Micro Prototyping and Fabrication in Manufacturing

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Abstract

The term Additive Manufacturing (AM) refers to a range of technologies that permits automated fabrication of computer-generated 3D models. AM generally uses an approach of segmenting the digital model data into thin, precise layers that are then bonded together to create the final solid object. Already established for larger-scale, lower-resolution applications, AM can also be used to fabricate complex geometry, micron-resolution models. Some of the basic AM technologies are

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explored, and how they can be used to make small, precise mechanical structures is identified. How these techniques have been adapted to specifically improve this area is examined, and how they can develop in the future is discussed in the end.

Introduction

Additive Manufacturing (AM) is rapidly becoming a manufacturing process of choice for many new products. While there are numerous limitations for the related technologies, these are counterbalanced by the time, cost, and geometric freedom advantages that they provide. Micron-scale parts are generally difficult to develop using these technologies due to the layer-additive approach used. Most layer thicknesses are in the order of a few tens to a few hundreds of microns, which characterizes resulting parts with a "stair-step" texture, particularly on highly curved geometry. However, some machines are better than others at providing fine detail, and there are even a number of machines that have been specifically developed to provide such detail.

This chapter will introduce the basic concepts of Additive Manufacturing. This will discuss in particular the reasons why fine detail is difficult to achieve. The machines that can provide the highest resolutions will be discussed in more detail. As mentioned, there are a small number of dedicated micro AM technologies that aim to provide finer-detailed parts and these will be discussed in a separate section. Other approaches that have yet to be commercialized will then be discussed, followed by a brief discussion on some of the concerns that are specifically related to such small-scale technologies.

Additive Manufacturing

Additive Manufacturing is a terminology applied to a specific range of technologies that add material, normally layer by layer, to form complex 3D structures (paraphrased from the ASTM definition (ASTM)). Formerly referred to as rapid prototyping and often popularly referred to as 3D printing, the key attributes to all these technologies are as follows:

1. An original model is designed using 3D CAD (computer-aided design) technology.
2. The CAD model is converted into a generic file format that is readable by the AM machine.
3. The file is segmented in (normally) layers.
4. These layers are added as material inside the AM machine.
5. Such material is added in a sequential fashion until the part has been completed.
6. The part is removed from the machine and some post-processing is carried out before use.

A typical sequence related to this description can be seen in Fig. 1. All commercial AM technologies apply this sequence in one way or another. There are

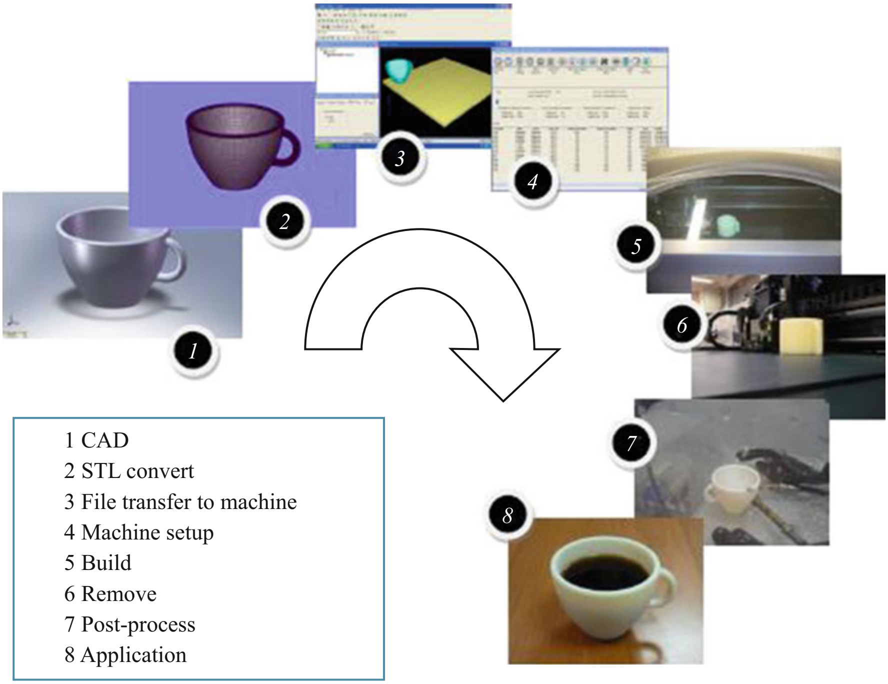

Fig. 1 A generalized process chain for Additive Manufacturing (Gibson et al. 2009)

other approaches, but since the implications for micron-scale fabrication are being discussed, the focus can be on three basic material delivery systems:

7. Liquid photopolymer resin systems
8. Powder-based systems
9. Extrusion-based systems

For the liquid photopolymer systems, this category can be further subdivided into vat systems and droplet deposition systems. The vat systems were among the first AM technologies to be commercialized, requiring a platform to be lowered into a container of liquid photopolymer resin. The first layer of build will occur when the platform is just below the resin surface where it will be exposed to light source (usually ultraviolet) that will harden, or cure, the resin. The light source will somehow describe the cross section of the model to be created. Earlier machines, like the stereolithography (3D Systems) process from 3D Systems, used a laser to scan over the resin surface. Later technologies used 2D projection techniques to expose the resin. The energy content and the exposure time of the light source determine how far into the resin the curing takes place. The first layer therefore penetrates into the resin a sufficient enough depth to reach and adhere to the platform. Between each exposure, the platform indexes down to allow recoating of the resin and subsequent layers adhere to the previous ones. There are alternative approaches to depositing and exposing the photopolymer resins, which are described in more detail later.

At this point it is worth mentioning that certain part geometries may not directly connect to the platform. In these circumstances it is necessary to build what is known as a support structure below these features. Eventually such features will combine with the main body of the part, but these supports will keep them in place until they do. Such supports must be removed once the build is complete as part of the post-processing. The supports can be designed in such a way that they connect only slightly with the part so they can be easily removed. It is not necessary for the supports to connect with the entire surface of the part since the layers above are very thin and light and will not easily sag or sink.

Powder-based technologies use fine powder particles to form the part. Such powders are spread over a build platform layer by layer. These particles are somehow combined together to form the solid part. Two methods are commonly used to create the solid cross sections. The first method is commonly known as 3D printing, as devised by researchers at MIT (Sachs et al. 1992). In this approach the powder particles are bound or glued together using printing technology to selectively deposit the binder. The second approach uses a laser to melt the powder particles so that they flow together and rapidly cool into a solid (as illustrated by the Selective Laser Sintering process (3D Systems)). In both cases the scanning only takes place where the part is and the remaining powder remains in its original state. Like all other processes, a platform increments the part for subsequent layers to be added. In the powder systems, there is a constraining container that keeps the powder from leeching out. This powder therefore acts as a surrounding support that removes the need for building supports in the manner described above.

Extrusion-based systems require material to be extruded through a nozzle. The extruded material must be in a liquid state as it passes through the nozzle and hardens at a later point to form the solid part. Some simple approaches can apply the material in a gel or paste form that essentially dries out to form the solid. The resulting solid material is understandably very weak when using this approach and a more common method heats up the material until it is molten and therefore cools down rapidly to form the solid, like with the Fused Deposition Modeling process (Stratasys). The material must therefore be thermoplastic in nature to achieve this. Before the material cools or dries, it must bond with the subsequent material to form a complete solid. The same problem arises with this process as with stereolithography with respect to support structures. With these processes however it is common to have a second nozzle so that a second material can be extruded as a support. This second material can be chemically different so that the support removal can be assisted. For example, the part material could be insoluble in water so that a water-soluble material can be used for the support. One need only place the whole piece in water to facilitate the removal process.

While it is not essential that material be added in a planar layer-wise fashion, currently every commercial system operates in this way. Thus, complex 3D objects are simplified as a sequence of 2D planar layers. A layer is generally interpreted as a

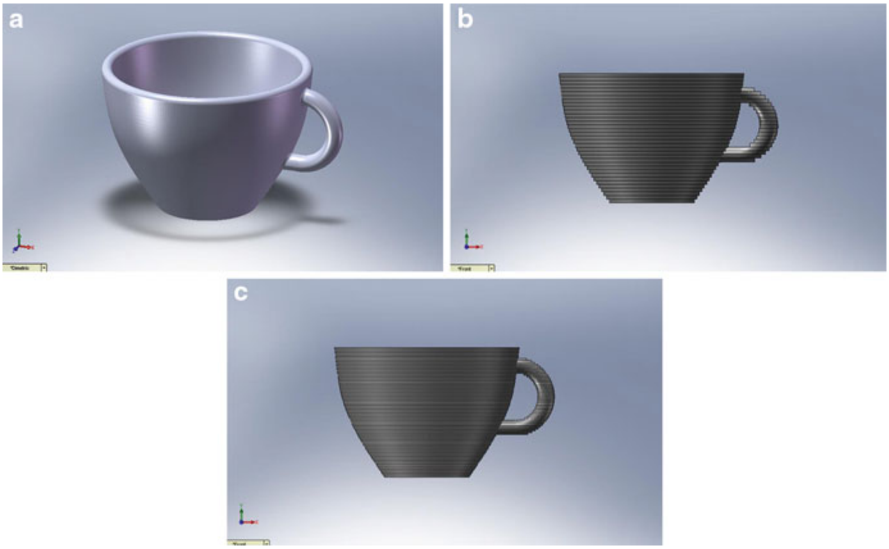

Fig. 2 A smooth CAD model (above) can be sliced with different thicknesses to produce more or less stair-stepping effects in the result (Gibson et al. 2009)

normal extrusion of a 2D profile intersection with the model data. One limiting factor of such technology is therefore the thickness of these layers (as seen in Fig. 2). Another limiting factor lies in the ability of the systems to create the layers themselves. Lasers have a beam width, extrusion heads have a nozzle diameter, printers have a droplet size, and projectors have a pixel resolution. The positioning of a laser, for example, can be achieved to a very fine precision, even submicron. The overall accuracy of a part may therefore be very good even though the minimum feature dimension, like the wall thickness, for example, may be comparatively large and based on the diameter of the laser beam or extrusion head, etc. Other factors like material shrinkage or vibration effects may also affect the accuracy of a part within a layer. Usually, the coarsest resolution results from the minimum layer thickness however and manufacturers have spent most efforts on trying to overcome this. It should be noted however that reduction of layer thickness will almost certainly increase the build time, and some systems provide a means of building with thicker layers when a part is required in as short a time as possible.

Conventional Commercial Systems with the Finest Resolution

There are numerous commercial technologies available. The vendors of these technologies are under pressure from competition to make their machines cheaper, faster, more accurate, and more capable of producing parts with improved mechanical properties. It is clear therefore that this is a matter of compromise, and so reducing the resolution of the parts may require the vendor to ignore other attributes. The fundamental aspects of some technologies allow parts to be made with higher resolution than others. It is therefore worthwhile considering each basic class in turn, even though photopolymer systems are currently the best in terms of accuracy. One may, for example, want the most accurate part that can withstand a certain temperature or require a certain minimum Young's modulus that is outside the capacity of photopolymer technology. Other less accurate systems may therefore be chosen accordingly.

The following sections describe the basic technologies that are applied for general Additive Manufacturing. There are some specialized systems that make use of similar technologies but specifically for creation of very fine-detailed parts.

Photopolymer Systems

Photopolymer systems are the most accurate currently available on the market. Liquid resins can be created with quite low viscosity and so can be delivered and controlled quite easily in low volumes when compared to molten polymers and powders. There are a variety of different ways in which photopolymers can be used in AM processes.

Stereolithography

As described earlier, stereolithography (SL) uses a laser to expose the photopolymer material by scanning across the surface. The part is built on a platform that is lowered into the vat of resin, thus growing the part from the bottom upwards. In order to ensure that surface tension does not disturb the surface of the resin and cause it to be uneven, a scraper (sometimes referred to as a doctor blade) redistributes the resin. This ensures that the part has a thin, precise layer of resin over the top of it. This spreading process can be used in conjunction with a "deep dip" that drags the part deep below the surface of the resin to ensure that resin does indeed cover the previous layer.

In order to maintain precision, precise mechanisms must be used. Leadscrew mechanisms with servomotor drive units maintain the positioning accuracy. Lasers scan using galvanometric mirrors and special optics are used to ensure the spot size is maintained over the entire build surface. Stability is maintained by having an enclosed build chamber where temperature and humidity are monitored and controlled so that the part does not swell during the process. Having said all this, there is still the possibility of part distortion due to uneven shrinkage of the part. This is very difficult to control since it is a function of the original part designed geometry. Parts taken off the SL machine will not be fully cured when taken off the machine and must be post-cured in a UV oven. If this post-curing is performed with the part still on the platform, distortion can be minimized. However, this may cause problems when cleaning up the part later, particularly when trying to remove the support structures.

SL machines are mostly supplied by one company called (3D Systems), who pioneered much of this technology. Although some machines claimed to have

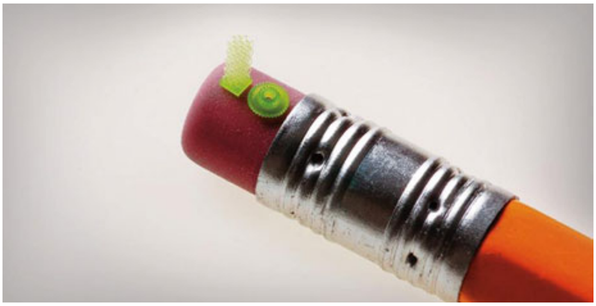

Fig. 3 Parts made using a Viper SL machine in high-resolution mode (Courtesy of FineLine Prototyping)

greater accuracy in the past, the most accurate machine today has a minimum layer thickness of 50 μm using their Zephyr recoating system. Apart from possible reliability issues in maintaining such a layer thickness, the reason for not going smaller than this value is probably due to the minimum laser diameter. The smaxllest laser spot size that can be achieved is 130 μm, although positioning of the laser is much more precise. This means however that the level of detail is limited by this dimension. While feature definition can be enhanced by correct orientation of the part within the machine, there is not much point in using thinner layers with this technique.

Another factor to consider is the build volume of the machine. SL machines can be 250 mm × 250 mm × 250 mm or larger in terms of build volume. If building large parts, scanning and resin distribution can take more than a minute for each layer. If using 50 μm layers, parts can take more than 4 days to complete. Most SL machines therefore have larger layer thicknesses and can even vary the laser spot size in order to reduce the overall build time. High precision is therefore only used commonly to make small parts using SL, and so the large vat size is therefore unimportant. Figure 3 shows some micron-scale parts that were made using the most precise SL equipment produced by 3D Systems with a resin specifically designed for this type of application.

Polyjet

The Stratasys Polyjet and Connex processes (originally developed by the company Objet, who subsequently merged with (Stratasys)) also use photopolymer resins. With this technology the resin is printed using drop on demand deposition heads, much like conventional 2D inkjet printing. The droplets of resin are printed using an array of print jets that make this a highly parallel process. Furthermore, there are different printheads for part material and support material. Once the droplets are deposited onto the platform or onto previous layers, a UV light follows the printhead to cure the resin. Part material will cure to a hardened solid polymer while the support material cures to a jellylike state that facilitates removal once the build has completed. The Connex process further elaborates this by allowing two separate part materials to be used and even permits the mixing of these part materials together in the build. Two materials of different colors can thus be blended to show gradient colors. It is even possible for two materials with different mechanical properties to be blended together using this process, and so hard and soft materials can be used to form a variety of different tactile effects.

The use of well-proven technology developed for the printing industry provides an excellent platform for quality and reliability. However, the photopolymer resins are still significantly higher in viscosity when compared to the inks that are normally dispensed by these devices. This means that care must be taken to prevent these nozzles from clogging. Further to this, only the lower viscosity resins can be used here and so the range of materials and properties is not as high as stereolithography. Since the droplets are extremely small, the resolution is equally small. The smallest layer thickness is approximately 15 μm. In-plane resolution is not as high since droplets will spread out and flatten on impact. However this is still very good and in the order of 50 μm. However build speed is still reasonable when compared with the laser-based technology due to the use of multiple print nozzles printing in parallel.

EnvisionTEC

This company initially introduced the Perfactory system (EnvisionTEC), which used 2D LCD arrays (similar to those used in flat screen computer monitors) as the mechanism to expose the photopolymer resin. This approach makes it possible to realize a very high resolution in all three Cartesian directions, especially since LCD screen resolutions have correspondingly increased in recent years. Since this enables exposure of a full layer, build speed is also quite high, albeit tempered by the lower light intensity that comes from LCD technology. This light is obviously in the optical range, and thus there is a need to have different resins compared with the other photopolymer systems, tuned to cure at a different frequency. Since the earlier systems, a range of new machines has been released by this company, aimed at specific application areas. There is a particular niche of small-scale medical applications, like in dentistry and the fabrication of in-the-ear hearing aids. Machines are also widely used in the jewelry industry as well due to the fact the materials work well with existing investment casting technology. Layer resolution is around 15 μm for some of their machines, dependent on which material is being used. In-plane resolution is about 45 μm, which is somewhat similar to the Objet machine.

Powder Systems

This approach makes use of powder to form the structure of the part. There are currently two technologies that make use of powders, powder binding and powder sintering. Powder binding is essentially the use of inkjet printing technology to glue powder particles together. Powder sintering makes use of polymer powders and uses laser energy to melt them, thus fusing them together to form a solid. Both of these technologies are limited by the powder particle morphology and dimensions. Unlike the resin-based systems, the particles are discrete and so cause problems relating to keeping them in place during the solidification process. The smaller the particle size, the more difficult this would be since the surface to volume ratio increases. With relatively low density polymeric materials, static charges are likely to attract the powder particles to surfaces, causing disturbance in position. Since there is no evidence of the powder binding systems being developed into a micron scale, it will not be described here.

While the term is somewhat misleading, the earliest powder-based technology was called Selective Laser Sintering. This process has been commercialized for polymers by the US company DTM, which was merged with 3D Systems a few years ago, and by the German company (EOS). Powder material is somehow deposited as a thin layer onto a build platform. There, laser energy is directed at the powder to cause localized melting (or at least sintering if the whole particles do not melt, hence the name), which rapidly solidifies to form the solid structure. Further powder is deposited onto the platform once it has been lowered by the thickness of one layer and the process is repeated. Constraining walls around the platform keep the part and un-melted powder in place. Since the surrounding powder is loose, there is no need for additional support structures.

One major benefit of powder-based systems is the range and quality of materials. These materials have some of the most superior mechanical properties available in Additive Manufacturing. Furthermore, this extends beyond polymer technology, with metal powders available, albeit requiring higher power laser technology as well as more precise control over the process parameters. This technology is also therefore currently among the most expensive.

The most limiting factor behind this process in terms of accuracy is the powder particle size. If particles are too small, it is difficult to prevent them from moving around the powder bed and adhering to other surfaces. It is possible to have smaller metal powder particles compared to polymer due to their higher density and also because polymers store electrostatic charge, which can cause them to move more. Particle sizes for polymer materials average around 70 μm, while metal powders can be lower. Unused powder from a previous build can be recycled into a later one. The elevated temperatures during the build can cause small particles to bind with others that will ultimately affect the final part accuracy.

Extrusion Systems

Extrusion-based technology is by far the most popular in recent times. This is partly because the material delivery process is the simplest of all. Material is extruded through a nozzle, which is mounted onto a three-axis positioning system. Material is therefore deposited using a single-channel approach with a phase change from molten (or gel state) to solid. The transition will cause the material to adhere to surrounding material, and the rapid cooling or solidification process will ensure the geometry remains intact. It is somewhat difficult to extrude material in a precise manner at a high feed rate, and so this process is considerably slower than competing processes. The competitive advantage therefore lies in the process simplicity that leads to low-cost machines. Recent expiration of key patents related to this technology and the publication of open-source designs have resulted in a large number of commercial systems exploiting this extrusion-based approach.

The most well-known and original technology is referred to as Fused Deposition Modeling and was commercialized through the company called (Stratasys). These machines are somewhat more sophisticated than the recent commercial systems because some patents remain in place that prevent the others from using environmental chambers to prevent temperature-based distortion in the parts. The Stratasys machines are therefore capable of making the highest quality and widest range of parts. Their extrusion heads are capable of melting high-temperature materials that can be used for functional application in demanding industries like automotive and aerospace parts. Furthermore, the more precise control of temperature permits the smallest nozzles to be used. However, even these machines are somewhat limited in accuracy compared with photopolymer and even powder-based systems. It is however worth mentioning extrusion-based technologies since it does have the capacity for creating micron-scale parts.

Commercial System Summary

The following Table 1 covers the current commercial technologies, indicating the most precise of the various systems available. These were taken from the published vendor information and were verified at the time of writing this chapter. Much of this technology can be considered relatively mature, and it is not expected that these machines are going to become much higher in resolution. Some specialist technologies have been developed specifically to push these barriers and that is the subject of the following section.

Table 1 List of Additive Manufacturing technologies with typical build dimensions from some of the referenced manufacturers

	Model	Build volume (mm)	Layer thickness (μm)	Minimum resolution (μm)
Stereolithography SL 3D Systems	iPro 8,000	650 × 750 × 550	50	130
Selective Laser Sintering SLS 3D Systems	sPro 60	381 × 330 × 457	80	100
Fused Deposition Modeling FDM Stratasys	Dimension Elite	203 × 203 × 305	254	254
Polyjet Stratasys	Objet30 Pro	294 × 192 × 148	16	100
Micro SL D-MEC	ACCULAS	150 × 150 × 50	5	2
Micro SLS EOS	EOSINT μ60	57dia × 30	5	30

[a]Note the figures are based on the manufacturer's claims in published data. Feature size is an estimate based on dimension of laser spot, nozzle diameter, head positioning accuracy, etc. The smaller model machines have been cited since these are likely to provide slightly higher accuracy

One is probably approaching the limit of resolution that these machines can reach. This is as much as anything to do with the speed at which these machines can produce parts and the constraints of building precision technology. If one is to build with much thinner layers than the current ones, the operating environment would probably have to include clean-room technology, parts would have to be fabricated to very high precision, and additional sensor/control systems would have to be implemented to monitor and maintain the system. All of this would make the machine cost-prohibitive to many users. It is clear that AM technology is moving towards a wider range of users, even for domestic use. If this is so, then it is not a good idea to add complexity and cost. It is therefore considered that micron-scale AM will take a different route to.

Dedicated Micro AM technologies

Two of the technologies mentioned above have been commercialized into micron-scale systems aimed at producing small, highly detailed free-form products. Until recently stereolithography was the only core technology that was available for this purpose. However, recent introduction of powder laser sintering technology at a micron scale has become available.

Micro-Stereolithography

As mentioned previously, stereolithography has proven to be the most popular and effective way of creating micron-scale AM parts. This is probably because liquid photopolymers are easier to handle compared with molten or powder materials. However, the polymerization process is still problematic. There appear to be two popular methods of causing polymerization: 2-photon and dynamic mask projection.

With 2-photon systems, instead of using UV light to cure the resin, high-intensity near infrared (IR) light is used. With UV, polymerization will take place at much lower intensity and roughly wherever the light hits the resin. As such, the resins used must be kept sealed and protected even from the UV radiation in ambient conditions. 2-photon polymerization is a more nonlinear process and really takes place when a very high intensity is present. As such, a near IR laser beam can be focused inside the resin, rather than on the surface and polymerization will only take place where that beam is focused. The focused region can be very small, in the order of 100 nm, which can result in very fine detail. Pulse duration can be in the femtosecond range and extremely high power (hundreds of gigawatts). Scanning time can be very fast, and since there is no requirement to raise or lower platforms or manipulate the resin during the build, small parts can be built very quickly. A full 3D geometry of 100 μm cube can be fabricated in a few minutes. Furthermore, the need for support structures is significantly reduced, although not completely eliminated.

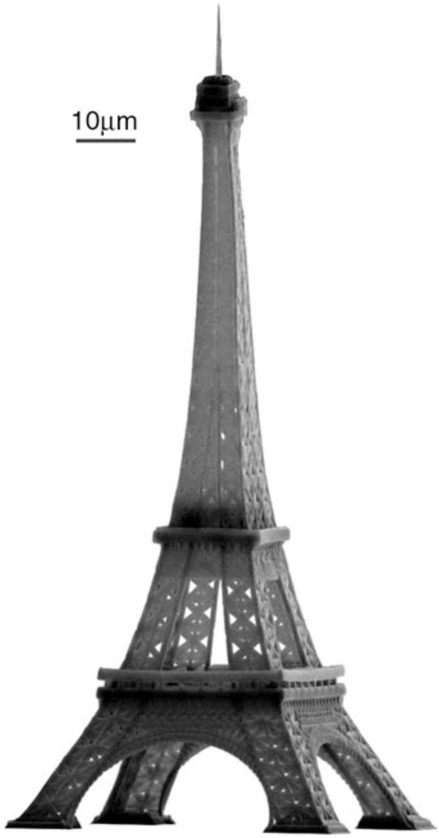

Fig. 4 Micro-stereolithography part (Courtesy of Nanoscribe GmbH)

The major disadvantage of 2-photon systems is the high cost. High-intensity fs IR lasers are expensive and somewhat rare. The optics required to focus these lasers and the positioning systems are all extremely difficult to build. Resins, although requiring careful formulation, are not so difficult to source since many have already been developed for the semiconductor industry as part of the wafer fabrication processes. However, it should be noted that fabricating and handling complex 3D parts that may be difficult to even see with the naked eye demand precise technologies regardless of which process is used. A 2-photon system is commercially available from the German company (Nanoscribe). A sample part built with features smaller than 1 μm using this process can be seen in Fig. 4.

The dynamic mask projection approach uses the more conventional UV curing approach. As such, there is a need for a build platform that raises and lowers so that layers can be created using mechanical positioning. Layers of around 5 μm can be achieved, but surface tension effects require careful handling of the resins, including allowing time for the resin to settle to a flat surface. The lower the viscosity of the resin, the quicker this settling will be. Raising the temperature of the resin can help to reduce this viscosity, but even so there are a limited number of resins that would work using this technology.

With UV curing, lasers are not a good option since polymerization does not require much energy. A single laser would take time to scan across the surface and resolution would be determined by the diameter of the laser. A more effective approach would be to use an approach that can expose a full layer at the same time, similar to the EnvisionTEC Perfactory process. A popular approach to achieve this is to use a digital micromirror device (DMD). This technology was developed for projector devices and consists of an array of tiny mirrors that can change position due to an attached actuator. By shining light onto or away from the surface of the resin, depending on the position of the mirror, it is possible to create a 2D mask. DMDs are high resolution (over 1,000 $\times$ 1,000 pixels) and can be focused to the correct dimensions using suitable optics. High-speed switching of the actuator can result in gray-scale exposure, but it is not clear whether this would work or has been used to improve the layer precision. Even so, with a conventional DMD and a 5 mm vat size, it is possible to achieve 5 μm resolution.

Support structures are necessary using this approach. However, the small scale of the system and the corresponding part dimensions means that only a few supports would be needed for any part. A technique that has been used is to place the supports in such a way that the part is not physically connected to the part. A small gap of one layer thick can be placed between them, relying on the surface energy of the liquid resin to keep the geometry in place. Such small parts would benefit from any approach that simplifies or reduces the amount of handling of parts coming from these machines. The ACCULAS system from Japanese company D-MEC uses a DMD approach (D-MEC), achieving a spatial in-layer resolution of 1 μm and a layer thickness of 5 μm.

Since the DMD-based technology is based on more readily obtained components, it is inevitably going to be cheaper. However, the resolution is not as good as 2-photon laser-based machines.

Micro Selective Laser Sintering of Metals

Already well-known for conventional SLS technology, the German company EOS recently introduced a micro SLS machine (EOS). At the time of writing, this machine is in beta testing but has already been used to produce many micron-scale parts (Fig. 5). The main advantage of this process is the materials used. EOS uses metal powders in a similar way to conventional SLS machines, the main difference being the scale of the machine. With metals being high density, it is possible to reduce the powder particle size to much lower than polymer powder systems without having problems with the material feed requirements. The quoted layer thickness for the EOS machine is a minimum of 1 μm, which must be the approximate size of the powders used.

The energy requirements for such a system to melt powders, even in thin layers, are quite high. Beam technologies, like lasers, are currently the only option for

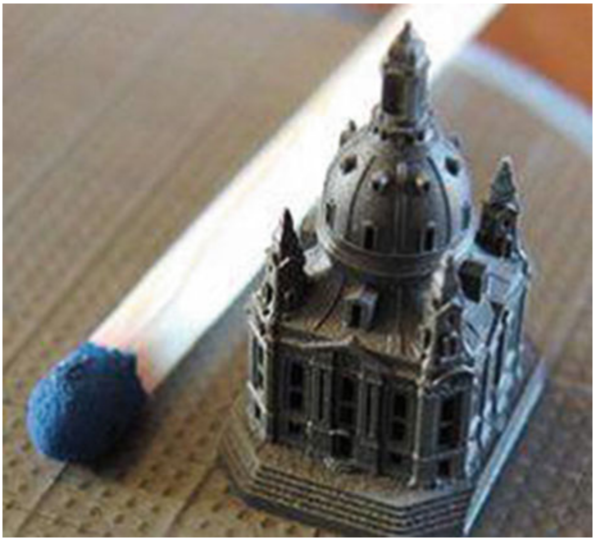

Fig. 5 A metal part fabricated using an EOS micro SLS machine (Courtesy of EOS)

metals in such machines. The use of a laser means much the same as mentioned previously that the processing (scanning) time is quite long and that there is a limited resolution correlating to the beam diameter. The laser beam used in the EOS machine is 30 μm, which corresponds to a minimum feature dimension of 50 μm due to thermal transfer effects in the melt region.

As a contrast, metal parts can also be produced using Microfabrica's MICA technology (Microfabrica). This technology uses lithographic processes developed for semiconductor device manufacturing. Materials like palladium, rhodium, and nickel-cobalt can be fabricated this way. Parts are generally quite flat, with 5 μm layers, features of around 1 μm, and gaps around 10 μm. Each layer has an extremely good surface finish.

Experimental Systems

There are numerous research projects investigating micron-scale Additive Manufacturing. Many are based on the micro-stereolithography systems described above. Work may involve new resin formulations, more precise positioning devices, higher resolution exposure systems, or better environmental control. Improvements are primarily incremental and most of the work can be easily searched.

Research into other technologies may not be so easy to find however. For example, attempts to fabricate micron-scale Fused Deposition Modeling technology may be overlooked. A requirement for micro FDM would be to reduce the extrusion filament dimensions, which would make layer thicknesses smaller as well as allowing finer-detailed parts to be defined in-layer. As the extrusion nozzle becomes narrower, so the outer surface to volume ratio decreases. This means that the shear forces observed at the walls of the nozzle start to dominate the material outflow. Pressure required to push material out of a nozzle becomes exponentially more difficult as the diameter decreases. If the shear forces vary in different parts of the barrel due to uneven polishing or scratching of the inside, the flow direction can also be affected and the material may not come out of the barrel straight. Since the distance between the nozzle and the platform or part on the platform is very small, this may not have a large impact, but all inconsistencies in the process can lead to inaccuracies. With most FDM systems, the material is heated in a chamber and cools during travel down the nozzle. One technique that could be adopted is to maintain the temperature during this travel to provide consistent flow. A proposed new design for a 50 μm FDM system with heated nozzle including a good study on how to model the molten material flow throughout the system can be found in (Monzón et al. 2013).

As mentioned previously there have been a number of developments in stereolithography technology that are moving away from the conventional approach used in larger systems. The 2-photon approach makes it possible for the resin to cure within a very sharp cutoff region, thus making it suitable for micro- and even nanoscale structures. The photopolymer molecules absorb two photons instead of just one in conventional SL and so are excited to a higher state. An experimental 2-photon system was developed by Lim et al. (Lim et al. 2005) that effectively demonstrates the feasibility of this approach, but it is clear that there is still much work to be done to make it a truly viable technology, including the development of appropriate polymer systems (Schafer et al. 2004).

Another approach that can be applied to micron-scale photopolymer technology is the use of two energy sources, namely, ultraviolet combined with infrared radiation in the form of stereo-thermal lithography (Bartolo and Mitchell 2003). The photopolymer requires to be formulated with both photo and thermal initiators. This makes the curing more localized and efficient, which turn will make the parts more accurate. The curing process can be very complex and involve a number of stages. While this is somewhat involved, an advantage is that multiple material parts can be possible.

Summary

It should be noted that micron-scale Additive Manufacturing is not the same as lithographic technology that was developed from the semiconductor industry and operates on the nanometer scale. AM is not just about being able to make parts using a layer-based approach but also being able to achieve this quickly and easily directly from CAD-generated 3D model data. Lithographic processes, like LIGA, can make some kinds of 3D shapes, but they are by no means as quick and versatile as what is expected from AM technology, particularly in terms of producing the geometric freedom required. Parts made from micro AM are therefore slightly less precise but considerably higher in geometric complexity.

When you reduce the scale of AM technology, some of the factors that were originally assumed to be negligible start to take effect. This can include surface tension of resins causing the parts not to be flat or the shear forces in nozzles causing material not to flow smoothly. For larger parts requiring lower resolution using conventional AM, these factors can be ignored. Furthermore, handling of such small parts can cause problems for the user, not only in terms of ensuring the part is not damaged, but also in how it may affect the system. Intensive calibration must be done every build to ensure the settings are correct.

Micro Additive Manufacturing is definitely a niche application field within the wider AM market. It makes use of similar approaches and devices that can be found in its bigger brother. However, in order to get the best out of it, new machines are likely to evolve away from this into more specialist technologies. They will still use a layer-based approach with direct driving from the CAD slicer software, but they will also have special features that assist in the material delivery at such a high resolution.

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