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Free-Form Fabrication- An Emerging Trend in Engineering

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***Abstract*—Free form fabrication is poised to bring about a revolution in the way products are designed, manufactured, and distributed to end users. This technology has gained significant academic as well as industry interest due to its ability to create complex geometries with customizable material properties. Free form fabrication has also inspired the development of the maker movement by democratizing design and manufacturing. Due to the rapid proliferation of a wide variety of technologies associated with Free form fabrication, there is a lack of a comprehensive set of design principles, manufacturing guidelines, and standardization of best practices. These challenges are compounded by the fact that advancements in multiple technologies (for example materials processing, topology optimization) generate a ‘‘positive feedback loop’’ effect in advancing Free form fabrication. In order to advance research interest and investment in free form technologies, some fundamental questions and trends about the dependencies existing in these avenues need highlighting. The goal of our paper is to discuss fundamental attributes of free form processes, evolution of the manufacturing industry, and the affordances enabled by the emergence of Free-form fabrication in a variety of areas such as geometry processing, material design, and education.**

***Index Terms*— Free-form fabrication, geometry processing, material design.**

I. INTRODUCTION

Thirty years into its development, additive manufacturing has become a mainstream manufacturing process. Additive manufacturing build up parts by adding materials one layer at a time based on a computerized 3D solid model. It does not require the use of fixtures, cutting tools, coolants, and other auxiliary resources. It allows design optimization and the producing of customized parts on-demand. Its advantages over conventional manufacturing have captivated the imagination of the public, reflected in recent mainstream publications that call additive manufacturing “the third industrial revolution.” ASTM has defined free-form manufacturing as ‘‘a process of joining materials to make objects from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing methodologies. Synonyms: additive fabrication, Additive processes, additive techniques, additive layer manufacturing, layer manufacturing, additive manufacturing, rapid manufacturing or rapid prototyping’’. This definition is broadly applicable to all classes of materials including metals, ceramics, polymers, composites, and biological systems.

Unlike conventional manufacturing techniques such as machining and stamping that fabricate products by

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removing materials from a larger stock or sheet metal, additive manufacturing creates the final shape by adding materials. It has the ability to make efficient use of raw materials and produce minimal waste while reaching satisfactory geometric accuracy. Using Free-form manufacturing, a design in the form of a computerized 3D solid model can be directly transformed to a finished product without the use of additional fixtures and cutting tools. This opens up the possibility of producing parts with complex geometry that are difficult to obtain using material removal processes. As such, it is unnecessary to consider design for manufacturing and assembly (DFM/DFA) principles in product design, which is conducive to design innovation. Free-form fabrication enables environmental friendly product design as well. Unlike traditional manufacturing processes that place many constraints on product design, the flexibility of AM allows manufacturers to optimize design for lean production, which by its nature eliminates waste. In addition, AM's ability to construct complex geometries means that many previously separated parts can be consolidated into a single object. Furthermore, the topologically optimized designs that Free-form fabrication is capable of realizing could increase a product's functionality, thus reducing the amount of energy, fuel, or natural resources required for its operation.

II. FREE-FORM FABRICATION METHODS

A large number of Free-form fabrication processes are now available; they differ in the way layers are deposited to create parts, in the operating principle and in the materials that can be used. Some methods melt or soften materials to produce the layers, e.g. selective laser melting (SLM), selective laser sintering (SLS) and fused deposition modelling (FDM), while others cure liquid materials, e.g. stereolithography (SLA).
Each method has its own advantages and drawbacks, and some companies consequently offer a choice between powder and polymer for the material that the object is built from. The main considerations made for choosing a machine are generally its speed, its cost that of the printed prototype, the cost and range of materials as well as its colour capabilities. Nowadays, there is a significant tendency towards Free-form fabrication of structural, load-bearing structures, by taking advantage of the inherit design freedom of such a process. Those structures need to be built from metal; therefore, focus is given to processes, such as SLS/SLM, DMD and EBM for industrial uses.

III. LASER-BASED PROCESSES

Laser-based Free-form manufacturing processes use a laser source of medium to low power in order to melt, solidify or cure the material. The laser-based processes can be distinguished in two sub-categories, depending on the phase change mechanism, namely laser melting and laser polymerization. In the laser melting processes, the material is supplied, in the form of powder, either to a powder bed or via nozzles directly to the processing head. A laser beam is used in order to melt the material, which then cools down and solidifies in order for the part to be produced. In laser polymerization, the material is usually a photosensitive resin, which is being cured upon its exposure to UV radiation, provided by a low-power laser source.

A. Laser polymerization

All laser polymerization additive manufacturing processes are based on the same material phase change principle; a liquid photosensitive resin that solidifies upon illumination from a (usually a low-power) laser source. Laser polymerization processes are limited in producing polymer parts of relatively low-strength resin, therefore, they are usable in prototyping and non-structural applications rather than in structural parts' production.

- **Stereolithography (SLA)-** Stereolithography is based on the photo polymerization principle of photosensitive monomer resins when exposed to UV radiation. The UV radiation source is a low-power He-Cd or Nd: YVO4 laser (up to 1000 mWin modern machines that solidifies a thin layer on the surface. An SLA machine mainly consists of a built platform, which is immersed into a bath of liquid resin and a laser source, including the appropriate hardware and software for control. A layer of the part is being scanned on the resin surface by the laser, according to the slice data of the CAD model. Once the contour of the layer has been scanned, the interior is crosshatched and hence solidified; the platform is being submerged into the resin, one layer below. A blade sweeps the surface to ensure flatness and the next layer is built, whilst simultaneously is attached to the previous one.
- **Solid ground curing (SGC)-** SGC is a photo-polymer-based additive manufacturing technology in which the production of the layer geometry is carried out by means of a high-powered UV lamp or laser

source through a mask. SGC was developed and commercialized by Cubital Ltd. in 1986. While the method offers good accuracy and a very high build rate, it bears high operating and changeover costs due to the systems complexity.

- **Liquid thermal polymerization (LTP)-** LTP is a process similar to SLA in the way that the part is built by solidification of successive layers of liquid polymer. However, the polymers used in LTP are thermosetting instead of photopolymers and hence, the solidification is induced by thermal energy rather than light. The thermal nature of the process makes the control of the size of the polymerization zone difficult, due to the dissipation of heat, therefore, the parts produced by this method are less accurate. Nevertheless, the process has a relatively high throughput and can be considered in applications where accuracy is not an issue.
- **Beam interference solidification (BIS)-** BIS is based on point-by-point solidification of photosensitive polymers at the intersection of two laser beams having different wavelengths. The first laser excites the liquid polymer to the reversible metastable state, which is subsequently polymerized by the radiations of the second laser. The process is associated with various technical limitations such as insufficient absorption of laser radiation at higher depths, shadowing effects of the already solidified material and diffraction of laser light, leading to difficulties in obtaining the precise intersection of the beams.
- **Holographic interference solidification (HIS)-** In this process, a holographic image is projected on a liquid photosensitive polymer contained in a vat so as for the entire surface of the polymer to be solidified, instead of point-by-point. In that essence, the process is really similar to that of solid ground curing.

B. Laser melting

Laser melting additive manufacturing processes use a laser source to selectively melt a material supplied in the form of fine powder. The material then cools down and solidifies to form the final part. Scanning optics is being used to steer the laser beam in the x-y plane, while a table moves towards the z direction.

- **Selective laser sintering (SLS)-** Selective laser sintering uses a fine powder, which is heated by a laser beam (ranging from 7Wfor plastic up to 200 W in such a way so as to allow the grains to fuse together. Albeit the process is known as sintering, it is not entirely true. Before the powder is sintered by the laser beam, the entire bed is heated just below the melting point of the material in order to minimize thermal distortion and facilitate fusion in the previous layer. After each layer has been built, the bed is lowered and a new powder layer is applied. A rotating roller is then used to spread the powder evenly. The sintered material forms the part, while the unsintered material powder remains in place to support the structure. The unsintered material may be cleaned away and recycled after the build has been completed. Materials, such as metal powders, nylon, nylon composites, sand, wax and polycarbonates, can be used. However, the process is still relatively slow (when compared to EBM for metallic structures for instance) and suffers from issues such as non-uniform thermal field distribution, which might lead to thermal distortion and cracks on the product. Despite that, SLS's high degree of accuracy and surface quality renders it one of the most commonly used metal AM processes.
- **Selective laser melting (SLM)-** Selective laser melting is a process similar to SLS; the two are instantiations of the same concept but differ in technical details. Instead of sintering, in the SLM process, powder melting occurs in order to form a part. Therefore, laser beam power is usually higher (around 400 W).
- **Direct metal laser sintering (DMLS)-** Direct metal laser sintering is another commercial name used for the description of a laser-based additive manufacturing process, similar to SLS/SLM. However, while SLS/SLM is able to process a variety of materials, the DMLS processes metallic powder only. The DMLS has been developed by EOS and it is a trademarked name. The typical laser power of the EOS machines is 200–400 W.
- **Laser engineered net shaping (LENS)-** Laser engineered net shaping uses a high-power laser to melt metal powder. A specially designed powder delivery nozzle injects the powder stream directly into the focused laser beam, and the laser head and powder nozzle move as an integral unit. Metal powders are delivered and distributed around the circumference of the head either by gravity or by using a pressurized carrier gas.

The laser beam creates a small molten pool on the substrate or previously deposited layers. The powder fed into this region is consumed in this puddle, causing its height to grow away from the substrate surface. The x-

y table is moved to fabricate each layer of the object. The head is moved up vertically as each layer is completed. This technique is equivalent to several trademarked techniques, such as DMD, LPD and SLC.
Compared to processes that use powder beds, such as SLM, objects created with this technology can be substantially larger, even up to several meters long; however, the accuracy and surface quality are usually lower.

- **Direct metal deposition (DMD)-** DMD is an additive manufacturing technique that uses a laser as the power source to sinter or melt powdered material (typically metal), with the laser automatically aiming at points in space, defined by a 3D model, binding the material together to create a solid structure. The operating principle is really close to the SLS/SLM process, albeit lacking in a powder bed; instead powder is fed by a number of nozzles (usually 3) directly to the processing head, similar to that of LENS.
- **Laser powder deposition (LPD)-** In this layered manufacturing process, a powder/air stream is injected directly into the laser beam focus point on the substrate. Variants of this process are LENS, SLC, SDM and DMD.
- **Selective laser cladding (SLC)-** Selective laser cladding is another commercial material processing technique that uses the laser as a heating source to melt metal powder to be deposited on a substrate. This technique is being applied, as a rapid manufacturing (RM) process, to generate a point-by point and a layer-by-layer part. It has been introduced as a means of creating functional metal parts with near-net shape geometries and has a significant advantage over the traditional RP techniques. This is due to the direct fabrication of a near net shape part compared to the two-step process, involving an intermediate step of mould preparation in conventional RP techniques.

IV. Extrusion Processes

The material extrusion processes are thermal and use a heated extrusion nozzle in order to soften or melt material, usually plastic, provided in the form of wire. After being melted, the material passes through an extrusion nozzle that deposits the material, which then cools off in order to solidify and form the final part geometry.

A. Fused deposition modelling (FDM)

The FDM technique uses a movable head, which deposits a thread of molten thermoplastic material onto a substrate. The material is heated up to 1 °C above its melting point, so that it solidifies right after extrusion and subsequently welds to the previous layers. The FDM system head usually includes two nozzles, one for the part material and one for the support material. The system’s advantage is that it can be viewed as a desktop prototyping facility, since it uses cheap, non-toxic, odourless materials, in a variety of colours and types, such as acrylonitrile butadiene styrene (ABS), medical ABS, PLA, investment casting wax and elastomers. The simplicity of the FDM process, the relatively cheap equipment and the raw materials render its use ideal by hobbyists as well as the production of low-cost plastic parts. However, accuracy and surface quality are relatively poor when compared to those of powder-based plastic AM processes.

B. Robocasting

Robocasting is a freeform fabrication technique that is based on layer-wise deposition of highly loaded colloidal slurries for dense ceramics and composites. The process is essentially binder less with less than 1 % organics and the parts can be fabricated, dried and completely sintered in less than 24 h.

V. Material Jetting

The material jetting processes use thin nozzles in order to “spray”, in a controlled manner, either molten material or more usually a binder (adhesive) in order to bind the powder in a solid object. The process operating principle is much like all the laser-melting processes, albeit no phase change occurs; instead, the binder holds the powder particles together.

A. Three-dimensional printing (3DP)

3DP is a layered manufacturing process, where parts are created inside a piston, containing a powder bed. In more detail, the piston is gradually dropped and a new layer of powder is spread across the top. The part is formed by “inkjet printing” the binder into the powder.

B. Inkjet printing (IJP)

IJP is a type of computer printing that creates a digital image by propelling droplets of ink onto paper, plastic or other substrates. Inkjet printers are the most commonly used types of printers and range from small inexpensive consumer models to very large professional machines that can cost tens of thousands of dollars or more.

C. Multijet modelling (MJM)

The principle underlying MJM is the layering principle, used in most other RP systems. The MJM builds models using a technique akin to inkjet printing applied in three dimensions. The MJM head moves in the x-y plane, depositing special thermo-polymer material only where required, building a single layer of the model. A UV lamp flashes through each pass to cure the thermo-polymer deposited. When the layer is complete, the platform is distanced from the head (z-axis) and the head begins building the next layer. The BPM process involves a stream of molten droplets ejected from piezoelectric inkjet printing nozzles to be deposited on the target substrate. The process still uses the 3D data of the solid model to position the stream of material on the substrate. Since the process is based on the material's melting, it is particularly suited for the materials, namely thermoplastics and metals that easily melt and solidify.

D. Thermojet

Thermojet is a process similar to multijet modelling. The system generates wax-like plastics models, albeit with less accuracy than SLA. The machine uses a wide area head with multiple spray nozzles. These jetting heads spray tiny droplets of melted liquid material which cool and harden on impact to form the solid object. This process is commonly used for the creation of casting patterns in the jewelry industry and other precision casting applications.

VI. ADHESIVE

Adhesive-based processes are of limited use nowadays. The operating principle involves (usually a laser) a cutter, which cuts a thin film of paper or plastic in the desired outlines. The film is then pressed down onto the previous one by a heated compactor, thus activating a heat curing adhesive present on the downwards face of the film, in order to be bonded to the substrate.

A. Laminated object manufacturing (LOM)

The material used in LOM is a special kind of paper, having a heat-sensitive adhesive applied to one of its sides. The paper is supplied from a roll and is bonded to the previous layer with the use of a heated roller, which activates the paper's adhesive. The contour of the layer is cut by a CO2 laser, carefully modulated to penetrate into a depth of exactly one layer (paper) thickness. Surplus waste material is trimmed to rectangles to facilitate its removal but remains in place during build-in order to be used as support. The sheet of material used is wider than the building area, so that, when the part layer has been cut, the edges of the sheet remain intact in order to be pulled by a take-up roll and thus to continuously provide material to the next layer.

B. Solid foil polymerization (SFP)

The process is based on complete polymerization of semi polymerized plastic foils on exposure to suitable light source. The semi-polymerized foil is first stacked on the previously solidified part and then illuminated such that bonding is achieved after complete polymerization. The excess foil that is not illuminated can be removed by being dissolved into suitable solvent, leaving behind the desired part.

VII. ELECTRON BEAM

Electron beam processes are identical to the laser-melting processes but instead of a laser beam, an electron beam is used as an energy source in order to melt or sinter the material.

A. Electron beam manufacturing (EBM)

EBM is a relatively new but rapidly growing process similar to SLS, albeit suitable for building metallic parts only. Powder is melted by an electron beam powered by a high voltage, typically 30–60 KV. The process takes place in a high vacuum chamber to avoid oxidation issues. EBM can also process a high variety of pre-alloyed metals. When compared to SLS, EBM can offer much higher throughput and more uniform thermal field distribution; however, accuracy and surface quality are lower.

NOTE: Occupational & environmental effects of Free-form manufacturing processes are as follows-

- SLA - Readily bio-degradable & has a potential to deplete oxygen from aqueous system.
- 2SLS - Eco-toxicity is low
- LENS - No hazardous decomposition products.
- FDM – No hazardous decomposition products.

VIII. Related Works

Several researchers have conducted their studies on free form fabrication. Number of reviews has been taken below to complete the present study.

Ref. [1] Mohammad Vaezi, Hermann Seitz and Shoufeng Yang classified 3D micro-AM processes into three main groups, including scalable micro-AM systems, 3D direct writing, and hybrid processes, and they reviewed the key processes comprehensively. They described the principle and recent progress of each 3D micro-AM process with the advantages and disadvantages.

Ref. [2] Kaufui V. Wong and Aldo Hernandez discussed on the relevant additive manufacturing processes and their applications. They reviewed the studies which were about the strength of products made in additive manufacturing processes.

Ref. [3] William E. Frazier reviewed rapidly emerging manufacturing technology that was alternatively called additive manufacturing (AM), direct digital manufacturing, free form fabrication, or 3D printing, etc. He provided a broad contextual overview of metallic AM.

IX. Conclusions

After 30 years of research and development, Free-form fabrication has evolved from a niche process for rapid prototyping to a legitimate manufacturing process for parts production. Many companies are producing commercial parts using Free-form fabrication process. For example, Boeing now has 200 different AM part numbers on 10 production platform. Several mainstream publications, including the Economist, Forbes, and USA Today, have brought public attention to the Free-form manufacturing technology. The April 2012 issue of the Economist billed Free-form manufacturing as the production technology of the future and called it “the third industrial revolution.” It is highly likely that AM will have a significant societal impact in the near future. A critical technical review of the promises and potential issues of Free-form manufacturing is beneficial for further advancing its development. This paper predicted many positive impacts of Free-form manufacturing, summarized as follows:

- Customized healthcare products to improve population health and quality of life. AM has been used to produce customized surgical implants and assistive devices in the healthcare industry. Researchers are now investigating the use of Free-form manufacturing to produce scaffolds for tissue engineering applications and drug delivery devices. Because Free-form manufacturing is well suited to produce customized products, it is expected to play a significant role in personalized healthcare to improve the safety, quality, and effectiveness of healthcare for the general population.
- Reduced environmental impact for manufacturing sustainability. Compared to conventional machining processes, Free-form fabrication is more efficient in terms of virginal material consumption and water usage. It does not require the use of coolant and other auxiliary process inputs, and thus produces less pollution to the terrestrial, aquatic, and atmospheric systems. It also requires less landfill. Therefore, Free-form fabrication is expected to become a key manufacturing technology in the sustainable society of the future.
- Simplified supply chain to increase efficiency and responsiveness in demand fulfillment. AM is conducive to innovative design and enables on-demand manufacturing. As a result, the need for warehousing, transportation, and packaging can be reduced significantly. With proper supply chain configuration, it is possible to improve cost efficiency while maintaining customer responsiveness using Free-form fabrication. With the advent of personal AM machine, the dream may come true where customers can obtain desirable products economically whenever they want and without leaving their home.

REFERENCES

[1] Mohammad Vaezi & Hermann Seitz & Shoufeng Yang, “A review on 3D micro-additive manufacturing technologies”, International Journal of Advance Manufacturing Technology, 2013, Page-1721–1754

[2] Kaufui V. Wong and Aldo Hernandez, “A Review of Additive Manufacturing”, International Scholarly Research Network ISRN Mechanical Engineering, Volume 2012, Article ID 208760, 10 pages

[3] William E. Frazier, “Metal Additive Manufacturing: A Review”, Journal of Materials Engineering and Performance, 2014.