

ME 3370 Manufacturing Processes Laboratory

Lab No. 4: Additive Manufacturing Processes

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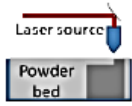
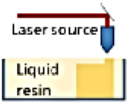
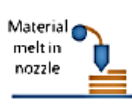
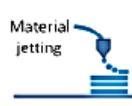
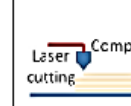
1.1. Background information

This lab will cover the different additive manufacturing processes, such as laser-based processes (stereo-lithography (SLA), solid ground curing (SGC), liquid thermal polymerization, beam interference solidification (BIS), selective laser sintering (SLS), selective laser melting (SLM), direct metal laser sintering (DMLS), laser engineered net shaping (LENS), direct metal deposition (DMD), laser powder deposition (LPD), and selective laser cladding (SLC). Additive manufacturing is a technology rapidly expanding on a number of industrial sectors. It provides freedom in the component's design and environmental/ecological advantages. It transforms design files to fully functional products. Physical phenomena associated with additive manufacturing (AM) processes are complex, including melting/solidification and vaporization, heat and mass transfer. The goal of the current lab is to introduce the available additive manufacturing methods based on their process mechanisms, and optimization approaches. The students will be having the chance to work with a 3 D printer as well as on preparation of it for the assigned geometries.

AM is defined as “the process of joining materials to make objects from 3D model data,

usually layer upon layer, as opposed to subtractive manufacturing methodologies, such as traditional machining” [1]. AM can deliver parts of very intricate and complex geometries with a minimum need for post-processing, built from tailored materials with near-zero material waste, while being applicable to a variety of materials, including plastics and metals. An example of the design freedom offered is that conventional assemblies can be redesigned in a single complex structure that could not be manufactured with the current manufacturing processes. The categorization of the AM processes is listed in Table 1 [2]. See Appendix A for more comparison and information.

Table 1. AM processes [2].

Additive Manufacturing (AM) Processes														
Process	Laser Based AM Processes					Extrusion Thermal	Material Jetting	Material Adhesion	Electron Beam					
	Laser Melting		Laser Polymerization											
Process Schematic														
Name Material	SLS		DMD		SLA		FDM		3DP		LOM		EBM	
	SLM		LENS		SGC		Robocasting		IJP		SFP			
	DMLS		SLC		LTP				MJM					
			LPD		BIS				BPM					
					HIS				Thermojet					
Bulk Material Type														
Bulk Material Type		Powder		Liquid		Solid								

AM involves a number of steps that move from the virtual CAD description to the final part. Different products will involve AM in different ways and to different degrees. Small, relatively simple products may only make use of AM for visualization models, while larger, more complex products with greater engineering content may involve AM during numerous stages and iterations throughout the development process. Furthermore, early stages of the product development process may only require rough parts, with AM being used because of the speed at which they can be fabricated [3].

At later stages of the process, parts may require careful cleaning and post-processing (including sanding, surface preparation and painting) before they are used, with AM being useful here because of the complexity of form that can be created without having to consider tooling.

Later on, we will investigate thoroughly the different stages of the AM process, but to summarize, most AM processes involve, to some degree at least, (a) CAD model, (b) conversion to STL, (c) transfer to AM machine and STL file manipulation, (d) machine setup, (e) build, (f) removal, (g) post-processing and (h) application (as illustrated in Fig. 1) [3].

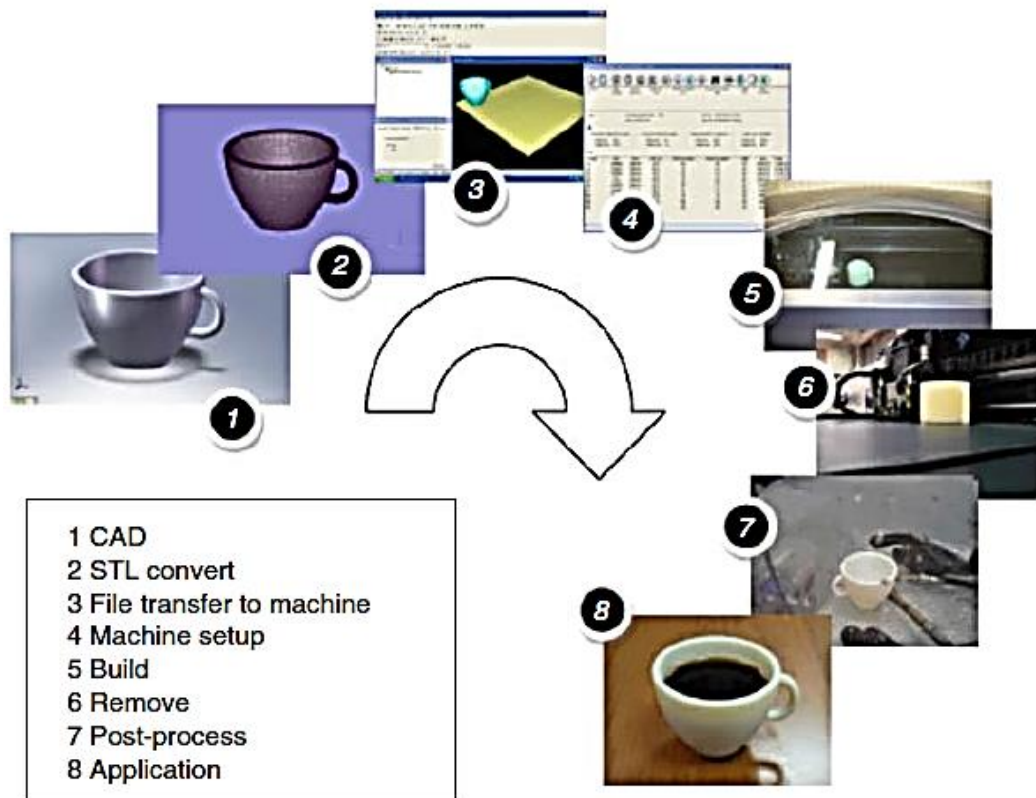


Fig. 1. Generic process of CAD to part, showing all 8 stages [3].

AM takes full advantage of many of the important features of computer technology, both directly (in the AM machines themselves) and indirectly (within the supporting technology), including:

- Processing power: Part data files can be very large and require a reasonable amount of processing power to manipulate while setting up the machine and when slicing the data before building. Earlier machines would have had difficulty handling large CAD data files.
- Graphics capability: AM machine operation does not require a big graphics engine except to see the file while positioning within the virtual machine space. However, all machines benefit from a good graphical user interface (GUI) that can make the machine easier to set up, operate,

and maintain.

- Machine control: AM technology requires precise positioning of equipment in a similar way to a Computer Numerical Controlled (CNC) machining center, or even a high-end photocopy machine or laser printer. Such equipment requires controllers that take information from sensors for determining status and actuators for positioning and other output functions. Computation is generally required in order to determine the control requirements. Conducting these control tasks even in real-time does not normally require significant amounts of processing power by today's standards. Dedicated functions like positioning of motors, lenses, etc. would normally require individual controller modules. A computer would be used to oversee the communication to and from these controllers and pass data related to the part build function [3].
- Networking: Nearly every computer these days has a method for communicating with other computers around the world. Files for building would normally be designed on another computer to that running the AM machine. Earlier systems would have required the files to be loaded from disk or tape. Nowadays almost all files will be sent using an Ethernet connection, often via the Internet.
- Integration: As is indicated by the variety of functions, the computer forms a central component that ties different processes together. The purpose of the Fig 2. Show how the above mentioned technologies are integrated to form an AM machine [3].

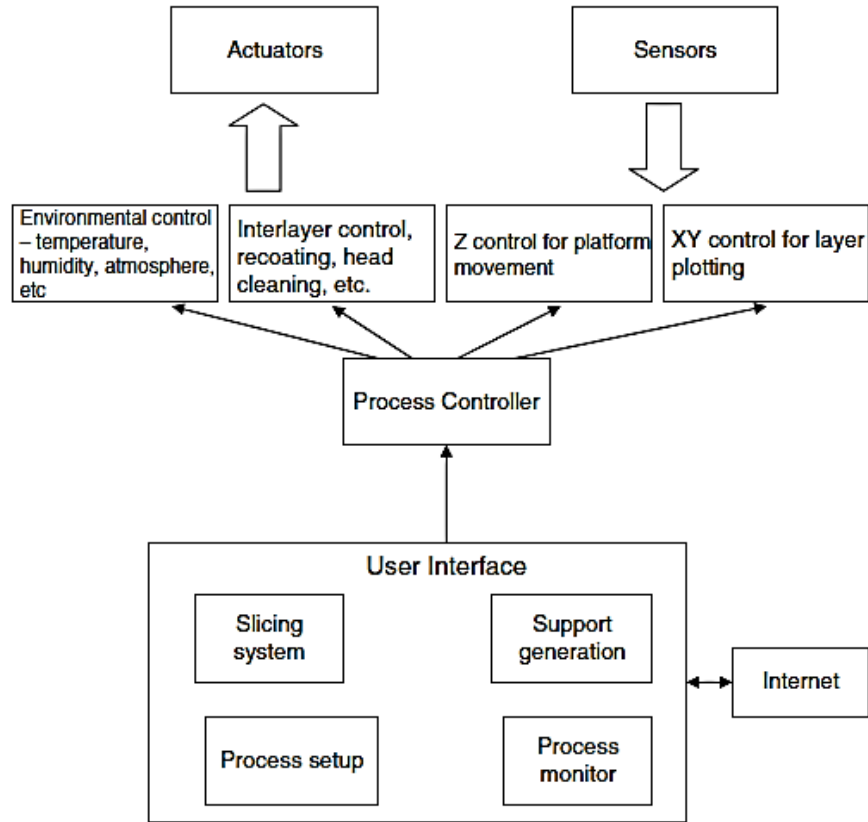


Fig 2. General integration of an AM machine [3].

1.2. Laser-based additive manufacturing processes

Laser-based additive manufacturing processes use a laser source of medium to low power in order to melt, solidify or cure the material [2]. 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 [2].

1.2.1. Laser polymerization

Most of the laser polymerization additive manufacturing processes are based on the same 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 (Fig. 1) [2].

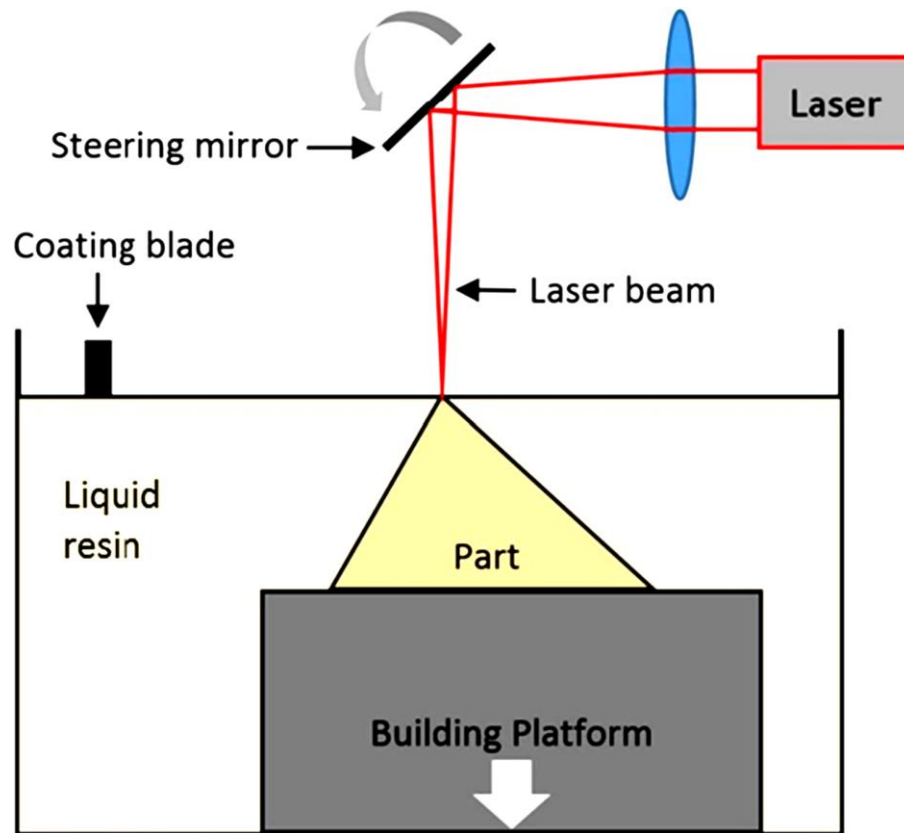


Fig. 1. Laser polymerization AM process schematic [2].

1.2.1.1. Stereo-lithography (SLA)

Stereo-lithography 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 mW in 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 [2]. SLA printers build accurate finished products of the designed CAD model by converting liquid

materials and composites into solid cross-sections using ultra violet light. Once a solid layer of the cross-section has been constructed the platform lowers and a new layer of liquid resin is coated onto the existing layer. This process continues until the whole part is completed. Once completed, the product is cleaned with a solvent solution in order to remove any leftover wet resin remaining on the surface. After soaking in the solvent the product is placed in a UV oven to complete the curing process. SLA allows complex, but precise parts to be manufactured in a timely fashion, especially when a number of functional prototypes are required for product testing or design. SLA parts utilize support structures and they require a bit more post-processing. However, the post-processing options are also some of SLAs greatest advantages. Models can be vapor honed, or bead or sand blasted. SLA parts can even be electroplated with metal, such as nickel. Electroplating not only makes the part significantly stronger, but it also makes the part electrically conductive and more dimensionally stable in moist environments.

To even further the benefits, SLA allows for lower material costs, as the unused resin stays in the vat for future projects. SLA printing has a wide range of applications because of its wide range of mechanical and physical properties. SLA materials are available for higher-temperature applications and clear materials are available with polycarbonate-like properties. Biocompatible materials are available for a wide range of medical applications such as surgical tools, dental appliances and hearing aids. Other materials are specifically formulated for patterns, offering low ash creation and high accuracy while also being expendable. SLA is mainly used in industry because of its required post-processing, but can offer a cost effective resource for business in any type of field need unique and readily available machine or model parts [4].

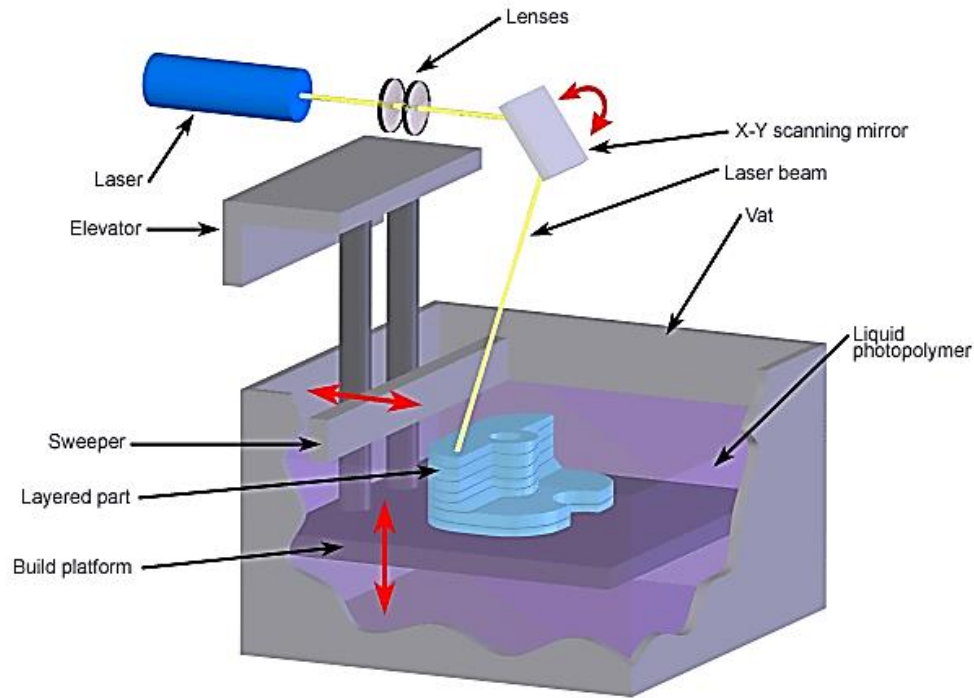


Fig. 2. Stereo-lithography apparatus [4].

1.2.1.2. 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 [2]. 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 system's complexity [2].

1.2.1.3. 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 [2], 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.

1.2.1.4. 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 [2].

1.2.1.5. Holographic interference solidification (HIS)

In HIS 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 [2]. In that essence, the process is really similar to that of solid ground curing.

1.2.2. 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 (Fig. 3).

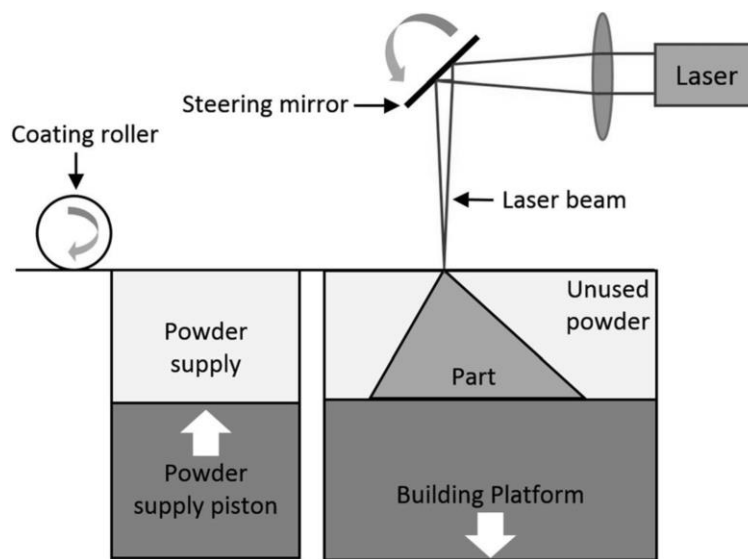
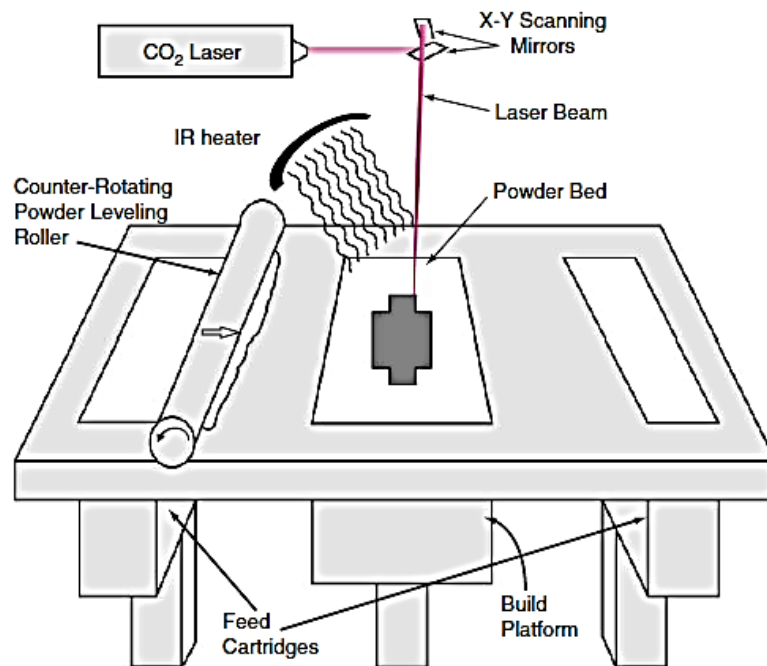


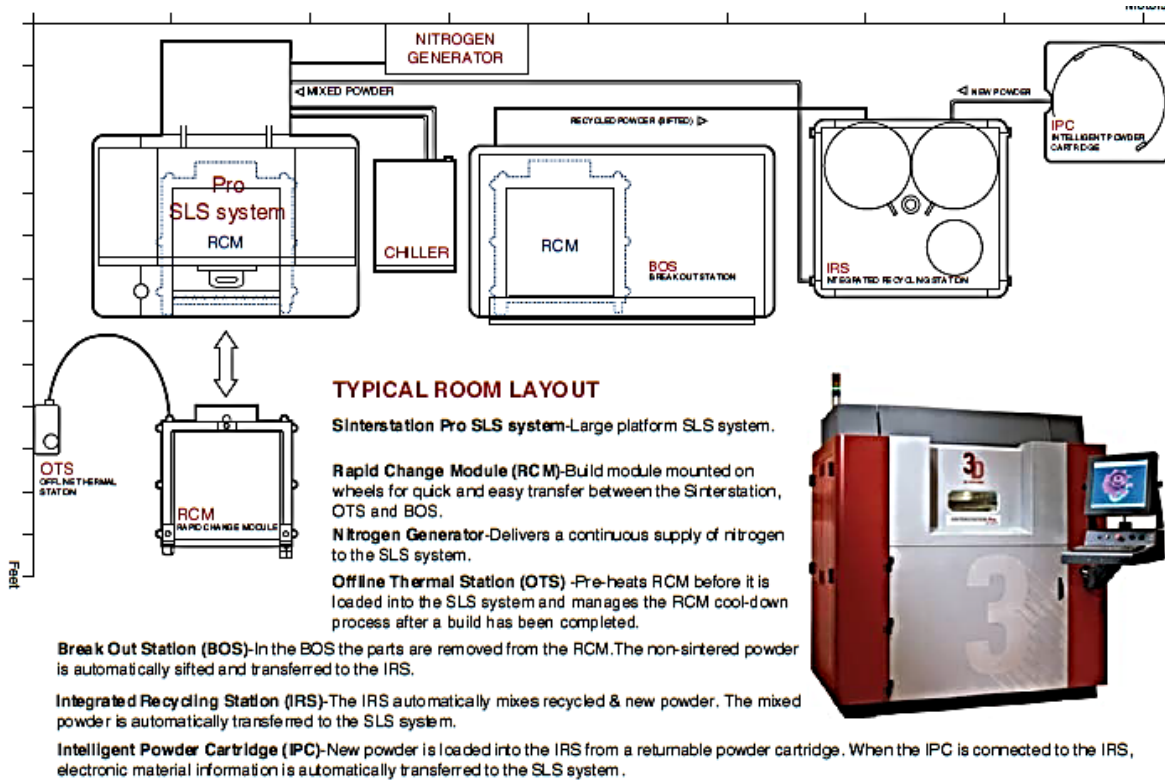
Fig. 3. Laser melting AM process schematic [2].

1.2.2.1. Selective laser sintering (SLS)

Selective laser sintering uses a fine powder, which is heated by a laser beam (ranging from 7 W for plastic up to 200 W) in such a way so as to allow the grains to fuse together [2]. 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 un-sintered material powder remains in place to support the structure. The un-sintered material may be cleaned away and recycled after the build has been completed [2]. 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.



(a)



(b)

Fig. 4. (a) Schematic of the selective laser sintering process, and (b) 3D systems sinter station Pro and its modular layout [3].

1.2.2.2. 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) [2].

1.2.2.3. 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 [2]. The DMLS printer uses a high powered fiber optic laser to melt metal powder in order to fuse it into solid parts. Within the build chamber is a platform for material dispensation and a build platform, in addition to a re-coater blade, which moves new powder on top of the build

platform. The laser then melts the powder in accordance with the cross-section of the computer design. The end product is created layer by layer, and each layer is approximately 40 micrometers thick. Once one layer is completed the build platform is lowered by the height of the layer and the process is repeated. Once the object is constructed the excess powder and easily be swept off of the object and reused again at another time. DMLS is a net-shape process, accurately creating parts that yield, high resolution, great surface quality and excellent mechanical properties [5].

The metal object created by DMLS is incredible durable and can be used almost immediately after it is produced. Common materials used for DMLS are an array of metals ranging from aluminum to steel, cobalt, titanium, and nickel alloys. These metals are extremely durable allowing for long-lasting and highly individualized products. DSML is one of the most widely used 3D printing processes because the functionality and diversity of the produced products. DSML is readily being taken advantage of in the aerospace, automotive, medical and tooling industries. It is also being used to make household lifestyle products with extreme individuality and cost effectiveness. The medical industry is increasingly using DSML to make artificial orthopedic and dental implants. Because the process is tool-less there is an extreme cost reduction for small, intricate parts needed for cars, airplane, or any other highly advanced machine [6].

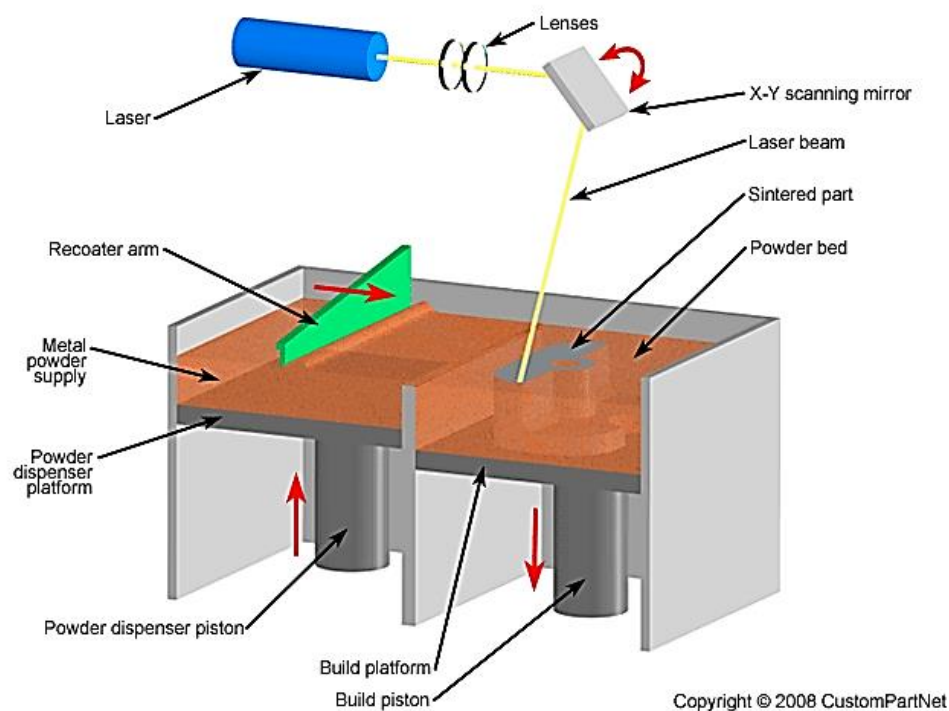


Fig. 5. Direct metal laser sintering schematic [5].

1.2.2.4. Laser engineered net shaping (LENS)

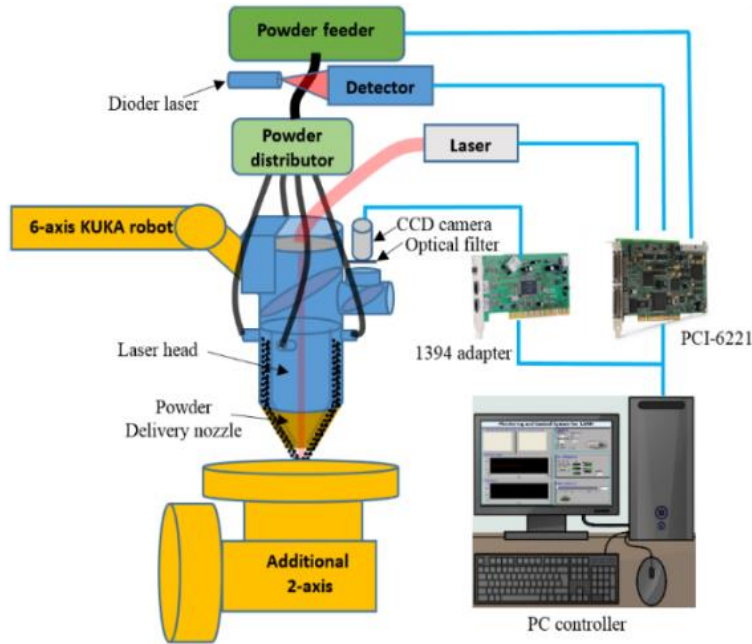
Laser engineered net shaping uses a high-power laser to melt metal powder. A specially designed powder delivery nozzle injects the powder stream directly into the focused laser beam, and the laser head and powder nozzle move as an integral unit. Metal powders are delivered and distributed around the 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 [2]. 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.

1.2.2.5. Direct metal deposition (DMD)

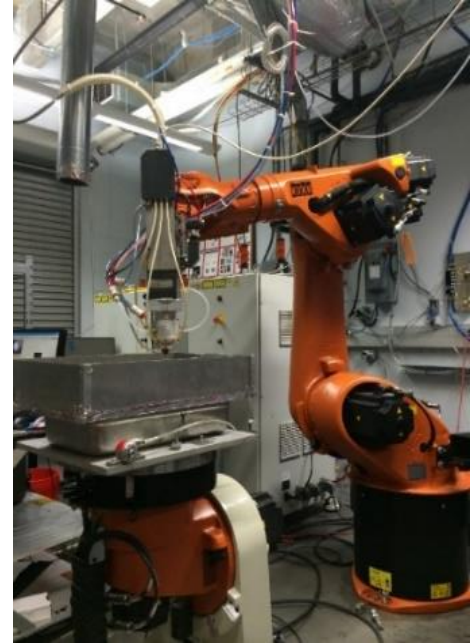
DMD is an additive manufacturing technique that uses a laser as the power source to sinter or melt powdered material (typically metal), with the laser automatically aiming at points in space, defined by a 3D model, binding the material together to create a solid structure. The operating principle is 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 [2].

1.2.2.6. Laser powder deposition (LPD)

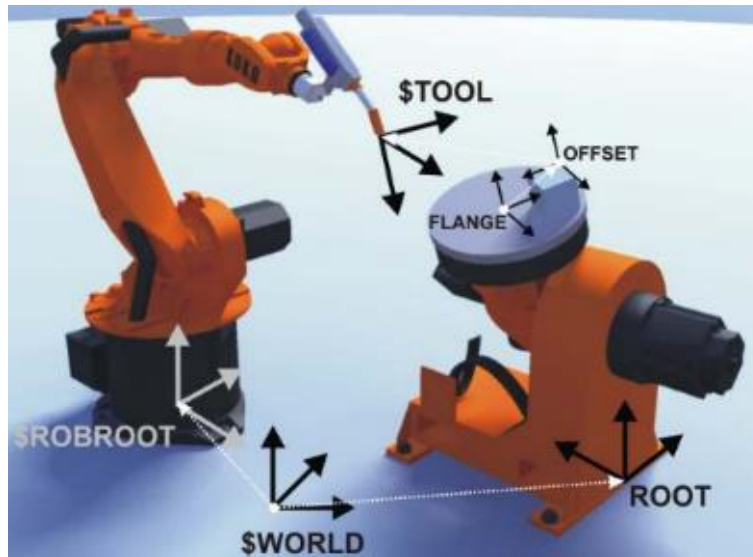
In this layered manufacturing process, a powder/air stream is injected directly into the laser beam focus point on the substrate [2]. Variants of this process are LENS, SLC, SDM and DMD [2]. Robotized laser-based metal additive manufacturing system is a newly developed technique in RCAM for manufacturing different geometries from wide range of materials. The schematic and the photo of the LPD system are shown in Fig. 6.



(a)



(b)



(c)

Fig. 6. Setup of the LPD system: (a) schematic, (b) photo, and (c) coordinate systems.

A 4 kW fiber laser with a wavelength of 1070 nm and a laser head is mounted on a KUKA 6-axis robot arm to perform the direct metal deposition process. For the process planning the system is represented by BASE kinematic system (additional 2-axis tilt and rotatory positioning system) that is spatially coupled with the 6-axis robot. As shown in Fig. 2c, six Cartesian coordinate systems are defined in the system: WORLD, ROBROOT, ROOT, FLANGE, OFFSET,

TOOL. The WORLD coordinate system is fixed and Coordinate systems for the Robot (ROBROOT) and for Tilt and Rotary table (ROOT) are defined in the context of WORLD coordinate system. The ROBROOT coordinate system and the ROOT coordinate system define the position of the 6-axis robot and the BASE kinematic system relative to the WORLD coordinate system respectively. The FLANGE coordinate system is located at the flange center point of the BASE kinematic system. The OFFSET coordinate system defines the position of the work-piece (substrate) relative to the FLANGE coordinate system. The TOOL coordinate system is located at the tool center point (TCP, it is the focus of the powder flow in this study). The TCP is relative to the OFFSET coordinate system when the kinematic system is spatially coupled with the 6-axis robot. In this model, the robot calculates its motion path in relation to the position of the kinematic system. If the kinematic system moves, the robot follows it with the TCP so that the position and orientation of the TOOL coordinate system remains constant relative to the moving base of the kinematic system. During the deposition process, paths are subdivided into a sequence of small linear segments, linear motion is used to traverse a line from the current position (the last point programmed in the program) to the position specified in the motion command $LIN\{E6POS: \{X, Y, Z, A, B, C, E1, E2\}\}$. The motion command parameters $\{X, Y, Z, A, B, C\}$ describe the position and orientation of the laser head with respect to the OFFSET coordinate system which is fixed with the substrate. Parameters $\{E1, E2\}$ denote the angular displacements of the two axes of the kinematic system, respectively.

During the deposition process, a powder feeder developed by RCAM feeds the powder. For the experiment, stainless steel powder 431L HC sized from 53 to 150 μm (a product of North America Hoganas High Alloys LLC) is chosen as the addition material. The argon carrier gas feeds the powder particles into an annular cone nozzle and injects them into the molten pool formed by the laser beam. The shielding gas (argon) is directed through the nozzle toward the molten pool to protect the molten material from contact with the atmosphere. A CCD camera equipped with an infrared filter is installed on the laser head to monitor the molten pool. A fire ware 1394 adapter is used to acquire the infrared images. A PC conducts the image processing and control tasks. The National Instruments PCI-6221 data control board is adopted to control the laser powder and the powder flow rate by sending analog signals to the laser control box and the servomotor of the powder feeder. LabVIEW is used to implement the image processing, control tasks, and the end user interface design.

1.2.2.7. 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 mold preparation in conventional RP techniques [2].

1.2.2.8. Multi fab machine

Multi-Fab additive technology is a recent development, which uses the fundamentals of traditional additive manufacturing, but can use multiple materials simultaneously to create very unique and durable geometries that can directly be used once completed [7]. The multi-Fab machines developed at SMU utilizes a combination of laser technology with welding, and CNC machining to create metal objects of higher quality than other methods of 3D printing (Fig. 7). This multi-fab method, lays down metal powder as a 4-kilowatt laser follows, sintering it in place [8]. The multi-fab technology developed at MIT uses 3D scanning techniques from machine vision, running a continuous loop of 3D scans allowing the machine to self-calibrate to maintain very high printing accuracy. The machine also has an embedding feature, which allows it to include complex electrical components, such as sensors and circuits [7]. Both institutions have created a process that uses a variety of materials to produce a usable, working part in a matter of hours at a low cost.

Multi-fab technologies, although early in development, already have huge application opportunities, especially with the military. It can be used to replace small engine parts of fighter jets as well as other complex vehicles at extremely low cost. It will provide soldiers the ability to machine parts on-site, as well as medical tools, even in remote locations rather than waiting for manufacturing and delivery from around the globe [8-10]. The technology can also be used in the medical industry to make orthopedic implants or scaffold using scans of the patient.

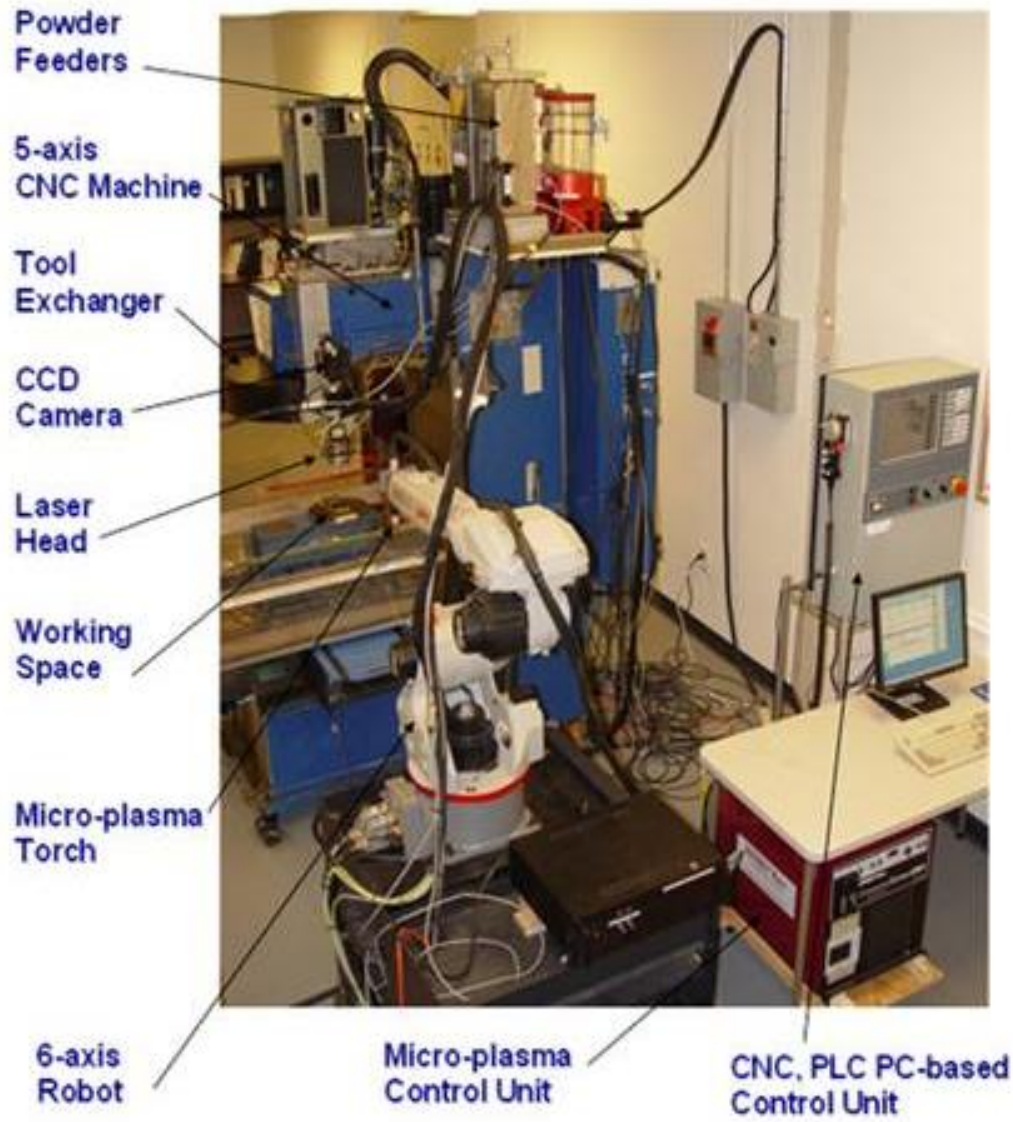


Fig. 7. Multi fab machine at RCAM.

1.2.3. 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 (Fig. 8).

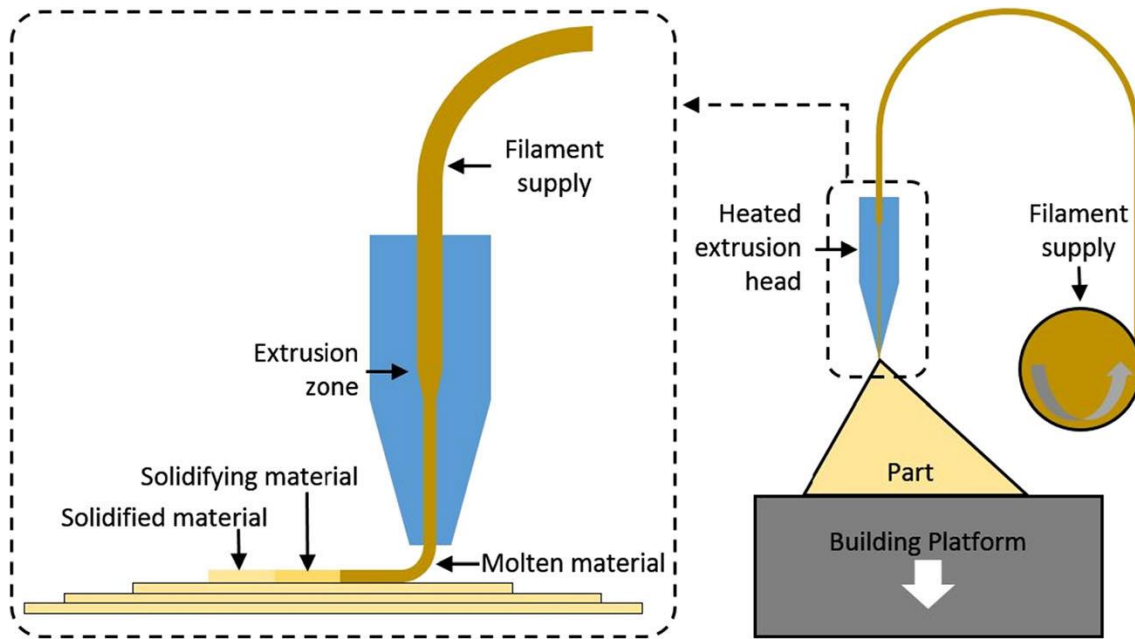


Fig. 8. Extrusion AM process principle and schematic [2].

1.2.3.1. 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, odorless materials, in a variety of colors and types, such as acrylonitrile butadiene styrene (ABS), medical ABS, PLA, investment casting wax and elastomers [2]. 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.

1.2.3.2. 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 [2].

1.2.4. 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 (Fig. 9).

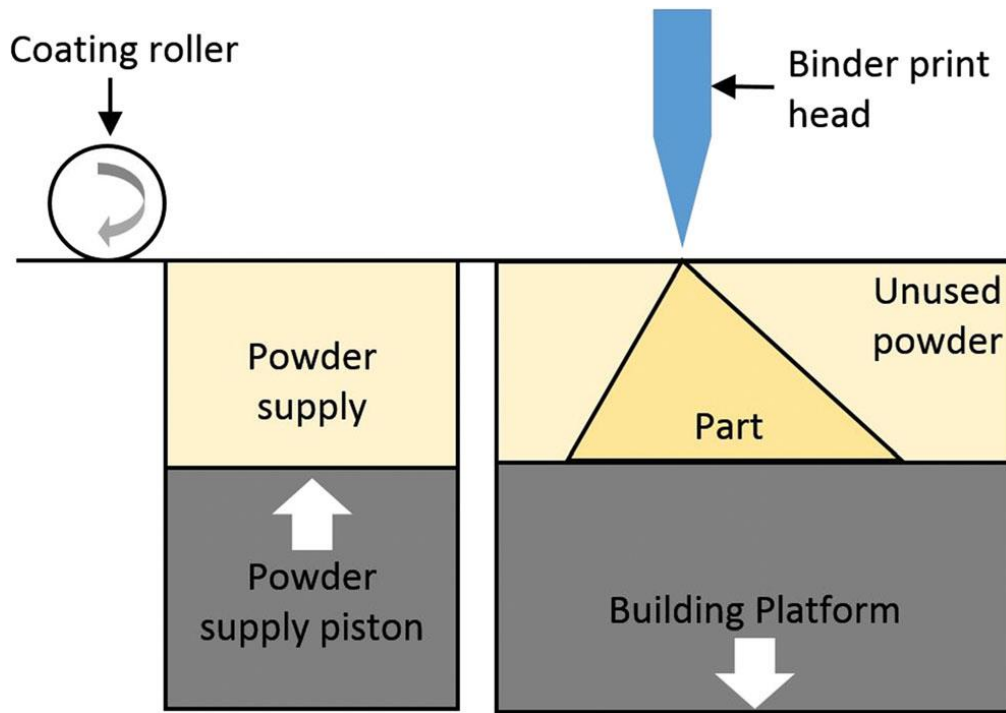


Fig. 9. Material jetting AM process principle and schematic [2].

1.2.4.1. Three-dimensional printing (3DP)

3 DP is a layered manufacturing process, where parts are created inside a chamber, 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 [2]. Fig. 10 shows the 3D printer as one of the first generations of the 3D printers.



Fig. 10. 3D Z-printer (a polymer powder bed printer) at RCAM, SMU.

1.2.4.2. 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 [2].

1.2.4.3. Multi-jet 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 (Fig. 11). When the layer is complete, the platform is distanced from the head (z-axis) and the head begins building the next layer [2].

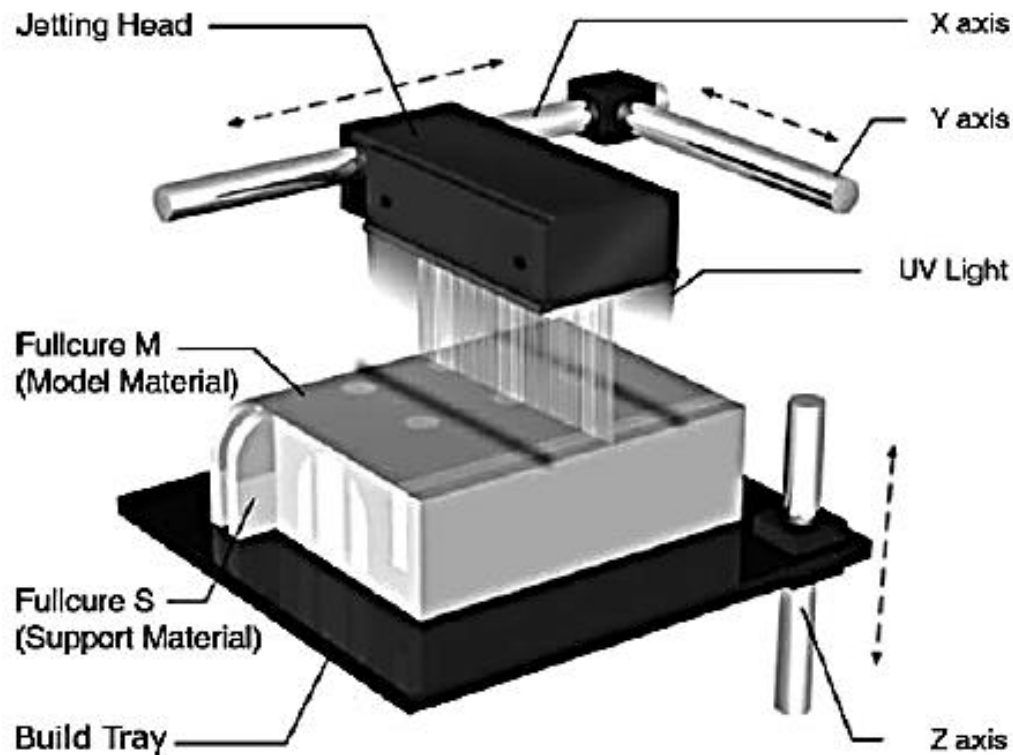


Fig. 11. Object Polyjet build process [3].

1.2.4.4. Ballistic particle manufacturing (BPM)

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 [2].

1.2.4.5. Thermo-jet

Thermo-jet is a process similar to multi-jet 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 [2].

1.2.5. 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 (Fig. 12) [2].

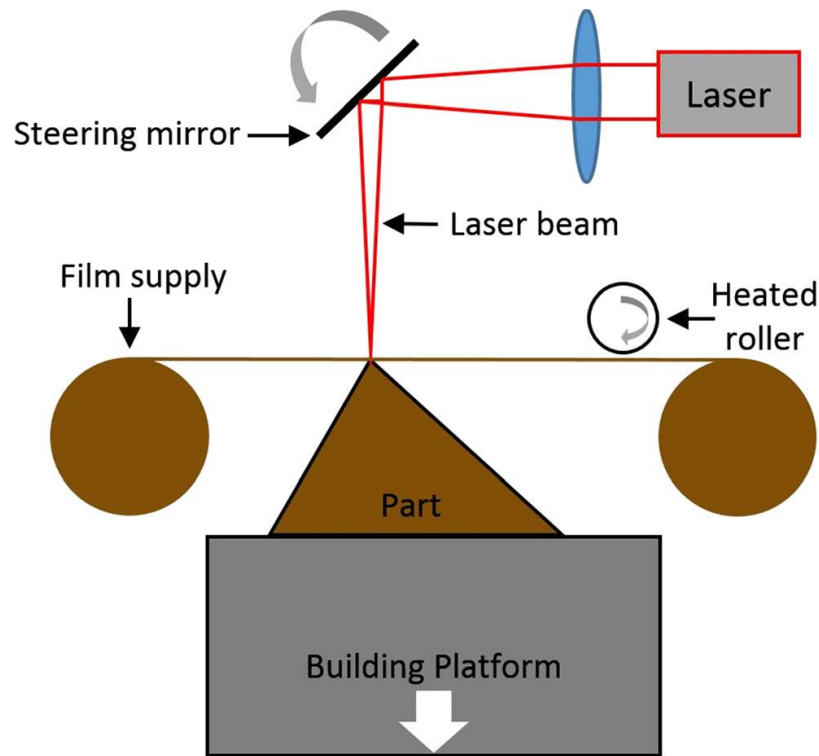


Fig. 12. Adhesive AM process schematic [2].

1.2.5.1. 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 (Fig. 13). 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

[2]. LOM uses a continuous sheet of material that is drawn across a build platform by a system of rollers. A heated roller is passed over the sheet material, often coated with an adhesive, on a build platform where a computer-controlled laser or blade cuts the designed cross-section out of the material. The laser then slices up the excess material in a crosshatch pattern for easy removal. After one layer of the object is formed the build platform is lowered by the thickness of the layer, a new sheet of uncut material is pressed across the existing layer and the process is repeated. The desired object is built up layer-by-layer until the geometry has been formed [11].

Common materials for LOM are different forms of plastic, paper, and sometimes metal. While LOM cannot create as complex or accurate parts as other 3D printing processes, there are no chemical reactions involved so no enclosed chamber is needed for printing. Furthermore, materials used in LOM are inexpensive, readily available and much understood. Because these two advantages, LOM is very ideal and affordable when trying to build large models. A downside to LOM is that it cannot produce hollow models or readily functional prototypes, so LOM is mainly used to create conceptual prototypes. Many industries that previously used LOM have stopped, but an Irish company called Mcor Technologies has begun revamping the field using its resources to help architects, artists, product developers and even doctors produce affordable models and finished goods [11].

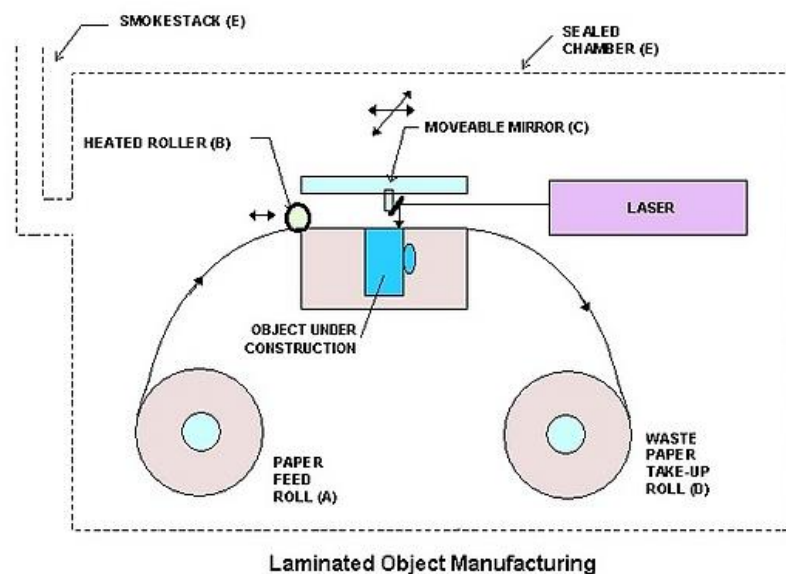


Fig. 13. Laminated object manufacturing schematic [11].

1.2.5.2. 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 [2].

1.2.6. 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 (Fig. 14) [2]. 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 [3]. When compared to SLS, EBM can offer much higher throughput and more uniform thermal field distribution; however, accuracy and surface quality are lower [2, 3].

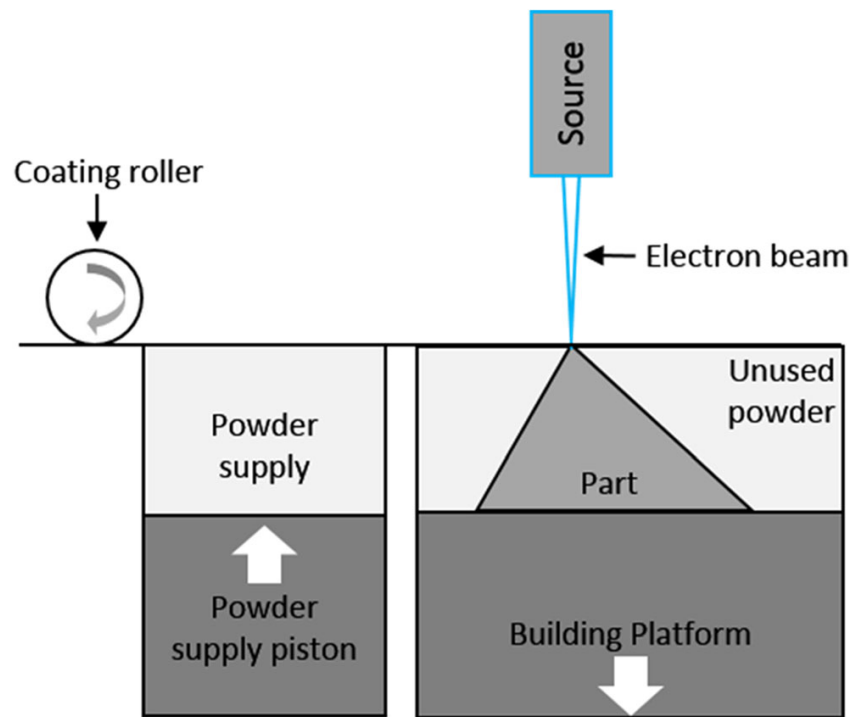


Fig. 14. Electron beam AM process schematic [2].

EBM takes place within a vacuum and at high temperatures producing products that are free from residual stresses and have a microstructure free from martensitic structures [12]. The part is designed using a three-dimensional CAD program. The first layer's geometry is then created through the layer of powder melting together at those points directed from the CAD file. Thereafter, the building surface is lowered the height of the previous layer, about a tenth of a millimeter, and the next layer of powder is placed on top of the previous. The procedure is then repeated so that the object from the CAD model is shaped until a finished metal part is complete [113]. The electron beam used is five to ten times more efficient than a laser beam, resulting in the creation of parts three to five times faster than other metal additive machining processes. In a laser based operation the majority of the light energy is reflected rather than absorbed by the metal powder (Fig. 15). Two variations of titanium alloys, Titanium Ti6Al4V and Titanium Ti6Al4V ELI, are used for EBM as well as Titanium Grade 2 and ASTM F75 Cobalt-Chrome. The different are used for different applications. The Ti6Al4V is primarily used for the racing and aerospace industry but also has marine and chemical industry applications. Ti6Al4V ELI and Titanium Grade 2 can be used in the aerospace industry as well, but are also very important in making orthopedic implants, such as replacing a jawbone or part of the skull. The Cobalt-Chrome alloy is primarily used to make dental implants and gas turbines [12, 13].

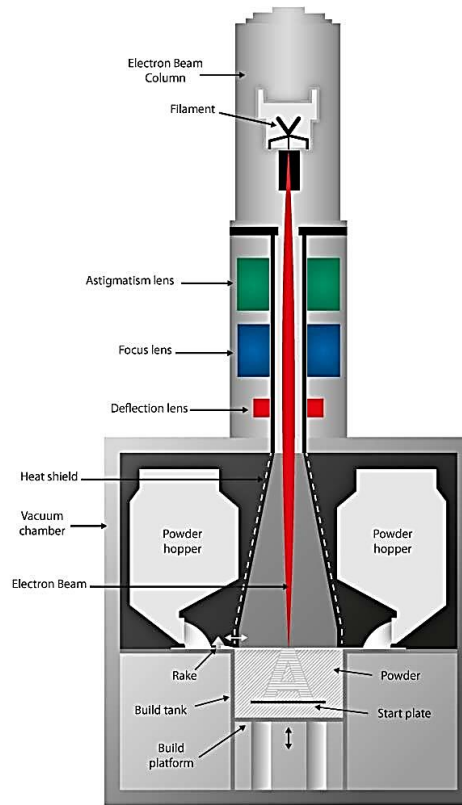


Fig. 15. Electron beam melting machine components [13].

1.3. CAD/CAM scanners for the reverse engineering

1.3.1. White light scanning

White Light Scanning is the technology of obtaining reliable information about a physical object through the process of recording, measuring, and interpreting photographic images. In other words, white light scanning uses multiple images of a three dimensional object on a two dimensional medium to recreate an accurate virtual three-dimensional model of the original object (Fig. 16). The system is made up of a projector and two cameras all mounted on a frame. By projecting a fringe pattern onto the object while simultaneously recording the pattern, the scanning software is able to create millions of reference points on the surface of the object. For large objects, where multiple pictures must be taken and physical reference points are manually placed on the object for better accuracy. After the measurements are taken the software processes the data aligning the point cloud with a single point-of-origin to create a visual model on the computer. The image is comprised of small triangular surfaces automatically created from the aligned point cloud [14]. White light scanning provides a precise non-contact method that creates an extremely

reliable database for a CAD model. Because of the automated and manually added reference points the model is scaled instantly and can easily be manipulated for any required modification to the final product. White light scanners are used to recreate soft and extremely contoured surface. Since the scanner can retrieve up to four million reference points, wood, plastic, rock and even leather surfaces can be accurately recreated using this scanning process. Furthermore, since white light scanning creates a 3D model automatically it is prominently used to reverse engineer objects or products. The CAD models can be used in industry for 3D printing or any other manufacturing process requiring such a virtual model [14].



Fig. 16. White light scanner [14].

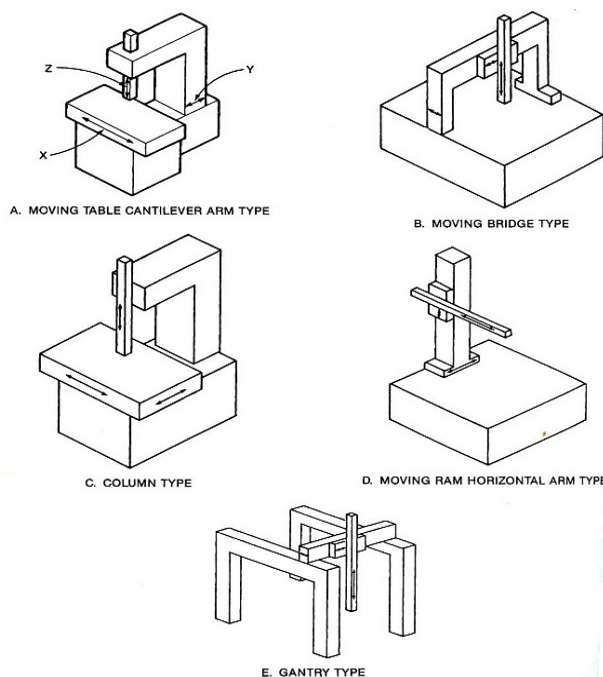
1.3.2. Coordinate measurement machine (CMM)

Coordinate Measuring Machines (CMM) are instruments that allow the user to locate point coordinates on three-dimensional objects all at the same time that is in the XYZ plane. The machine automatically integrates in two and three dimensions and when linked to a computer eliminates the need for single-axis measuring devices like micrometers and height gages. There are five basic types of CMM's (Fig. 17):

- Moving table cantilever arm
- Moving bridge
- Column
- Moving ram horizontal arm
- Gantry

Each different CMM configuration has three perpendicular axes (X, Y and Z), each being fitted with a precision scale, measuring device, or a transducer, that continuously records the displacement of each to a fixed reference. The third axis carriage is attached with an electric probe that when touched to a surface reads the displacement of all three axes. The probe used can either be a contact probe, as just described, video or laser-scanning probe. Now since the three axes are finite lengths there is a certain space that the probe can work in which is called the work envelope [15].

CMM's have taken lead roles in aerospace, automotive, electronics, health care, plastics, and semiconductor industries. Being able to take quick and accurate measurements to evaluate three-dimensional data separates CMM's from all other measurement devices. CMMs are incredibly useful in short run production where tooling and products must be inspected quickly and when there are multiple features to inspect within the product. In addition, if reworking or scrapping is very costly during production CMM's are often used to calculate the dimensions of the unit before proceeding further with production [15].



(a)



(b)

Fig. 17. (a) Schematic of five types of coordinate measurement machines, (b) a real scale CMM [15].

1.3.3. Laser scanner

A laser scanner uses an emitted laser light to produce a swift capture of three-dimensional information reflected from an object's surface to a light sensor. It uses this light reflection to create a representation of the object as a "point cloud", which is a result of multiple scans that have all been unified through a process called registration (Fig. 18). Once the point cloud is consolidated, 2D planes, elevations, and individual section of the model can be extracted and converted into a CAD model that can manipulated, reverse engineered, or manufactured using a 3D printer. This eliminates hours of building a CAD model from scratch. Like a traditional camera, laser scanners see only what the viewer observes and cannot scan inside or through objects. Laser scanners can reveal deformations from poor construction or wear and tear due to time [16].

Laser scanner are used heavily for any project that requires accurate "as-built" information about an object. A laser scanner can produce measurement accuracy of 2 millimeters or less. It can create shorter project times with a rapid turnaround of information. Point clouds can be checked and measured using free viewing software, from any scan location, making it virtually accessible to every area of industry. Laser scanner are also used in industries that use additive manufacturing processes so that a model does not have to be completely made from scratch or an existing model or product can be improved or modified [16].



Fig. 18. (a) Tripod laser scanner [16], and the 3D scanner at RCAM.

1.4. Three (3) D printer in RCAM and its procedure

3D Printing encompasses a large number of techniques but what makes them all similar is the way in which parts are made. This is the way of adding one layer after another to a part. All these layers must be melted together as well, that is another property of 3D Printing. The way in which the material is made into a layer and the way that the layers are put together are different with all the different techniques. Fig. 19 shows the 3D printer with its components that the students would work on in this class.

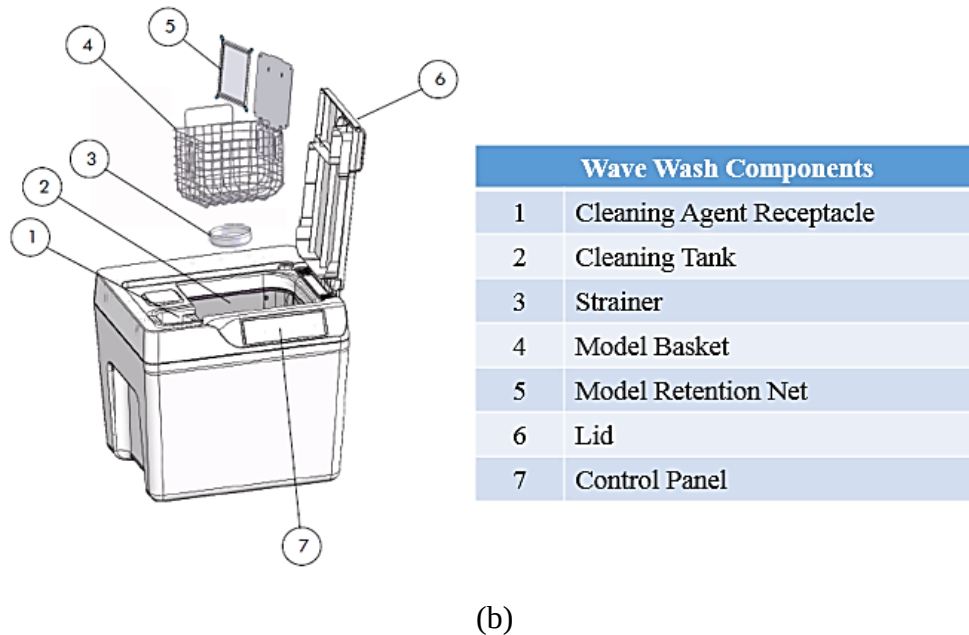
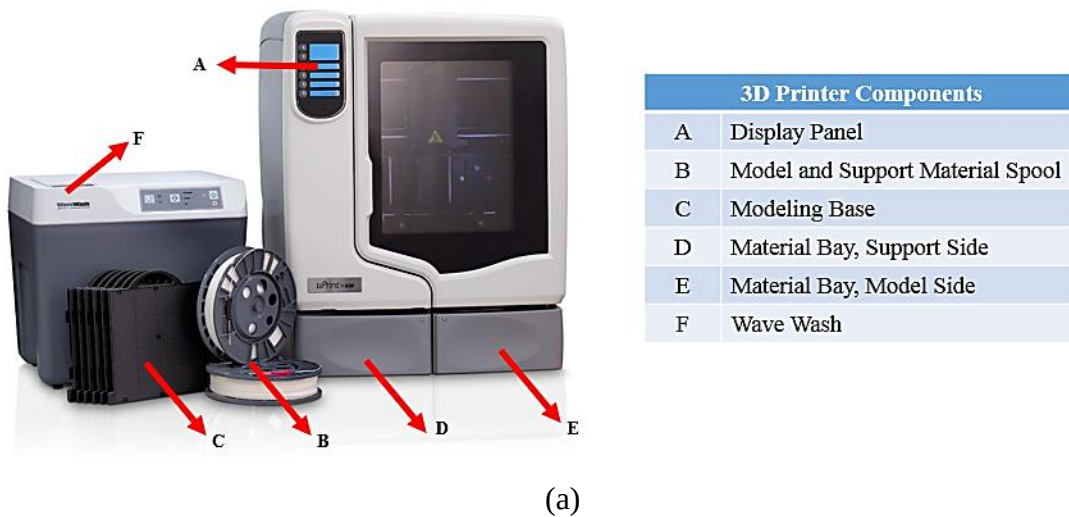


Fig. 19. (a) 3D printer (uPrint SE Plus) based on the FDM (Fused Deposition Modeling), and (b) wave-wash machine, in the SMU machining shop.

The 3D printer (uPrint SE Plus) uses FDM (Fused Deposition Modeling) Technology to build parts layer-by-layer from the bottom up by heating and extruding thermoplastic filament. The usable material is ABSplus thermoplastic in white and also it can be found in different colors in market. 3D printing process can be divided into three steps:

- 1- **Pre-processing:** Build-preparation software (Catalyst) slices and positions a 3D CAD file and calculates a path to extrude thermoplastic and any necessary support material.
- 2- **Production:** The 3D printer heats the thermoplastic to a semi-liquid state and deposits it in ultra-fine beads along the extrusion path. Where support or buffering is needed, the 3D printer deposits a removable material that acts as scaffolding.
- 3- **Post-processing:** The user breaks away support material or dissolves it in Wave-wash machine, and the part is ready to use.

In this lab, students are going to practice some useful examples to get more familiar with software and also built one part as shown below in the uPrint machine. The geometry of the sample that the students will work on is sketched in Fig. 20.

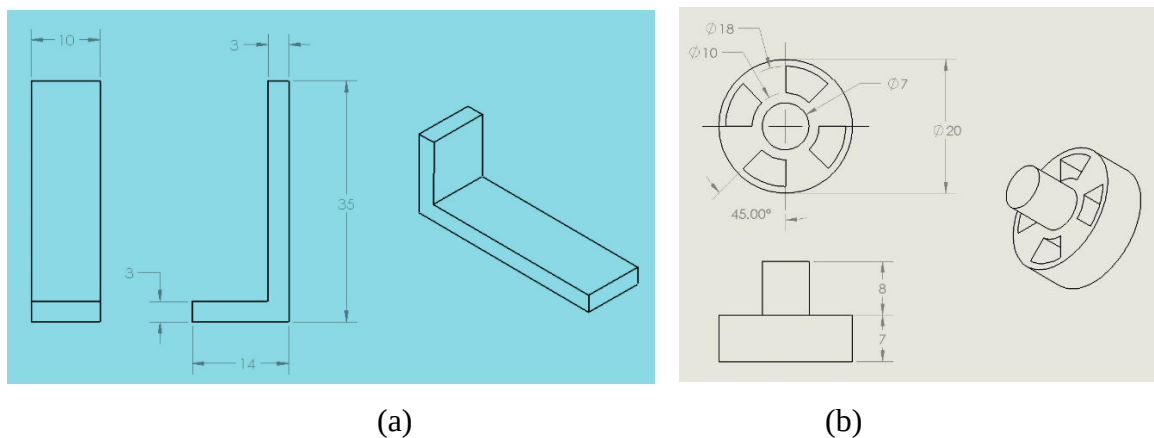


Fig. 20. The geometry of the parts (a) sample 1 and (b) sample 2 for the exercise on the 3 D printer.

In order to start a job with uPrint 3D Printer machine, please follow the instruction below:

1.4.1. Pre-processing

The following steps should be taken in order to do the pre-processing in this system.

Step 1. Create your CAD model using SolidWorks software

- Use Save As to save part or assembly as STL
- Open options
 - Output as binary
 - Set STL units (typically inches or mm)
 - Set resolution (coarse, fine, or custom (adjust deviation and angle sliders); avoid files larger than about 20MB
 - Check “Show STL info before file saving”
 - Check “Save all components of an assembly in a single file”
- Save STL file

Step 2. Catalyst (.cmb file creation)

- File/Open STL
- General tab
 - Set layer resolution (normally 0.010”)
 - Set model interior to solid, sparse-high density, or sparse-low density (see mounted samples)
 - Set support fill (usually SMART)
 - Set STL units
 - Set scale as needed
- Orientation tab
 - Click bottom, top, or front surface, then click on planar face to orient. Consider minimizing support material, minimizing stairsteps, etc.
 - Set rotation angle if desired, and click on X, Y, or Z axis
 - Change view as needed
 - Click Process STL
 - Click to Add to Pack
- Pack tab
 - Drag parts toward rear left (top left) corner
 - Do not overlap parts (will appear crosshatched)
 - Delete parts as needed (click to select, then press delete)
 - Click Save As to save .cmb file

Step 3. Catalyst (sending file to uPrint)

- File/Insert CMB (if not already loaded)
- View Pack tab
- Verify there's enough model and support material for the build (if not, unload spools that don't have enough material (if you don't want the build to stop) and load new material spool(s) as needed).

1.4.2. Production (uPrint machine):

- Remove orange base with corrosion inhibitor
- Install new modeling base; make sure the blue latches are engaged
- Empty the blue waste bin in the rear left and then hook it back on; gloves are recommended
- Load material if needed; filament should protrude about 1" from carrier. If end of filament isn't cleanly cut, cut it perpendicular to filament using wire cutters in cabinet.
Note: Until carrier is inserted into machine, "load" will not be an option.
- Don't press "Wait for Part" on the uPrint. Rather, click "Print" in Catalyst and then "Start Part" on the uPrint
- After verifying that the part is printing well, turn off chamber lights.

1.4.3. Post-processing (after building the part in uPrint machine)

- Remember to wear safety glasses
- Remove the base with model
- Try to remove the support by gently lifting it in a way not to damage the part. If that doesn't work, try gently flexing the tray by twisting it between your hands, but not enough to damage the tray or your part. If neither of these is sufficient, then without cutting yourself, gently use a chisel and mallet to remove the part from the tray without gouging the tray.
- Put used base in drawer with others already there Wave-wash machine:
- Ensure that drain hose is directed into sink!
- Switch unit on if off (switch is on the rear above power inlet)

- Load parts into cage; if parts are small enough to fall through cage, try to attach to underside of lid using mesh
- Adjust lid to correct height (half or full load)
- Look up correct cycle time (short, medium, long) for SR30 support in WaveWash user guide
- Select load size using button, select cycle time, then start
- When job is completed, remove cage, leave lid open to allow drying, turn off unit unless will be used soon.

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Appendix A.

Table of Technologies				
Technology	Method	Advantages	Disadvantages	Materials Used
Multi-Fab	High powered laser sintering many different powder materials.	-Many different materials -Ready to use end parts -Can include electrical parts including sensors and circuits -self calibrating using machine vision	-Very early in development -Currently very expensive machine	-almost all metal alloys -plastics -wire -sensors
Electron Beam Machining	-uses electron beam to melt metallic powder in place in a vacuum	-more effective than normal laser beam -vacuum allows no oxidation deformations -three to five times faster than other additive manufacturing processes	-vacuum limits operation sites -very expensive -take a lot of energy to preform	-Titanium Ti6Al4V - Titanium Ti6Al4V ELI - Titanium Grade 2 - ASTM F75Cobalt-Chrome
3D Prnting	Creates 3D product from a CAD model by slicing it into cross	-Faster than traditional machining processes -able to make	-CAD software is not always easy to use -some processes won't create a	-liquid polymers -metal powders -ceramics -glass -wires

	sections and building it layer by layer	extremely complex geometries -CAD model can be scanned or made from scratch -heavily used in the manufacturing industry	useable product -still to complicated to be widely used in households	-paper -sheet rock -lasers
Stereolithogrpahy	Converting liquid polymer into solid layers by UV light	-very common -very timely -cost effective -can be vapor honed or bead, or sand blasted -products can be electroplated with metals -low material cost and reusable resin	-have to be post processed -product may have deformities due to left over polymer resin -need support structures during progress	-plastic polymers -composite polymers -urethanes -nylon
Fused Deposition Modeling	-Melts plastics threads (support and modeling) extruded from a nozzle to make cross-section	-can make end-use parts -the thermo plastics used can endure heat, chemical and mechanical stresses -even used in food and rug packaging	-need support materials -not as precise as other processes -support materials must be dissolved off after printing is complete	- acrylonitrile butadiene styrene (ABS) - polycarbonate (PC) - polyetherimide (PEI)

		industries		
Laminate Object Manufacturing	Uses a continuous sheet of material, that is cut then pressed to form a layer of the cross-section	-materials are cheap and very understood -no chemical reactions -very affordable for making large models -great for conceptual models	-Cannot produce very complex geometries -not as accurate as other printing systems -cannot produce working parts	-plastics -paper -sometimes metal
Direct Metal Laser Sintering	Uses a high powered laser to melt metallic powder in the form of the desired cross section	-extremely accurate from of printing -used widely in all areas of industry -high resolution -great surface quality -excellent mechanical properties	-not readily available to the public -a little longer process than other 3D printers -printing systems and materials are expensive	-aluminum -steel -cobalt -titanium -nickel alloys
White Light Scanning	Uses a projector and two cameras to turn photographic images into 3D models	-can create millions of reference point from one picture -very fast and effective -is not limited to any object	-if object is large have to manually attach reference point to object -produces some gaps and overlaps that must be deleted	-two cameras -projector -adhesive reference points

			in converted CAD model	
Coordinate Measuring Machine	-Using a probe and three axes system, the machine measures an objects dimensions	-very effective means of measurement -eliminates the use of 2D measuring devices	-measurement is limited to work envelope -not portable	N/A
Laser Scanner	Uses reflected light in order to form a 3D image of an object	-fast and easy to use -portable -quickest from of scanning	-usually needs multiple scans to complete	-laser scanner