UNIT-5

OTHER ADDITIVE MANUFACTURING PROCESSES

5.1 Introduction About Material Jetting

Material jetting is an inkjet printing process where inkjet-type printheads apply droplets of material to print a model slice. These "inks" can be pure photopolymer or pure waxes, or they can contain ceramic or metal particles. Some machines have heads for applying color to the model. Material jetting falls into three categories, by the nature of the materials they use:

1. **PolyJet**: PolyJet builds plastic prototypes by jetting photopolymer droplets into the build platform and solidifying them using UV light.
2. **NanoParticle Jetting (NPJ)**: NPJ is a technology developed by XJet. It uses suspensions of powdered material (usually metal or ceramic) to build parts.
3. **Drop on Demand (DOD):** DOD uses the bubble-jet approach to apply wax to a Z-table moved in the X-Y plane to build casting patterns for fine components like jewelry.

5.2 Materials for Material Jetting

While industry players have so far introduced printing machines that use waxy polymers and acrylic photopolymers exclusively, research groups around the world have experimented with the potential for printing machines that could build in those and other materials. Among those materials most studied and most promising for future applications are polymers, ceramics, and metals. In addition to the commercially available materials, this section highlights achievements in related research areas.

For common droplet formation methods, the maximum printable viscosity threshold is generally considered to be in the range of 20–40 centipoise (cP) at the printing temperature [4–6]. An equivalent unit of measure is the milli-Pascalsecond, denoted mPa s if SI units are preferred. To facilitate jetting, materials that are solid at room temperature must be heated so that they liquefy. For high viscosity fluids, the viscosity of the fluid must be lowered to enable jetting. The most common practices are to use heat or solvents or other low viscosity components

5.2.1 Polymers

Polymers consist of an enormous class of materials, representing a wide range of mechanical properties and applications. And although polymers are the only material currently used in commercial AM machines, there seems to be relatively little discussion on polymer inkjet production of macro three-dimensional structures in
the published scientific literature.

Gao and Sonin [8] present the first notable academic study of the deposition and solidification of groups of molten polymer microdrops. They discuss findings related to three modes of deposition: columnar, sweep (linear), and repeated sweep (vertical walls). The two materials used in their investigations were a candelilla wax and a microcrystalline petroleum wax, deposited in droplets 50 μm in diameter from a print head 3–5 mm from a cooled substrate. The authors first consider the effects of droplet deposition frequency and cooling on columnar formation. As would be expected, if the drops are deposited rapidly (_50 Hz in this case), the substrate on which they impinge is still at an elevated temperature, reducing the solidification contact angle and resulting in ball-like depositions instead of columns (Fig. 7.1a). Numerical analyses of the relevant characteristictimes of cooling are included. Gao and Sonin also consider horizontal deposition ofdroplets and the subsequent formation of lines. They propose that smooth solid lineswill be formed only in a small range of droplet frequencies, dependent upon thesweep speed, droplet size, and solidification contact angle (Fig. 7.1b). Finally, theypropose that wall-like deposition will involve a combination of the relevant aspectsfrom each of the above situations.

Reis et al. [9] also provide some discussion on the linear deposition of droplets.They deposited molten Mobilwax paraffin wax with a heated print head fromSolidScape. They varied both the print head horizontal speed and the velocity ofdroplet flight from the nozzle. For low droplet speeds, low sweep speeds createddiscontinuous deposition and high sweep speeds created continuous lines(Fig. 7.2a–c). High droplet impact speed led to splashing at high sweep speedsand line bulges at low sweep speeds (Fig. 7.2d–f).

From these studies, it is clear that process variables such as print head speed,droplet velocity, and droplet frequency affect the quality of the deposit. Theseprocess variables vary depending upon the characteristics of the fluid being printed,so some process development, or fine-tuning, is generally required when trying toprint a new material or develop a new printing technology

5.2.2 Ceramics

One significant advance in terms of direct printing for three-dimensional structureshas been achieved in the area of ceramic suspensions. As in the case of polymers,studies have been conducted that investigate the basic effects of modifying sweepspeed, drop-to-drop spacing, substrate material, line spacing, and simple multilayer forms in the deposition of ceramics [16]. These experiments were conducted with amixture of zirconia powder, solvent, and other additives, which was printed from a62 μmnozzle onto substrates 6.5mmaway. The authors found that on substrates thatpermitted substantial spreading of the deposited materials, neighboring drops wouldmerge to form single, larger shapes, whereas on other substrates the individual dotswould remain independent (see Fig. 7.4). In examples where multiple layers wereprinted, the resulting deposition was uneven, with ridges and valleys throughout.A sizable body of work has been amassed in which suspensions of aluminaparticles are printed via a wax carrier [4] which is melted by the print head.Suspensions of up to 40 % solids loading have been successfully deposited atviscosities of 2.9–38.0 cP at a measurement temperature of 100 _C; higher concentrations of the suspended powder have resulted in prohibitively highviscosities. Because this deposition method results in a part with only partialceramic density, the green part must be burnt out and sintered, resulting in a finalproduct which is 80 % dense but whose dimensions are subject to dramaticshrinkage [17]. A part created in this manner is shown in Fig. 7.5.

5.2.3 Metals

Much of the printing work related to metals has focused upon the use of printing for electronics applications—formation of traces, connections, and soldering. Liu and Orme [20] present an overview of the progress made in solder droplet deposition for the electronics industry. Because solder has a low melting point, it is an obvious
choice as a material for printing. They reported use of droplets of 25–500 μm, with results such as the IC test board in Fig. 7.7, which has 70 μm droplets of Sn63/Pb37.

In related work, a solder was jetted whose viscosity was approximately 1.3 cP,continuously jetted under a pressure of 138 kPa. Many of the results to which theyrefer are those of researchers at MicroFab Technologies, who have also producedsolder forms such as 25 μm diameter columns.

There is, however, some work in true three-dimensional fabrication with metals.Priest et al. [21] provide a survey of liquid metal printing technologies and history,including alternative technologies employed and ongoing research initiatives.Metals that had been printed included copper, aluminum, tin, various solders, andmercury. One major challenge identified for depositing metals is that the meltingpoint of the material is often high enough tosignificantly damage components ofthe printing system.

Orme et al. [22, 23] report on a process that uses droplets of Rose's metal(an alloy of bismuth, lead, and tin). They employ nozzles of diameter 25–150 µmwith resulting droplets of 47–283 µm. In specific cases, parts with porosity as low as0.03 % were formed without post-processing, and the microstructure formed ismore uniform than that of standard casting. In discussion of this technology,considerations of jet disturbance, aerodynamic travel, and thermal effects are all presented.

Yamaguchi et al. [24, 25] used a piezoelectrically driven actuator to depositdroplets of an alloy (Bi–Pb–Sn–Cd–In), whose melting point was 47 _C. Theyheated the material to 55 _C and ejected it from nozzles 200 µm, 50 µm, and lessthan 8 µm in diameter. As expected, the finer droplets created parts with betterresolution. The density, or "packing rate," of some parts reached 98 %. Other examples of fabricated parts are shown in Fig.

5.3 Material Jetting Machines

The three main companies involved in the development of the RP printing industry are still the main players offering printing-based machines: Solidscape, 3D Systems, and Stratasys (after their merger with Objet Geometries). Solidscape sells the T66 and T612, both descendants of the previous ModelMaker line and based upon the first-generation melted wax technique. Each of these machines employs two single jets—one to deposit a thermoplastic part material and one to deposit a waxy support material—to form layers 0.0005 in. thick [63]. It should be noted that these machines also fly-cut layers after deposition to ensure that the layer

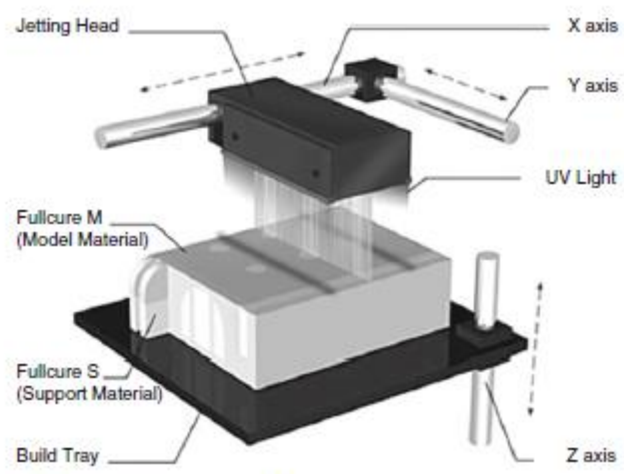

Fig. 7.14 Stratasys Polyjet build process [64]

is flat for the subsequent layer. Because of the slow and accurate build style as wellas the waxy materials, these machines are often used to fabricate investmentcastings for the jewelry and dentistry industries.3D Systems and Stratasys offer machines using the ability to print and cureacrylic photopolymers. Stratasys markets the Eden, Alaris, and Connex series of printers. These machines print a number of different acrylic-based photopolymer materials in 0.0006 in. layers from heads containing 1,536 individual nozzles, resulting in rapid, line-wise deposition efficiency, as opposed to the slower, point-wise approach used by Solidscape. Eachphotopolymer layer is cured by ultraviolet light immediately as it is printed, producing fully cured models without post-curing. Support structures are built in a gel-like material, which is removed by hand and water jetting [64]. See Fig. 7.14 for an illustration of Stratasys' Polyjet system, which is employed in all Eden machines. The Connex line of machines provides multimaterial capability. For several years, only two different photopolymers could be printed at one time; however, by automatically adjusting build styles, the machine can print up to 25 different effective materials by varying the relative composition of the two photopolymers. Machines are emerging that print increasing numbers of materials.

In competition with Stratasys, 3D Systems markets the ProJet printers, which print layers 0.0016 in. thick using heads with hundreds of nozzles, half for part material and half for support material [11]. Layers are then flashed with ultraviolet light, which activates the photoinitiated polymerization. The ProJets are the third generation of the Multi-Jet Modeling family from 3D Systems, following the ThermoJet described above and the InVision series. A comparison of the machines currently available is presented in Table 7.3.

5.3.1Process Benefits and Drawbacks

Each AM process has its advantages and disadvantages. The primary advantages of printing, both direct and binder printing, as an AM process include low cost, high speed, scalability, ease of building parts in multiple materials, and the capability of printing colors. Printing machines are much lower in cost than other AM machines, particularly the ones that use lasers. In general, printing machines can be assembled from standard components (drives, stages, print heads), while other machines have many more machine-specific components. High speed and scalability are related: by using print heads with hundreds or thousands of nozzles, it is possible to deposit a lot of material quickly and over a considerable area. Scalability in this context means that printing speed can be increased by adding another print head to a machine, a relatively easy task, much easier than adding another laser to a SL or SLS machine.

As mentioned, Stratasys markets the Connex machines that print in two or more part materials. One can imagine adding more print heads to increase the capability to many different materials and utilizing dithering deposition patterns raise the number of effective materials into the hundreds. Compatibility and resolution need to be ensured, but it seems that these kinds of improvements should occur in the near future.

Related to multiple materials, colors can be printed by some commercial AM machines (see Sect. 8.3). The capability of printing in color is an important advance in the AM industry; for many years, parts could only be fabricated in one color. The only exception was the selectively colorable SL resins that Huntsman markets for the medical industry, which were developed in the mid-1990s. These resins were capable of only two colors, amber and either blue or red. In contrast, two companies market AM machines that print in high resolution 24-bit color. Several companies are using these machines to produce figurines for video-gamers and other consumers (see Chaps. 3, 8, and 12).

For completeness, a few disadvantages of MJ will provide a more balanced presentation. The choice of materials to date is limited. Only waxes and photopolymers are commercially available. Part accuracy, particularly for large parts, is generally not as good as with some other processes, notably vat photopolymerization\ and material extrusion. However, accuracies have been improving across the industry and are expected to improve among all processes.

Material jetting is used widely in the more demanding applications for 3D printed parts. Examples of industries and their applications are:

1. **Medical**: Colored and precise parts are often used for medical visualization models, for example, printing organs and structures within a patient built from PET scan models.
2. **Jewelry:** DOD wax printing is widely employed to make casting patterns for limited production runs by lost wax casting.
3. **Engineering:** PolyJet systems are widely used in the production of engineering test pieces or prototypes. These printed parts offer very high resolution and accuracy and allow at least partial simulation of real material behavior in highly detailed and delicate parts.