Evaluation of the Effectiveness of Digital Fabrication Technologies

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Introduction

Digital Fabrication is also known as Digital Manufacturing, Rapid Prototyping, Solid Freeform Fabrication (SFF), Rapid Manufacturing, Desktop Manufacturing, Direct Manufacturing, Direct Digital Manufacturing (DDM), and Layered Manufacturing. It primarily includes additive methods that build objects in layers, but it also includes systems that combine additive and subtractive technologies. The following paper traces the evolution of patterned controlled to numeric controlled to subtractive computer numeric controlled to additive and hybrid computer controlled manufacturing methods. It describes and evaluates each of these methods for their existing possible applications based on its systematic limitations.

Origins of Numeric Control for Manufacturing

The automation of manufacturing to increase production speed, accuracy and product quality, while reducing labor cost, gave rise to types of patterned mechanisms for managing manufacturing processes. The use of punched paper rolls and punched cards to instruct looms as to the pattern to weave offers examples of process control mechanisms that foreshadowed numeric controls.

In 1725, Basile Bouchon[i], a textile worker in Lyon, France and son of an organ maker, used a roll of perforated paper tape to partially automate the process of setting up drawlooms[ii]. These devices employed cords as part of their figure harness to lift each weft thread in order to weave patterns into fabric. Bouchon's punched paper roll increased the accuracy of patterning by directing the action of the figure harness. In 1728, Bouchon's assistant, Jean Batiste Falcon, improved the process by replacing the punched paper tape with an endless loop of sewn together rectangular cards with its punched holes arranged in rows. The process still required two workers, a weaver to operate the shuttle and tension the weave and a drawboy to manage the figure harness according to the punched pattern. In 1745, the inventor Jacques de Vaucanson, who created automatons including a life sized flute player with a repertoire of twelve songs, a tambourine player and a duck that could drink, eat grain and defecate, developed an automated loom advancing Bouchon's and Falcon's punched control systems. The weavers of Lyon, however, did not adopt the Vaucanson design until Joseph Marie Jacquard adopted its principles in the creation of his successful Jacquard loom in 1801. As the son of a family that owned a mill, Jacquard could implement and benefit from the use of his device, a position Vaucanson lacked in overcoming weaver objections to the labor savings his invention enabled. The Jacquard process and its variants rapidly became methods for weaving patterned fabrics due to their cost savings and improved accuracy.

Beginning in 1946, John T. Parsons and Frank L. Stulen[iii] used punch card controlled computers to calculate the complex curves required for machining of helicopter rotor blades. By 1948, the US Government awarded Parsons' company a contract for complex curve aircraft wing manufacture. IBM with its computing capabilities and MIT with its expertise in servo-mechanics participated as subcontractors for the project. The developments of this group for servo controls and programming language led to computer numeric control (CNC), the basic carriage mechanism for subtractive and later additive digital fabrication. On May 5' 1952, Parson filed the patent titled, *Motor Controlled Apparatus for Positioning Machine Tool*, which the US Patent Office awarded him in January of 1958, US Patent # 2,820,187.

During the early 1980s, Chuck Hull[iv] created one of the first additive digital fabrication methods, which he termed Stereolithography (SLA), for which USPTO awarded him US patent # 4,575,330 in 1986. During that same period, Dr. Carl Deckard of the University of Texas at Austin developed Selective Laser Sintering (SLS).

Additive and Hybrid Digital Fabrication Methods

Stereolithography (SLA or SL)

According to 3D Systems, the largest manufacturer of additive digital fabrication equipment, 75% of additive digital fabrication products used Stereolithography[v] (SLA or SL), which uses 3-D CAD data to target laser emitting UV energy to fuse liquid photo-reactive resins materials and composites into solid cross-sections, layer by layer, in order to build three-dimensional parts. SLA technology has proven useful for concept development, design validation, form and fit analysis, molding and casting patterns, wax forms for jewelry casting, dental forms, architectural models, and some machine molds & parts. It is limited to prototypes, models, casting forms, and small plastic products, all of which using photopolymers available for SL processing. UV curable SL chemistry contains photo-initiators that are relatively costly and potentially hazardous ingredients. Most SLA resins are acrylates that use the free radical photo initiators. The photo-initiated process involves both diffusion of the UV radiation and oxygen inhibition of polymerization. It also suffers from slow production speed and visible artifacts from the layering and curing process. Some of the photopolymer chemistry is difficult to sand and paint.

Micro Stereolithography (MSL)

Like standard stereolithography, micro stereolithography forms 3-D items through layer-by- layer coating and laser UV curing photosensitized resins[vi]. MSL, however, uses very fine resin solids that provide layers as thin as 1 micrometer.

Researchers have developed a number of strategies for refining the resolution of standard stereolithography processes to produce layers in the single digit micrometer to nanometer range that eliminate visible artifacts and feature resolutions that enable functions at micrometer and nanometer scales. Some system designs refined the focus of lasers within the layer as opposed to others that targeted the surface of the layer. Other systems reduced the diffusion of the laser's UV radiation to improve acuity.

MSL includes the D-MEC (Japan) Acculas Micro Laser Modeling System. It is used for producing MEMS (Micro Mechanical Electrical Systems) prototypes and manufacturing MEMS devices and master molds for nanoprint lithography.

Our presentation will also evaluate Film Micro Stereolithography (FMSL).

Laser-Engineered Net Shaping (LENS)

LENS uses a print head that moves in X, Y, and Z-axes with tilt and rotate, pitch and yaw options on some devices. High-intensity fiber laser light is focused through the print head to sinter the metal powder as it exits the head and attaches to the target substrate in an atmosphere of inert gas to prevent oxygen from contaminating the process. Defense, Aerospace, Energy Industries and medical device manufacturers use LENS fabrication systems to both repair and fabricate metal parts using titanium, nickel, cobalt, stainless steel and other alloys. Optomec, headquartered in Albuquerque, NM, manufactures the LENS MR7, LENS 750 and LENS 850-R systems.[vii] The LENS 850-R offers a work area envelope of 900x1500x900 mm.

LENS ability to form fully dense parts with high performance characteristics along with its ability to repair as well as manufacture parts has favored high tech industries using it. One drawback to LENS is its lack of support fillers, which can result in an object with excess material that requires post-processing machining.

LENS is also termed Direct Metal Deposition (DMD).

Selective Laser Sintering (SLS) Direct & Indirect

SLS uses a laser to cure photosensitive powder, to selectively sintering it and bond it to form a thin layer on the object. It builds objects layer-by-layer in a temperature controlled oxygen-free chamber (typically in a nitrogen atmosphere) on a build piston platen. A powder leveling roller coats the build piston after each scanning laser curing until the object is fully built. SLS can fuse small particles of ceramic, glass, plastic or metal layer-by-layer into functional products or parts. Direct Selective Laser Sintering use materials, such as metal powders without binders, that once sintered do not require post processing. Indirect Selective Laser Sintering employs binders with metallic and ceramic powders that require post processing, such as kiln heating, after sintering to create the finished item.

Selective Laser Melting (SLM)

Selective Laser melting (SLM) is an additive metals manufacturing process that is very similar and practically identical to SLS. While SLS is used to fuse ceramic, glass and plastic in addition to metals, SLM is primarily employed to fuse metal powders. SLM commonly employs an ytterbium fiber high-powered laser to weld metal powders together layer by layer in accordance with computer aided design (CAD) instructions. Like SLS, the SLM system recoats a layer of metal powder ranging from 20 to 100 micrometers. After each layer is laser fused where intended, a powder coating system deposits a fresh layer of powder in thicknesses ranging from 20 to 100 microns in preparation for laser action. Not fused metal powder serves as support until the SLM device fully forms part and removes the not fused metal powder. The process produces fully dense metal pieces from titanium, cobalt chrome, stainless steel and tool steel.

The Dental, Orthopedics, Defense, Aerospace and Electronics Industries use this technology.

MTT Technologies Group of Staffordshire, England UK manufactures two SLM devices, the MTT SLM125 and MTT SLM250. Both devices use argon gas as a build atmosphere.

Electron Beam Melting (EBM)

EBM uses an electron beam to melts metal powder in a layer-by-layer build process. The build occurs in a vacuum enclosure to prevent oxidation and other chemical reactions that could contaminate the fabricated item. Its elevated and even temperature build environment results "in stress-relieved parts with material properties better than cast and comparable to wrought material."[viii] EBM typically first scans the metal powder bed to produce the optimal elevated temperature for the specific alloys being melted. It then melts the build item's contours and lastly, the interior mass. EBM does not use mirrors or other optics, like SLA, SLS and SLM, to control energy used for fabrication. Instead electromagnetic coils control the electron beam, which enable high precision control without optical diffusion and a very fast build process. It can also employ deflection electronic to melt multiple locations at the same time.

EBM is particularly effective for fabrication with titanium alloys, including combinations with aluminum. The process is also used with zirconium, niobium, tantalum, nickel and cobalt. Its builds are fully formed and dense, thereby not requiring thermal post processing. EBM produces excellent mechanical and physical properties for its output, which include implants for the medical applications and parts and castings for the aerospace and automotive industries. Arcam AB, headquartered in Gothenburg, Sweden, manufactures two EBM devices, its A1 for implants and A2 for large industrial parts. The major limitation to EBM is its capital cost, current equipment build size of 20x20s35 cm, its 0.2 to 1.0 mm beam spot diameter and its exclusive use with metal powders.

Electron Beam Freeform Fabrication (EBF^3)

EBF^3 feed a metal wire to an e- beam that, in an inert atmosphere, melts the material that is then deposited. It typically deposits titanium, nickel, stainless steel, and refractory alloys. It can vary alloy and chemistry types throughout the formed item component to vary strength, fatigue performance, & toughness. It provides hybrid structures with lugs and bosses without high fault zones associated with castings. It also offers a very fast fabrication method for the modification and repair of metal objects manufactured using other technologies.

NASA's Langley Research Center in Hampton Roads, Virginia developed EBF3 as a tool to rapidly fabricate structures with desired performance characteristics.[ix]

Sciaky Inc. of Chicago, IL, (a subsidiary of Phillips Service Industries) manufacturers the Direct Manufacturing Electron Beam Freeform Fabrication systems.

Fused Deposition Modeling (FDM)

FDM is an additive digital fabrication process that melts, extrudes and deposits layers of thermoplastic polymer from a coil. Stratasys, the second largest manufacturer of additive fabrication systems, employs FDM with its line of FORTUS industrial build devices. They use

Acrylonitrile Butadiene Styrene (ABS), Polycarbonate (PC), Polyphenylsulfone (PPSF/PPSU) thermoplastic coils. The FORTUS lines ability to process PC and PPSF/PPSU chemistry enable it to provide functional prototypes and direct digitally manufactured parts for some applications.

FDM also offers a relatively low capital cost avenue for hobbyists and students to be introduced to and use 3-D digital fabrication process. MakerBot of Brooklyn, New York and Bits From Bytes (BFB) of Clevedon, North Somerset, UK, produce low-cost FDM kits that purchasers can assemble into operating digital manufacturing systems. Additive digital manufacturing's first and largest supplier, 3D Systems acquired Bits From Bytes as part of its vision to expand digital fabrication beyond computer added design users to a broader audience. BFB manufactures two FDM type printers: BFB 3000 Plus pre-assembled fabricator and the RapMan 3.1 kit. MakerBot offers the Thing-O-Matic and the Cupcake kits. BFB offers its 3000 Plus with from one to three extrusion heads. For the BFB 3000 Plus and the RapMan 3.1 kit, it supplies coil deposit chemistry including: Poly Lactic Acid (PLA), Acrylonitrile Butadiene Styrene (ABS), Poly Propylene (PP), High Density Poly Ethylene (HDPE), Low Density Poly Ethylene (LDPE), and un-plastised Poly Vinyl Chloride (uPVC). PLA derives from cornstarch and a biodegradable plastic that is useful for making prototypes. ABS is use for making automobile bumpers. PP makes automotive batteries, facemasks, containers, filters and many other items. HDPE fabricate fuel tanks, water and gas pipes, snowboards and plastic bottles. LDPE can produce corrosion-resistant parts, food storage and pliable parts, while uPVC is good for forming pipes, gutters and other building parts.

MakerBot offers PLA and ABS coils for both the Thing-O-Matic and the Cupcake. PLA and ABS are easy to sand and paint without training or experience.

FDM offers an entry-level technology for students and hobbyist due to its low equipment cost. It is limited to thermoplastics. Its deposited layers are about 100 micrometers thick and require post process sanding and finishing to eliminate visible artifacts.

3D Inkjet

3D inkjet methods use inkjet print heads to generate fluid drops, which either change directly from liquid to solid, with or without radiation curing, or add polymer to powder to form an object layer-by-layer. 3D inkjet systems include systems from the following companies:

Fujifilm Dimatix: DMP series; Z-Corporations: Z402 Inkjet System; Three Dimensional Printing; Multi-Jet Modeling; Xaar; Ricoh; Samsung; UniJet.

Our presentation will delineate and evaluate the various 3D Inkjet systems.

Polyjet Matrix Printing

Objet Connex^{TM} PolyJet Matrix is a type of 3D Inkjet fabrication. Objet Ltd of Israel developed and manufactures it. It uses 8 Ricoh print heads, with 96 nozzles per head, each nozzle with a 50-micron diameter. Each print material employs at least two print heads. The system synchronizes the deposit of different acrylic-based photo polymer model materials with varying hardness, tensile strength, elongation, response to heat, flexibility and color in one simultaneous build. It produces resolution of 600x600 dpi.

Robo-casting

Robo-casting uses computer-controlled deposition of ceramic slurries, mixtures of ceramic powder, water, and trace amounts of chemical modifiers, through a syringe. It typically deposits the material in thin layers on a heated base. Syringe deposited materials include: silica, alumina, lead zirconate titanate, hydroxyapatite colloidal particles, polymeric, metallic, and semiconducting colloidal inks. It is a relatively inexpensive and faster way of fabricating complex ceramic parts.

Shape Deposition Manufacturing (SDM)

Shape Deposition Manufacturing combines additive and subtractive methods, alternately depositing and shaping or machining each layer of support materials to both fabricate and assemble items. SDM permits access to a formed product's internal geometry and the enables the embedding of actuators, sensors and other components. It can vary the type and thickness of deposited materials and property characteristics of the built product.

Laminated Object Manufacturing (LOM)

Helisys Inc., now Cubic Technologies, developed LOM, which laminates sheets of paper, plastic or metal with a heated roller; a laser or knife traces the desired object shape and cross hatches waste areas for each layer to facilitate it's removal. LOM involves no chemical reactions. It is useful for large object. The paper-based models have a wood-like character. The process is relatively low in capital costs.

Solid Ground Curing (SGC)

The now defunct Cubital Inc. of Ra'anana, Israel developed Solid Ground Curing (SGC), a.k.a. the Solider Process. We include a description of its process because the Israeli company Objet owns the intellectual property of this technology and that it offers an example of a hybrid additive and subtractive system.

First, the system generated laser exposed photo masks for each layer it was to expose. It sprayed a layer of photosensitive resin, placed the mask for that layer in between the UV light source and the sprayed surface, opened the lamp shutter exposing the whole layer at once hardening it, removed the mask, vacuum removed the uncured polymer, roller coated wax into the cavity left by the removed resin for build support. The whole resin and wax layer was then milled and the debris vacuumed away. The SGC system then repeated the process for each layer. SGC could process multiple parts at once and its large build area of 500 × 500 × 350 mm enabled the fabrication of larger objects than some other methods. It was more expensive and less accurate than SLA. It also generated significant waste and required the removal of the supporting wax before recovering the fabricated object.

Conclusion

Our presentation will also include evaluations, which publication space limits for this document, of Ultrasonic Consolidation (UC), Very High Power Ultrasonic Additive Manufacturing (VHP UAM), Bio-fabrication, Selective Area Laser Deposition (SALD), Cold Metal Transfer (CMT), Laser Cladding, Integrated Extrusion Deposition and Near Field Electro-spinning. Digital Fabrication is a rapidly growing Industry with new advances and technologies emerging from research and development laboratories frequently.

References

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