us the development of new materials for AM.

In the PBF process the phenomenon called "melt pool" appears in a very small area where the laser source is describing the melting pattern. However nowadays we find very fast technologies based on heating bulbs as the Multi Jet Fusion Technology from HP where there is not a specific sintering/melting spot but the whole layer sintered at the same time.

Melt pool behaviour and energy deposition will vary depending on the process parameters and of course every material will require specific sets of processing parameters.

1.7.2 Electron Beam Technology (PBF-EB/M)

PBF-EB/M uses high-energy electron beam to fuse metal powders. The process takes part under a very high vacuum environment which allows reducing oxygen content during the heating-melting process. The production rates of the PBF-EB/M are much faster than the PBF-LB/M because of the high beam speed and the layer thickness parameter (higher than PBF-LB/M due to bigger particle size distribution in comparison with PBF-LB/M). Process is carried out while the powder and build platform is preheated so that parts manufactured by PBF-EB/M have neither internal stresses nor distortions. Process temperatures can vary depending on the material to be processed.

Since the particle size distribution (PSD) of PBF-EB/M is bigger, the feedstock used in this technology is cheaper than the one used in PBF-LB/M (sieving yields are more optimistic for bigger particles). As drawbacks, since the process is done while preheating, the "cake" obtained once the build ends is made up of parts surrounded by slightly sintered powder which makes difficult the part cleaning, especially when there is presence of small ducts and channels where powder remains trapped, for this reason a powder recovery systems (PRS) is required in the PBF-EB/M process, the aim of this so-called "PRS" is to blast powder from the same nature that the one processed in order to remove the sintered powder attached to the processed parts. Moreover, due to the increased size of particles in comparison with LPBF particles, surface roughness is especially accentuated in PBF-EB/M parts.

PBF-EB/M Components

In the PBF-EB/M production chain we will find the components pointed out in the following lines, all of them must be ATEX (Atmospheres EXplosible) approved:

– PBF-EB/M Machine: (3D Printer) core of the process where the parts are produced inside the high vacuum cabinet.
– Loading trolley: powder is stored in two hoppers that deliver a small amount of material to cover the build area each layer, the trolley is needed to handle the hoppers that can weigh between 40–80 kg.
– Powder Recovery System (PRS): (sandblasting equipment) the same powder used during the fabrication is also applied at high speed in this PRS in order to remove the sintered powder sticking to the parts. This powder is used again in further builds.
– Vacuum cleaner: after each build, the PBF-EB/M cabinet is opened and must be cleaned up from powder present all over the chamber. Powder recovered by the vacuum cleaner is sieved and used again in further builds.

PBF-EB/M machines are made up of three basic units: EB-Gun cabinet where the e-beam is generated, build chamber where the parts are built and control unit where the technicians manage the process parameters and mechanical adjustments. Giving a closer look at the PBF-EB/M Chamber, we can see two hoppers (tanks where the powder is stored before any build starts) and a heat shield placed just beneath the build area. The heat shield is a metal-plate structure necessary to keep the upper surface and the powder cake at a certain temperature during the whole build, this part prevents the damage of other componentes placed inside the chamber.

Regarding the build area, a rake is in charge of the powder delivery, it moves from one hopper to the oher picking a specific amount of powder that is deposited in the melting area where the parts are built. An overview of the PBF-EB/M technology is presented in Fig. 1.18.

On the other hand, the EB-Gun is made up of different kind of "lenses" present along the beam EB-Colum, focusing lens is aimed to increase or decrease the diameter

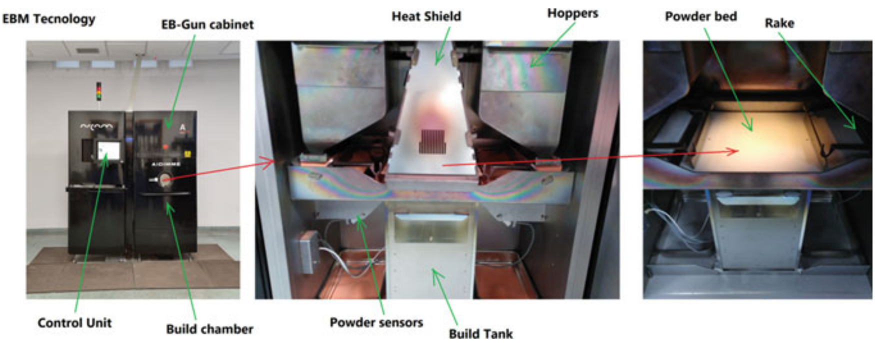

Fig. 1.18 PBF-EB/M overview (*Source* AIDIMME facilities)

of the spot. This parameter gives us the opportunity to modify the energy denisity deposited, whereas the deflection lens is aimed to describe the melting patterns stored in the layered file. These are not really lenses but magnets that distort the electron beam shape before it hits the powder bed.

Regarding the materials that PBF-EB/M is used to process, Arcam has the monopoly of EB technologies, and they are offering specific machines for specific materials as TiAl. But by large Ti based alloys and CoCr are the standard alloys.

It does not mean that the machines are not able to process other materials, as it has been demonstrated by AIDIMME several times, process (not only software but also hardware) can be adjusted so that the machine deals with nonstandard materials as pure Copper, Nickel based superalloys, and nanomodified Ti64 between others.

PBF-EB/M Workflow

Process starts from the very fist step of machine preparation where the technician cleans the build chamber from the previous build; it requires specific tools and liquids specially designed in order not to damage the components. During this fist step, powder that might have been spreaded within the chamber must be removed using an ATEX vacuum cleaner.

Once the machine has been cleaned up, there are certain short-term replaceable parts that must be doublechecked and changed if necessary, as the filament, the heat shield plates or rake plates and the thermo couple and ground wire. Technician must doublecheck the state of those parts as a preventive action in order to avoid possible issues. Provided that the machine is clean and the spare parts changed powder hoppers full of material are introduced into their clamping system, some powder is delivered by the rake so as to perform what in AM we call "bed levelling" in addition a beam calibration and powder measuring sensors calibration are mandatory as well.

Build preparation must be carried out by experienced technicians since a proper procedure will lead to a flawless build.

Once the machine is prepared and the powder loaded, air is pumped outside of the chamber until vacuum gauges reach a certain value. High vacuum is required in order not to damage the raw material and get good results in the consolidated parts.

Parallel to the tasks described below, the job file is prepared. The technician allocates the parts inside the build volume trying to face them in an optimal position, this is so important since many support structures can be replaced by positioning the part in a strategic place. Three different softwares are used to prepare a job file:

- Materialise Magics: is used to put the parts inside the build envelopment, support structures can be tailored in Magics for different materials and also for different technologies, during the allocating process the scale factors are applied to each model in order to compensate possible part distortions, these scale factors are controlled each build. Supports and scturtures are generated in Magics.
- Build assembler: is used to generate the project file (Arcam Build File). The model generated in the previous "Magics" step is loaded into this software in order to separate the different geometries (wafer, support, melt) so that specific process

parameters are usead for each kind of geometry, layer thickness is also set in this step.
- PBF-EB/M Control software simulator: prior to running a job, the build must be simulated so as to prevent possible issues as defects in the layering or supports. This step is carried out in order to verify the build file. In the PBF-EB/M simulator the technician is able to doublecheck every single layer of the build.

Once the 3D models are layered and loaded into the EB-Build software, a first step of start plate preheating takes part, this task is aimed to ramp up the temperature of the build platform that will be kept withing the entire build by several preheatings performed on the top surface of every single layer. Part construction phase is dividided into various steps as: powder preheating, contour melting, hatch melting, and wafer (supports and structures). During this phase a huge amount of variables and complex formulas modify the energy deposition depending on the trajectories to be described.

Once the process completes the last layer, a controlled cooling-down phase takes place. When the bottom temperature reaches a certain low temperature, machine can be opened and cake recovered. This cake full of semi-sintered powder is sandblasted and parts appear attached to the build platform by the support structures that are removed afterwards.

Many variables are controlled during the process and can be assessed in order to troubleshout possible issues that sometimes arise. A log file as well as a report is generated after the process in order to evaluate these variables.

Last but not least, when it comes to process parameter development for nonstandard materials, the user is able to modify plenty of variables such as scanning speed, focus offset, line offset, beam current, process temperature, number of contours, layer thickness and many other complex functions that affects the results obtained in the molten material.

1.7.3 Laser Melting (PBF-LB/M) Technology

Laser based powder bed technologies (PBF-LB/M) are the most common and extended metal additive manufacturing nowadays. These Additive Manufacturing machines offer different specifications such as as low temperature preheating, mutiple lasers, very small area for fine detailed parts and huge build envelopments for bigger parts.

PBF-LB/M uses similar principles as PBF-EB/M since both selectively melt the powder bed that is delivered layer by layer. However, there are some important diferences between these metal AM technologies.

Particle Size Distribution of PBF-LB/M powder is finer ((15–53 μm or 20–63 μm) therefore layer thickness parameter in this technology is slightly thinner than in PBF-EB/M. Foreseeably the parts obtained by laser-based technologies present better surface roughness but on the other hand the production rates are longer and the feedstock prices higher (sieving yields of finer particles are lower). PBF-LB/M technologies work under protected atmosphere, normally Ar or N, but in this case the chamber is at room temperature or low preheating temperatures up to 400 °C, which means that parts suffer from internal stresses and therefore post heat treatments are necessary to be applied as post processes. Nonetheless working at room temperature brings some benefits as non sintered powder nearby the processed parts, this eases the powder removal from the inner channels/geometries. Hence, we can manufacture very complex internal geometries because non melted powder is easy to remove afterwards.

PBF-LB/M Components

Laser based machines are made up of the build unit itself, a protective gas generator or deposit and the powder recovery system that gathers the non melted material and sieves possible contaminating particles.

- PBF-LB/M Machine (3D Printer): core of the process where the parts are produced. Latest laser based technologies lauched are equipped with a closed powder control loop in charge of the powder handling and storing.
- Powder Recovery System: powder recovered after each build is used again in further builds.
- Protective gas deposit/generator: provides the machine with inert gas so as to generate the protective atmosphere during the whole process.

Inside the build chamber, we can find the build tank where the build platform moves downwards and the powder deposits. Layer by layer the squeegee blade picks a cerain amount of powder that is delivered into the build envelopment.

An overview of the PBF-LB/M technology is presented in Fig. 1.19.

Most parts of the PBF-LB/M machines offered in the market are equipped with a fiber laser which works in a wavelength of 1064 nm (red spectrum laser). This is so because the absorption values of the standard materials present good values at this wavelength levels. Nevertheless, latest developments show that lasers of different wavelengths as the green laser (505 nm) can be usefull for specific materials which present low absorption.

Regarding the standard materials that Laser based technologies are used to process, we can find stainless steel 316, aluminium, titanium alloys, maraging stells, copper alloys, 17-4ph, chromium cobalt or inconels between others.

PBF-LB/M Workflow

As pointed out in the PBF-EB/M section, the first step in laser-based technologies is machine preparation and build job assembly, technicians must clean the machine up and make sure that the powder is properly stored in the deposits of the PBF-LB/M machine. Short-term spare parts must be changed as well, in this process the squeegee blade must be double-checked since it could have been damaged while delivering powder during the build.

Bed levelling process must be carried out in order to ensure good weldability in the very first layers and chamber inertization as well.

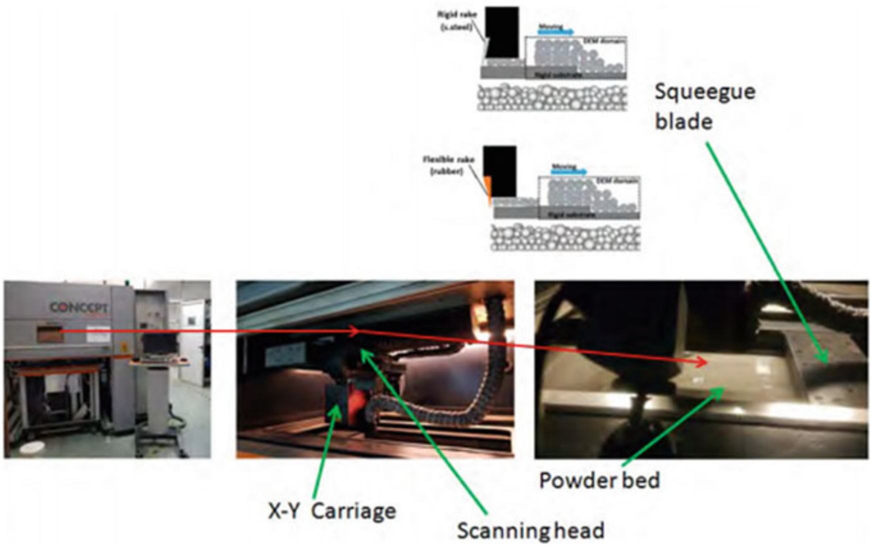

Fig. 1.19 PBF-LB/M overview (*Source* AIDIMME facilities)

PBF-LB/M build preparation is quite similar than PBF-EB/M but some considerations must be kept in mind as for instance the fact that we cannot nest parts in the Z axis but only if they are connected by support structures to parts attached to the build platform. Normally support structures required in PBF-LB/M technologies are denser than in PBF-EB/M technologies because of the room temperature conditions (non sintered powder) and the very fast cooling rates that take place during the process.

Regarding the melting process of laser based technologies, it varies depending on the strategy that each machine manufacturer follows, but normally the approach in laser based process is to perform controlled melting areas with equivalent energy. Concept laser M3 linear machine for instance follows the island pattern in which every layer is basically split into small squares of a certain dimension (5×5 mm) that are randomly melted afterwards in order not to accumulate the energy in specific areas of the layered geometries. These approaches are considered in order to reduce the swelling phenomenon.

Parameters that can be modified within the process are; current, laser speed or frecuency if the laser is pulsed, focus diameter (affects the shape of the laser), vector pattern (direction of the scanning vectors), overlap between scan tracks hatch-contour, number of contours between others.

Metal additive manufacturing processes are managed by very complex functions that vary the energy deposition. When it comes to a process parameter development for a new material, many variables can be modified in order to achieve good results in the consolidated material.

1.7.4 Selective Laser Sintering (PBF-LB/P) Technology

Selective laser sintering (PBF-LB/P) is an additive technology that uses a laser source (normally a CO_2 laser of 10,600 nm) to transform polymeric-based powder into solid parts based on 3D CAD models.

PBF-LB/P was one of the first additive manufacturing technologies developed in the mid 80-s, since then, the process has been adjusted to a wide variety of materials.

In the PBF-LB/P machines we can normally find two powder tanks where fine powder of a PSD 20–80 μm is stored and the build platform located in the middle. PBF-LB/P works under protected atmosphere (normally Nitrogen) and at a certain process temperature which is specific for each material. This temperature ramps up the temperature of the powder layer up to 12–16 °C below the melting point and the laser puts the remaining energy to melt the polymeric powder.

Some of the benefits of Selective Laser Sintering technologies are: (i) big parts can be manufactured, (ii) high strength polymers can be processed as polyamide, (iii) PBF-LB/P does not need support structures, thus design rules are much more flexible just trying to reduce the material as much as possible, and (iv) PBF-LB/P is able to reproduce very small geometries.

Nevertheless, powder not transformed into a part is affected by heat during the process; hence it must be refreshed with virgin powder in order to be reused again in the next build. Most part of the production costs of the PBF-LB/P technology comes from the feedstock; therefore, powder reusability is a key factor in order to cut down the part costs.

As a drawback, depending on the machine temperature stability is an important issue to deal with, because slight variations in the temperature whithin the process will lead to part distortions, curling and other typical issues of additive manufacturing.

PBF-LB/P Components

Among the components required within the PBF-LB/P process it can be found:

- PBF-LB/P cabinet where parts are built.
- Mixing station where already used powder is mixed and refreshed with virgin powder after each build.
- Powder recovery system where powder is sieved and possible comntamination or over sintered powder is removed.

Focusing on the production station and especially on the sintering unit, a low power CO2 laser is located on the top part of the machine. This laser is guided by two galvo mirrors that deflect the laser up to the powder bed. The roller picks a small amount of powder from the tanks and delivers it through the workpiece area creating a thin layer which is heated and melted.

In the PBF-LB/P machines we can also find several heaters allocated in diferent areas, some of them are aimed to preheat the workpiece area whereas others heat the powder tanks so that powder delivered is slightly heated before the deposition and therefore distortions are minimized.

In case of polyamide 12, which is the most common material processed by sintering technologies, process temperature is ramped up to 178–180 °C, it is rather important to keep a constant temperature along the entire build in order to reduce part distortions.

An overview of the PBF-LB/P technology is presented in Fig. 1.20.

PBF-LB/P Workflow

As described before machine and build preparation are crucial to achieve good results; the chamber must be cleaned up from powder of the previous build and bed levelled. Some preventive actions should be carried out in order to improve the results as for example cleaning the exit window of the CO2 laser since some very fine powder remains sticked to the face inside the chamber after each build.

Given the benefit of a support free technology means that parts can be placed anywhere within the build envelopment. Nowadays, it can be found nesting softwares as Materialse Magics which supports the technician in the parts allocation improving the build density as much as possible. The more parts fit in the build envelopment the cheaper the unitary costs will be.

Once the machine has been cleaned up and the powder stored in the tanks, the chamber is inertized and heaters are turned on.

Te build platform starts moving down while the powder is spreaded in a first phase called warm-up. This warmup stage aims to create a 10–12 mm height cake with no parts which pretends to create a heat barrier between the parts and the build platfor avoiding in this way phenomena like curling.

Once the warmup phase reaches 10–12 mm build starts; powder is dispersed by a roller in the shape of a fine layer. During the whole process a couple of heaters keep the temperature of the build platform at a certain point below the melting point of the material to be sintered. Once the layer has been deposited the laser source scans a cross-section of the 3D model (layered model) fusing the particles together

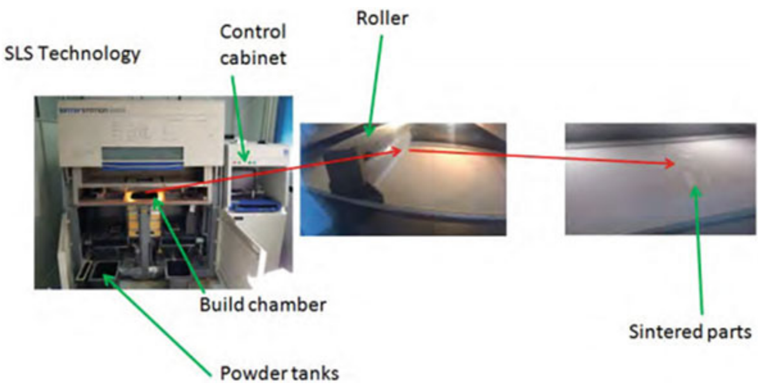

Fig. 1.20 PBF-LB/P chamber scheme (*Source* AIDIMME facilities)

in order to create a solid part. This process is repeated for each layer until parts are completed.

Once the build ends there is a cooling down phase where temperature is reduced in a controlled manner. A drastic cool down can lead to part deformation and distortions thus it is very important to naturally cool down the cake before removing the parts manufactured in each build. This phase takes between 12–24 h depending on how high the so-called cake is.

Powder reusability in PBF-LB/P is critical since most part of the production costs come from the feedstock itself, therefore a wrong powder reusability methodology can lead to a very affected powder batch that does not allow us to create high quality parts since phenomenon called "orange peel" appears (Fig. 1.21). For this reason, depending on the area where we recover the powder, we will treat the batch as more affected by heat or less affected by heat (Fig. 1.21).

It can be found in bibliography some methods like the Melt Flow Rate Test (MFRT) where we can quantify how affected the powder is. This method measures the time while a certain amount of powder is melted through an extruder at a specific temperature. Depending on this value already used feedstock must be refreshed in a controlled manner improving the reusability yields.

Looking deep into the selective laser sintering process, there are many variables that can be controlled (depending on the manufacturer) so that process can be adjusted to different materials. Some of them are: slicer fill scan spacing (distance between lines), laser power, and number of contours, layer thickness and temperature control variables.

Standard materials processed by PBF-LB/P are: Polyamide 11 & 12 & glass filled, TPU.

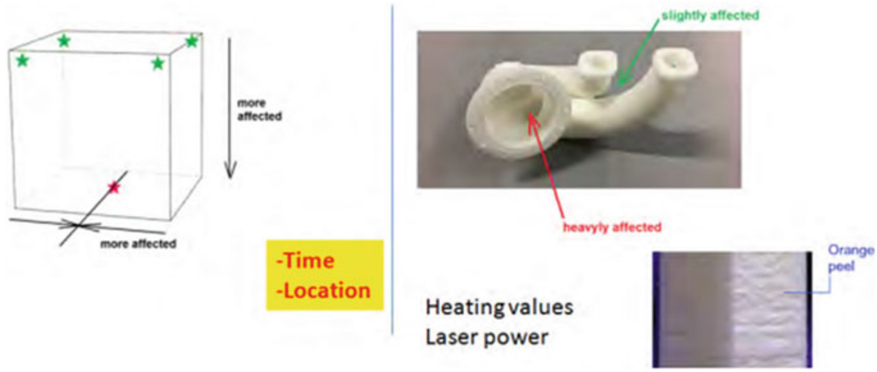

Fig. 1.21 Powder recovery from PBF-LB/P cake. Affected areas (*Source* AIDIMME)

1.7.5 HP Multi Jet Fusion (PBF-IrL/P) Technology

Multi Jet Fusion (PBF-IrL/P or MJF) is the named technology of the manufacturer Hewlett Packard (HP) developed in the last few years. Based on a similar concept like selective laser sintering but a complete new approach this technology allows creating end-use polymeric parts in high production rates and low cost per part.

The groundbreaking concept developed by HP has revolutionized the additive manufacturing scenario because parts conceived by this technology are completely isotropic and due to the high speed and production rates it can substitute injection molding at certain points for low production industrial parts for end-use and not for prototyping.

As benefits respect conventional PBF-LB/P, as pointed out, the build ratios and high strength materials isotropically consolidated by the technology, there is no need of support structures, PBF-IrL/P is able to reproduce very small and accurate details and most important; process stability and temperature stability are completely controlled by the HP software. This closed control loop leads to very good repeatibility and reliability in comparison with standard PBF-LB/P Systems.

As drawback, process parameters are locked thus development of new materials is not a possibility for these machines.

Standard materials offered are: polyamide 11 & 12 and gass filled PA, and TPU.

PBF-IrL/P Components

As an industrial scale 3D printer, the entire production chain is monitorized by the PBF-IrL/P software, on the one hand we can find the build unit where powder is processed and transformed into solid parts, on the other hand the PRS and part recovery station which manages the powder reusability ratios and mixes the powder from the last build in order to ensure good part quality.

Within the PRS we can also find the fast cooling unit that enables a slightly faster cool down phase and is normally used when parts are not so slim.

Part recovery requires minimal time and labor. After the print job is completed, finished parts are recovered from the cake and excess of powder is removed using auxiliary sandblasting equipments.

An overview of the PBF-IrL/P components in pointed out in Fig. 1.22.

PBF-IrL/P Workflow

Giving a closer look to the printing unit, it is equipped with high intensity High Voltage bulbs that heat the chamber, a powder dispenser and binding head.

As in any AM technology, machine preparation is similar; printing module is loaded with powder and machine cleaned up.

Warm up volume is also required in order to generate the heat barrier and after the warmup phase, parts are manufactured layer by layer. At this step the powder dispatcher moves back and forth and deposits a thin powder layer on the build area. Binding/UV head moves above the powder layer injecting two components called “fusing agent” and “detailing agent”. Fusing agent is aimed to reduce the melting

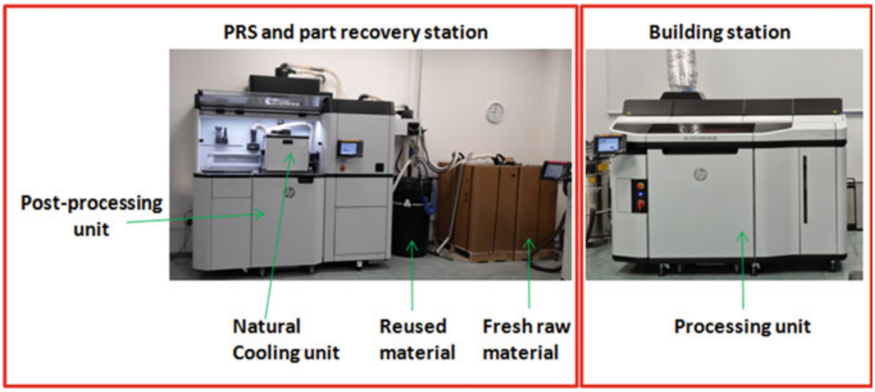

Fig. 1.22 PBF-IrL/P technology components (*Source* AIDIMME facilities)

point of the powder (black agent) powder that is injected with this material will be transformed into parts. Whereas detailing agent is aimed to increase the melting point, the detailing agent is applied in the border between the part and the non sintered powder in order to improve the surface quality and to stop the heat dissipation, it some way it creates a heat barrier that surrounds the part.

Once the build ends a natural cooling or a fast cooling can be carried out depending on different factors as the shapes included in the cake. Fast cooling is normally used when parts are small-size.

1.7.6 Metal Binder Jetting (MBJT) Technology

During the last few years, the additive manufacturing scenario has been evolving with a recent batch of innovative technologies where Metal Binder Jetting can be found.

MBJT follows the principles of Metal Injection Moulding (MIM) applied to a layer-by-layer technique (Binder jetting process).

Even tough the MBJT is not widespread yet, many important companies related to the additive manufacturing market are about to launch their own MJBT machines. Some of the benefits that this technology are very fast production ratios, very small features compared to the conventional Metal AM technologies like PBF-LB/M and PBF-EB/M, support free parts during the construction process (not during debinding and sintering) and a wide variety of materials (any material that can be sintered).

In addition, metal powders are not melted during the printing process thus many issues related to part distortions (residual stresses) dissapear.

As drawbacks, parts need to be debinded and sintered after the part construction. Debinding can lead to part distortions if not properly done and sintering leads to srinkage thus part size in this kind of process is cruzial.

MBJT Components

As basic components in the production chain of metal binder jetting, we observe that a debinding furnace and a high temperature furnace (sintering) will be required as well as a sandblasting equipment in addition to the 3D printer itself.

Metal binder jetting machines are made up of a powder dispatcher head or raking system that delivers fine powder layers and a binder jetting head with multiple inkjets that deposits very small droplets of binder in order to join the particles and a curing system to polymerize the binder agent.

Parts manufactured up to this step remain in a fragile green state infiltrated with a polymeric matrix and require being post processed in a sintering furnace that creates the full-metal part.

Binder jetting machines can work with a huge range of metal alloys, but they can also handle ceramic and sand-based materials.

1.8 Material Extrusion Additive Manufacturing (MEX) Technologies

Material extrusion additive manufacturing (MEX) consists of pushing soft material through an orifice and deposit such material in layers to build a 3D structure. Extrusion based additive manufacturing processes are among the most widely used AM processes, particularly when working with thermoplastics and thermoplastic composites. However not only thermoplastic materials can be extruded; some examples include low melting temperature metals, glass, ceramic slurries, suspensions containing graphene and other nanoparticles, silicones and concrete. Compared to other AM processes, the equipment used for MEX can be inexpensive and very easy to operate. Therefore, the main advantage of MEX is rapid and economical reproduction of standard components or prototypes with a variety of polymeric materials, low melting temperature metallic alloys and other materials.

Unlike other AM techniques, extrusion based additive manufacturing techniques are well suited for multi-material deposition and can be used with a wide range of thermoplastic materials. In general, most of the MEX machines are equipped with a single extrusion head, but there is the possibility of adding two or more extrusion units to allow for multi-material fabrication. Meanwhile new devices have been developed that allow mult-material printing with a single nozzle by fusing different filaments together before they are fed to the extrusion unit, for example the Palette 2S manufactured by Mosaic Manufacturing Ltd. (Toronto, ON, Canada) or the multi-material unit by Prusa Research (Praga, Czech Republic). The working principle of MEX suits itself for the fabrication of composite materials with continuous fibres; machines like the ones developed by Markforged Inc. (Watertown, MA, USA), and Anisoprint LLC (Moscow, Russia), allow the deposition of continuous fibres in a particular location where the reinforcement is needed, thus saving on the cost and weight of the manufactured components. Finally, the simple principle of operation of

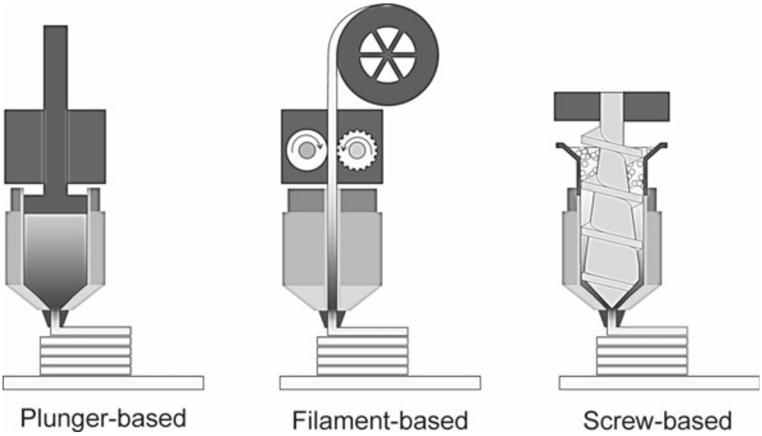

Fig. 1.23 Material extrusion additive manufacturing types (Gonzalez-Gutierrez, J.; Cano, S.; Schuschnigg, S.; Kukla, C.; Sapkota, J.; Holzer, C. Additive Manufacturing of Metallic and Ceramic Components by the Material Extrusion of Highly-Filled Polymers: A Review and Future Perspectives. Materials 2018, 11, 840, licensed under CC BY 4.0)

the extruder allows it to be mounted on machines with up to six-degrees of freedom, such as robotic arms, which further increase the functionality and versatility of MEX.

The basic principle of material extrusion additive technology involves loading and liquefaction of the material, moving the material through a nozzle or orifice by applying force or pressure, plotting liquefied material according to a pre-defined path in a controlled manner, and layer-by-layer bonding of the material to itself or secondary build material to form a coherent solid structure. After a layer is completed, the build platform moves down or the extrusion head moves up, and a new layer of material is deposited and adhered onto the previous layer. Whenever necessary, support structures are included in the process to enable fabrication of complex geometrical features. This basic principle enables the production of complex parts without a shaping tool other than a die with a simple geometry, generally round. Depending on the type of extruder used, one can classify Material Extrusion Additive Manufacturing (MEX) into different types, and they will be described in the following section and are schematically shown in Fig. 1.23.

1.8.1 Material Extrusion with Plungers

Extrusion with plungers occurs when a soft material is pushed through an orifice with a piston, or fluids like compressed air (pneumatic system). The material is loaded in cartriges and the piston squeezes out the material through a nozzle, similar to a syringe. This type of extrusion system is generally used with suspensions or slurries with a high fluidity and it is referred as robocasting, direct ink writing, direct-write assembly or microrobotic deposition. Examples of the materials used in extrusion with plungers, sometimes referred as inks, are highly concentrated (35 to 50 vol.%) colloidal suspensions designed to solidify via a drying induced pseudoplastic to dilatant transition; and colloidal gels consisting of a percolating network of attractive particles capable of transmitting a force above a critical powder loading. In order for the extrusion and the deposition of these materials to be more reliable their composition needs to be tailored in order to obtain the required rheological properties. The inks should have a relatively low viscosity under stress (shear thinning) and a high elastic modulus and high yield stress upon deposition, in this way the shape retention after deposition does not depend on the solidification or drying of the feedstock material. Therefore, there are no thermal gradients, and the extrusion pressures are smaller. Inks containing ferroelectric, metallic, bioactive, polymeric, graphene and numerous ceramics have all been successfully processed by plunger based-MEX.

Other relative low viscosity materials that can be extruded with a plunger system are silicone elastomers. Silicones can consist of a single component that cures with moisture, and multiple components including cross linker agents that can be cure thermally, or by UV hydrosilation. When the viscosity of the pre-elastomer silicones is sufficiently low a pneumatic system is used to push the contents of a barrel with a check valve to control the deposition of the material as the printing head or the platform moves to shape a three-dimensional object.

A piston can also be used to push thermoplastics and thermoplastic-based composites. One example of this technology is the process known as Thermoplastic 3D-Printing (T3DP) in which a particle-filled thermoplastic feedstock material is pushed through a nozzle in a drop-wise manner. The micro dispensing units have a nozzle with an orifice of 160 μm, and a piezo-driven hard metal piston moves up and down to produce droplets instead of strands. The thermoplastic used in this system is generally a mixture of paraffin and beeswax and using this technology different ceramics, metals and metal-ceramics components have been produced.

In general, plunger extrusion machines with plungers are meant to be used for shaping parts that eventually will be require post shaping steps in order to obtain the final product. For example, the silicones require a curing step, the inks used in robocasting, the thermoplastic suspensions used in T3DP, need to be sintered to obtain metal or ceramic specimens. The technologies that require sintering have feedstock materials containing a large amount of powder (35 to 55 vol%). The thermoplastic suspension uses similar materials as used in the well-established process of powder injection molding (PIM).

1.8.2 Material Extrusion with Filaments

Material extrusion of filaments was first patented by the company Stratasys and commercialized as Fused Deposition Modelling or FDM™. However, such name could be applied to other AM techniques that melt materials and deposit them onto a platform or onto previously deposited layers of material, such as pneumatic extrusion, micro injection of droplets (e.g. Freeformer), screw extrusion of pellets, and ram extrusion with rods. Also, FDM™ is a registered trademark of the company that first introduced the technology. Therefore, an alternative terminology was introduced as Fused Filament Fabrication or FFF. FFF is the most widely used MEX technique. The main reasons of its popularity are its safe and simple fabrication process, low cost of the equipment and the availability of a variety of filaments for printing. In the FFF process, the filament is extruded through a nozzle and deposited on a building platform one layer at a time where it solidifies. The printing chamber and bed are kept at temperatures below the material´s melting point, but higher than room temperature to promote adhesion to the printed bed and to reduce thermally induced stresses.

FFF machines are ram extruders, with the filament being the ram that pushes the softened material out of the printing head. In conventional FFF machines, the filament is first pulled by the driving wheels and then it is pushed by the same wheels into a liquefier and later on into a nozzle. Therefore, sufficient mechanical strength is required for the filament to retain its shape after being forced through the drive wheels. The filament has to transfer the force provided by the driving wheels forward into the liquefier. The force that is generated by the motors must be transferred to the filament via the wheels. This transfer of force can be altered by a number of factors. First, the motors must generate sufficient torque. Next, the wheels must have enough friction with the filament to transfer the force from the wheels to the filament. At the same time, the filament must be strong enough to avoid shearing due to the pinching from the wheels. Finally, the filament must not buckle between the drive wheels and the entrance to the liquefier. That is, the force transferred from the drive wheels to the filament should be efficiently transferred into the centre of the liquefier in the direction of the melt flow, with minimal loss due to filament buckling and compression. In addition to these requirements, the filament should also be flexible enough to be spooled, so that the filament can be easily stored in a compact place and fed in a continuous manner into the liquefier. As it can be expected not all materials can fulfil all of these conditions, yet numerous thermoplastics-based materials are available as filaments for FFF.

Examples of non-filled thermoplastics filaments commercially available include: acrylonitrile butadiene styrene (ABS), polylactic acid (PLA), acrylonitrile styrene acrylate (ASA), polyamide (PA), polypropylene (PP), polycarbonate (PC), polyphenylsulfone (PPSF, PPS or PPSU), polyetherimide (PEI), butenediol vinyl alcohol (BVOH), thermoplastic polyurethane (TPU), polyethylene terephthalate (PET), recycled PET (rPET), thermoplastic elastomer (TPE), high impact polystyrene (HIPS), thermoplastic copolyester elastomer (TPC), polyvinyl alcohol (PVA), polyether ether ketone (PEEK), polyvinlydene floride (PVDF), polyoxymethylene (POM), polyhydroxyalkanoate (PHA) blended with PLA and some other blends of the previously mentioned polymers. Examples of composite materials commercially available for FFF include: ABS reinforced with carbon fibers; PP reinforced with glass fibre, PLA with carbon fiber, graphite, stainless steel, bronze, brass, copper, bamboo fibers, wood fibers and iron particles; PA with carbon fibre, PET with carbon fibers; the filler content of these composites is between 5 and 40 vol.%. Examples of highly-filled (35 to 55 vol.%) polymeric materials for FFF plus sintering include fillers like 316 L steel, 17-4PH steel, Ti6Al4, NdFeB, copper, zirconia, alumina, silicon nitride, lead zirconate titanate, fused silica, tricalcium phosphate, hard metals, and cermets. Using these filaments and finding co-sintering conditions, it was possible to obtain multi-material parts combining ceramics and metals.

The process of extrusion of filaments was pioneered by Stratasys and in 1991 they introduced the first AM system of this kind. Their FFF system had two extrusion heads and used two spools of material, one material used to build the part and the second one for the support material. Based on the FFF system, a novel system for the manufacturing of multi-material parts was presented by the Rutgers research group, the Fused Deposition of Multiple Ceramics (FDC). Four extrusion nozzles were included in the system, i.e. four materials could be deposited at the same layer. Different demonstrators, such as piezoelectric components with layers of soft and hard piezoelectric ceramics were produced. Expiration of the Stratasys patents on FFF process and growing demand of customized products has driven other companies such as Beijing Tiertime Technology Co. Ltd as an emerging competitor in this market. In addition, personal fabrication markets are being encouraged with the open-source RepRap projects and several small and medium companies such as German RepRap GmbH, Apium Additive Technologies GmbH, Aleph Objects, Inc., MakerBot Industries, LLC., 3D system Inc., Delta Micro Factory Corp., Hage Sondermaschinenbau GmbH & Co KG, EVO-tech GmbH, BigRep GmbH, Printbot LLC, Indmatec GmbH, Rokit Inc., Ultimaker BV, Sharebot srl, MarkForged Inc., 3D Platform, Titan Robotics Ltd., Vixel8, Shenzhen Yuejiang Technology Co., Ltd., Wanhhao, Xery 3D Science and Technology Inc., Prusa Research a.s., CEL-UK Robox, Zortrax S.A., KUMOVIS GmbH, WASP c/o CSP S.r.l., Mass Portal SIA, Robert Bosch GmbH, XYZprinting, Inc., FlashForge Co., FELIXprinters, Modix Modular Technologies LTD, gCreate, Fusion3 Design, LLC, and Cosine Additive Inc., are producing FFF machines to mention a few.

1.8.3 Material Extrusion with Screws

Production of slurries, rods or filaments represents an additional task that requires special extrusion lines and know-how to obtain slurries with the right rheological behavior and filaments or rods with constant cross-sectional area and ovality, which are prerequisites to deposit the adequate amount of material and therefore have a reliable process in MEX machines. Also, not all materials can be made into filaments with the required mechanical properties to obtain a filament that can be spooled, but at the same time rigid enough that it can be pushed by the feeding mechanisms of FFF machines. Therefore, several research groups and companies are looking into screw-extrusion AM machines that can utilize thermoplastic pellets.

A screw extruder is divided into several zones. In the solid conveying zone pellets are transported to the melting zone where pellets are softened under heat and friction, and the metering zone in which the molten material is submitted to high pressure before its eviction through the nozzle. The rotating screw has a pumping effect and thus it moves the material from the feeding zone to the nozzle. Controlling the flow of the extruder for depositing the material in a precise manner can be a challenging task and requires other tools as compared to ram extrusion with filaments. Also, the size of the pellets should be controlled in order to obtain a uniform flow of extruded material. Nevertheless, solutions have been found and here some examples of screw extruder AM machines are described.

Bellini et al., developed a system called mini extruder deposition (MED), which consist of a mini screw-extruder mounted on three high precision linear motor tables. The three tables were connected to three digital servo drives to monitor the torque, velocity and rotational speed. The servo drives were also equipped with digital notch filters to eliminate mechanical resonance. The driver‘s position, speed and acceleration of the three axes could simultaneously be controlled. A separate controller was used to regulate the heaters and the motor of the extruding screw. Material temperature was checked at the entrance of the liquefier and closer to the nozzle. Even though the developed preliminary configuration shows opportunities for the use of wider range of materials, it can only be considered as a starting point for further development, due to the limited information provided by the researchers and the lack of follow up publications.

Cruz et al., developed their own screw-based extrusion system. The equipment consisted of a vertical single screw extruder with screw length of 90 mm, screw diameter of 15 mm and die with 2 mm diameter. Two band heaters were placed around the barrel to ensure a constant temperature (up to 250 °C) during the plastification process. The building platform was capable of moving in XYZ directions, controlled by step motors to control the trajectory and the material deposition. The printing process was controlled by a logical controller and a computer was used as an interface to enter the processing conditions (barrel temperature, screw rotational speed and material rate of deposition) and monitor the process. The designed extruder was capable of processing the feedstock with 59 vol.% of carbonyl iron; however no further details in terms of printability and printed parts were shown.

Tseng et al., constructed a screw extrusion-based additive manufacturing for processing PEEK. The extruder subsystem was firmly attached to a rigid frame fixed on a granite plate (600 mm × 600 mm × 50 mm). The thermal control subsystem included a thermal control panel, a heating plate installed in the build platform, and heaters installed within or around the barrel of the extruder. Three heaters were used to control the feeding, compression and metering zones. Usual temperatures to process PEEK were 180, 340, and 380 °C respectively. The build platform was installed on the X–Y-Z traversing subsystem, and quartz glass and stainless steel were the investigated build platform materials. It was found that a temperature of 280 °C at the build platform provided sufficient adhesion to build the parts. It was demonstrated that this printer is capable to print PEEK specimens with around 2% porosity that lead to an ultimate strength 95% of that of bulk material.

Yu et al., used a screw-based system to print pastes of yttria-stabilized zirconia ceramic pastes at room temperature. The feedstock used was a colloid fabricated by dispensing zirconia nanoparticles in an aqueous solution. The dispersant was ammonium polymethacrylate, and methyl cellulose as binder agent. The paste contained 60vol.% of solid particles and it was blended and homogenized using a vacuum mixer. The printer used was a delta robot with a pressurized cylindrical tank to store the paste and the paste was fed to a screw extruder at room temperature. The build-platform was also kept at room temperature during the printing process. Using this unique system and after debinding and sintering, zirconia parts with a relative density of 98.1% were achieved and the mechanical properties were better than parts fabricated by binder jetting and SLS.

One company that has developed and is commercializing a screw-based extrusion AM machine is AIM3D GmbH (Rostock, Germany). The AM machine from AIM3D is called ExAM 255 and it has two extruders that can take commercially available pellets from thermoplastics or metal injection molding (MIM) feedstock to build a tree-dimensional object. The building volume is a cube with 255 mm on all sides. Like many other systems the extrusion head moves in the x–y plane, while the building platform moves in the z-direction. As indicated in their website, the only material that is not in the beta phase of development is a MIM feedstock with stainless steel particles.

The company Pollen AM, Inc. (Paris, France) has also developed and is currently commercializing a screw based system capable of printing with up to four different materials. This machine is capable of mixing two materials during the printing process. Materials available include unfilled thermoplastics and filled thermoplastic pellets with natural fibers, carbon fibers, minerals and metal particles. The maximum printing temperature is 350 °C. The area available for printing is 300 × 300 mm^2 and the maximum printing speed is 400 mm/s.

Cincinnati Inc. (Cincinnati, OH, USA) and Oak Ridge National Laboratories (Oak Ridge, TN, USA) have developed a screw extrusion machine for large size additive manufacturing. The setup is called Big Area Additive Manufacturing or BAAM. It consists of a single screw extruder mounted vertically on a machine frame, similar to the frames used for laser-based AM machines. The extruder has a feed rate of 36 kg/h and a unique automatic taping mechanism, which is used to flat the deposited material to increase the contact between deposited layers. The setup is available in two sizes: 7.8 × 3.7 × 3.3 m^3 and 10.8 × 3.9 × 4.4 m^3. The motion system is driven by linear motors and the absolute position accuracy is ± 0.127 mm. Using BAAM the manufacturers have been able to print sections of car bodies and sections of buildings. The materials that have been tested include pellets of acrylonitrile–butadiene–styrene (ABS), polyphenylenesulfide (PPS), polyetherketoneketone (PEKK) and polyetherimide (PEI), as well as, composites materials containing carbon, glass fibers and NdFeB particles. Other companies selling screw-based MEX systems for large industrial applications are Cosine Additive Inc. (Houston, TX, USA), Modix Modular Technologies LTD (Ramat Gan, Israel), BLB Industries (Värnamo, Sweden), CNC Barcenas (Ciudad Real, Spain), and Titan Robotics LTD (Colorado Springs, CO, USA).

Using screw-based extruders and gantry systems new larger MEX machines are being developed and very large pieces are now being manufactured. For example, the

University of Maine Advanced Structures and Composites Centre manufactured a boat with a length of 7.6 m and weighing 2268 kg in October 2019. The machine used to build the boat has a building envelope with a length of 30.5 m, a width of 6.5 m and a height of 3 m. The extruder is capable of printing speeds of about 225 kg/h.

1.8.4 Disadvantages of Using MEX

The main disadvantages of using MEA include a rougher surface, which is limited by the nozzle radius; the accuracy and speed can be low compared to other AM technologies; there is anisotropy of the mechanical properties, with weaker properties in the Z-direction due to the lower cohesion of the deposited layers; and support structures are needed, since the building material is deposited only where it is needed.

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