CHAPTER 1

INTRODUCTION TO RAPID PROTOTYPING

1. Introduction to Rapid Prototyping

This chapter covers detailed explanation of rapid prototyping and its general methodology. A comprehensive classification of rapid prototyping techniques along with relative advantages and disadvantages are also presented. The application areas of various rapid prototyping techniques have also been reviewed. The main focus of this research deals with the modeling and simulation of welding based rapid prototyping techniques therefore a detailed comparison between various weld based techniques is given. The problematic areas have been identified and reviewed comprehensively.

1.1. Introduction

In mechanical engineering, rapid prototyping (RP) is the process of building prototype objects to see whether a proposed design will be successful. Verifying "successful" designs has several aspects, including correct shapes, correct sizes, adequate strength, and others. The field of rapid prototyping has seen the recent introduction of automated systems that can convert a computer solid model into a three-dimensional artifact. These technologies have also been called "layered manufacturing" or "solid freeform fabrication". Layered manufacturing implies that these artifacts are built in two-dimensional layers which greatly simplifies these processes and enables their automation. One of the first known approaches to layered manufacturing was used by the Egyptians to build the pyramids. Solid freeform fabrication implies that complex shapes are as easy to build as simple shapes because due to the breakdown in 2D layers there is no need of specific tooling. With the original idea of quickly making models of parts a variety of SFF processes have been developed with a common general concept.

1.2. RP Methodology

RP using layered manufacturing techniques, the process begins by creating a solid model of the product using any CAD interface. This solid model is then fed into a special rapid prototyping program called "Process Planner" which breaks down the geometry into layers and generates the required deposition path for each layer. This layer-wise data is send to deposition system to build up the part layer by layer. To accommodate geometries with overhanging features the parts are embedded in a sacrificial supporting material during buildup. The process automation and subsequently shorter production time is the primary advantage of rapid prototyping over traditional manufacturing processes. Conventional manufacturing process like machining require part specific tooling and reorientation of part during manufacturing but rapid prototyping process usually do not require any fixture or need very simple fixtures. The part is built from the bottom layer to the top layer with each layer bonding to the previous layer. Once the bottom layer has been attached to the substrate or platform, the part is built up layer by layer without ever having to remove, reorient, and re-fixture the part.

1.3. Classification of RP

The rapid prototyping processes can be broadly classified as those involving removal of material or addition of material. There are two material removal processes, namely the Desktop Milling (DM) and Laser Milling (LM).

According to Kruth [1] the material addition process can be classified by the state of prototype material before the part is manufactured. The prototype material may be Liquid Polymer, molten material, powder, solid sheet or electroset fluids. Liquid polymer may require laser to solidify and molten material or electroset fluid solidifies when they come in contact with a substrate. Process using powder or discrete particles may entail laser to bind them along with a binder. The solid sheet can be bonded by light or adhesive material. Table 1-1 gives a tabulated presentation of rapid prototyping classification.

Based on the state of prototype material the various rapid prototyping techniques have been compared below.

1.3.1. Material Addition

1.3.1.1.Liquid Polymer

This category uses electromagnetic radiation to solidify the liquid polymer. The process can build an entire layer at once or by moving from one point to another. Brief descriptions of various methods are given below.

Stereolithography (SL)

In this process ultra violet (UV) light is used to solidify photosensitive liquid polymers, Jakobs[2]. The substrate is in the form of a platform which is lowered when a layer is completed. The UV source scans and hatch the surface of resin using the information provided by the CAD model. The photopolymer used for making prototype also acts as the support material. The process requires post processing by post-curing in UV oven.

Liquid Thermal Polymerization (LTP)

Except for the use of thermosetting resin and laser source this process is similar to SL. Shrinkage and large distortions are the main draw back of LTP as compared to SL.

Holographic Interference Solidification (HIS)

Developed by Batelle development Corporation, in this process the entire layer is solidified by projecting a holographic image over the surface of resin. This process is in its infancy with no commercial system available.

Solid Ground Curing (SGC)

It is a process similar to Stereolithography. It uses erasable masks to expose only those sections of the liquid resin that should be cured, Levi [3].The resin must be photopolymer and the light source radiation used is UV. The support material used is wax.

Rapid Micro Product Development (RMPD)

RMPD uses a mask based technology similar to that of photolithography. Photolithography is the process of transferring geometric shapes on a mask to the surface of a silicon wafer. CAD data is used to produce the mask and this mask is used for photo polymerization of resin by lasers. The minimum layer thickness can be 1µm with the X-Y resolution of about 10 µm. it is used for development of micro components.

Object Quadra Process (Object)

This is a multi channel process employing 1536 nozzles and 2 UV lamps for the deposition and curing of the photosensitive resin. The intensity of light is so adjusted that it does not require any post curing. Support material is deposited for the overhanging areas and undercut.

1.3.1.2.Molten Material

In this category of processes the prototype material is deposited in molten form on a solid substrate. The prototype material solidifies as it comes into contact with the relatively cooler substrate. The layer is build up as the material is deposited sequentially. The molten material may be metal or polymer. A brief description of some of the processes is given below

Ballistic Particle Manufacture (BPM)

Ballistic particle manufacturing (BPM) uses 3-D data about a solid model to position streams of material on a target. 3-D objects are generated in a way that is comparable to how inkjet printers produce 2-D images. A stream of molten particles is Sachs[4] ejected from nozzles which get cold welded on striking the substrate.

Multi Jet Modeling (MJM)

MJM works similarly to an inkjet printer. Small droplets of material are accelerated onto the surface of the part in layers. A printer head with up to 96 nozzles is used. The deposition head moves in X-Y plane depositing material where necessary. Presently only waxy materials (fragile) can be processed. MJM is often used for lost wax castings of metal parts.

Fused Deposition Modeling (FDM)

FDM is the second most widely used rapid prototyping technology, after Stereolithography. Developed by STRATASYS [5], a plastic filament is unwound from a coil and supplies material to an extrusion nozzle. The nozzle is heated to melt the plastic and has a mechanism which allows the flow of the melted plastic to be turned on and off. The nozzle is mounted to a mechanical stage which can be moved in both horizontal and vertical directions. As the nozzle is moved over the table in the required geometry, it deposits a thin bead of extruded plastic to form each layer. The plastic hardens immediately after being squirted from the nozzle and bonds to the layer below. The entire system is contained within a chamber which is held at a temperature just below the melting point of the plastic. Several materials are available for the process including Acrylonitrile-Butadiene-Styrene (ABS) and investment casting wax. ABS offers good strength, and more recently polycarbonate and poly (phenyl) sulfone materials have been introduced which extend the capabilities of the method further in terms of strength and temperature range. Support structures are fabricated for overhanging geometries and are later removed by breaking them away from the object. A water-solubie support material which can simply be washed away is also available. A schematic of the process is given in Figure 1-1

Welding Based Deposition

This category of rapid prototyping technique comprises of all those methods which use welding as a metal deposition process. A welding arc provides the heat to melt the wire, fed by a wire feeding system, while a CNC program developed using the CAD data is used to place the welding torch at required position for deposition. This method is also referred to as 3D Welding and is still in its experimental phase, as research is in progress to reduce the problem associated with weld base deposition like residual stresses, poor surface finish and deformations, Beradsley and Kovacevic[6] This method has the capability of producing form fit and functional parts. A major development is the Hybrid RP system which uses gas metal arc welding and CNC milling. 3D welding and milling is a novel freeform fabrication process and allows the fabrication of metallic prototypes by combined additive and subtractive techniques. Figure 1-2 shows the process principle of 3D Welding and Milling. First, a layer is built by depositing single beads side by side with bead offset h_s. Depending on the welding parameters such as welding speed v_s and welding power P, the bead thickness t varies. The distance between single beads h_s is an important process parameter determining the overlapping of beads and thereby the layer's surface quality. When deposited, the top surface of the layer is machined to a prescribed thickness for further deposition. Combining the deposition with subsequent face milling enables us to make appreciable changes in the layer thickness. This is, in fact, a unique feature of the process in that an adaptive slicing with variable layer thickness is enabled. When the sequence of deposition and face milling is finished, surface finishing is applied in the same setup to remove remaining stair steps on the surface. Any dimensional and geometrical inaccuracy resulting from the deposition can be completely compensated for by this final surface finishing. It has been demonstrated that prototypes with simple geometries such as thin-walled and solid rectangular shapes can be built with this process. The deposition by gas metal arc welding is a cost effective method of metal deposition; however its beads are of lower quality than laser welding beads with respect to accuracy and surface quality. Since a post-processing step, e.g. surface machining is required for most of the parts built by direct deposition approaches, the relatively low accuracy and surface quality of arc-welded beads is acceptable. GMAW also offers a distinct technical advantage with regard to the possibility of vertical wire feeding: the welding result is independent from the change of the relative movement between the wire nozzle and the x–y table.

GMAW and GTAW are the two most commonly used method of metal deposition by 3D welding. The advantage of GMAW is the high rate of metal deposition and the ease of welding, on the other hand in GTAW the rate of deposition is relatively low but gives good surface finish since the wire feed rate is independent of welding current. Moreover the beads can be partially or fully overlapped with no influence on arc stability. Due to reduced spatter in GTAW process, surface milling after each deposited layer is avoided, which increases the process speed.

Precision Droplet Based Manufacture (PDM)

A droplet based net-form manufacturing technique is under development at University of California-Irvine (UCI) that is termed precision droplet-based net-form manufacturing (PDM). The crux of the technique lies in the ability to generate highly uniform streams of molten metal droplets such as aluminum or aluminum alloys. The capillary stream breakup phenomena of liquid jet are used to produce metal droplets of uniform shape, size and thermal state. These droplets are deposited over a substrate attached to X-Y table. The movement of X-Y table is controlled by the CAD data. No commercial system is available.

Shape Deposition Manufacturing (SDM)

Shape Deposition Manufacturing is an SFF process which was started at Carnegie Mellon University and developed by Stanford University to produce metallic parts based on welding and laser deposition, Merz et al[7]. Unlike other SFF processes like Stereolithography and laser sintering, Shape Deposition Manufacturing is a layered manufacturing process which builds fully dense metal parts by incremental deposition and CNC shaping of material layers, as shown in Figure 1-3, SDM comprises of a series of operations starting from a deposition station where material either primary or support is added using a weld based deposition process called microcasting. The part is then transferred to a CNC milling platform where material is subtracted and finally to a shot peening station to remove residual stresses. First, a computer aided design model of a part is sliced into layers. The layers are in the z-direction and derived by custom planning software. Next a layer is deposited. The layer is deposited as near-net shape. This near-net shaped layer is then milled to final dimensions by a 5-axis CNC mill. Support material is then deposited around the layer to protect the features of this layer and provide a base for overhanging features in following layers. The next layer of the part material is then deposited, and the process continues. The combination of layered manufacturing and sacrificial support material enables the production of complex features such as undercuts or conformal cooling channels. Also this technique lends itself to the production of multi-material structures, Fessler et al [8]. For instance, an insert can be produced which is primarily a hard ferrous alloy with copper deposits for enhanced thermal conductivity. Using the multi material strategy, sensors can also be embedded in the die during the build sequence to develop "smart dies." The process can be used for both metal and polymers.

1.3.1.3.Discrete Particles

This group of processes uses metal or ceramic powder to produce prototypes. The powder is bonded by laser or separate binding material. Some of the main processes of this group are;

Selective Laser Sintering (SLS)

This process uses CO_2 laser and a powder bed, heated to its melting point, to sinter the particles. The laser is modulated in such a way that only selective area of powder bed is effected. The CAD model is used to generate the code for the motion of laser beam. The powder which is not sintered acts as the support material. This process requires post processing of the green part. Laser sintering Technology (LST) is a process similar to SLS but is a multiple channel process and uses two laser sources for heating.

Laser Engineered Net Shaping (LENSTM)

In this process the powder particles are feed through a nozzle on to the part bed and simultaneously fused using a laser. The heating via laser facilitates remelting of previous layer and good interlayer bonds. There are a number of systems developed using this principle e.g. direct metal deposition, DMD and AeroMet Laser additive manufacturing. AeroMet Laser is a laser powder forming process and mainly aimed at producing large parts from reactive materials such as titanium for aerospace applications. Final machining is necessary before parts can be used, but much less than would be typical if a part was machined from a solid billet.

Gas Phase Deposition (GPD)

To generate solid parts this method uses laser to decompose a gas. Three slightly different method are investigated in literature SALD, Table 1-1, in which the solid phase of decomposed gas is all what is required for the part, in LCVD, Table 1-1 a thin layer of powder is spread and the decomposed gas fills in the space in between, while in SLRS, Table1-1a chemical reaction between the gas and layer of powder is initiated by laser. This reaction is used to generate solid.

Direct Photo Shaping (DPS)

This process employs a large number of microscopic mirrors, around 500,000, to reflect visible light on a to photo curable slurry, Ventura et al.[9] These mirrors can be titled while reflecting the light. For each layer the projected image is changed according to the CAD data describing the object being built and solidification takes place by photo-curing of the exposed areas. Multiple layers are dispensed and photo-cured to fabricate the object of interest. A final rinse with a suitable solvent allows the removal of any uncured ceramic dispersion. The porous free formed 'green' ceramic object can then be fired and sintered into a highly dense ceramic part.

Three Dimensional Printing (3DP)

The process builds parts by first applying layers of powder to a substrate and then selectively joining the particles using a binder sprayed through nozzle. Once the part is build the excess powder which acts as the support material is removed.

1.3.1.4.Solid Sheet

The process present in this category used foil to generate prototypes, some of the techniques are

Laminated Object Manufacturing (LOM)

LOM uses paper or ceramic, plastic or metal sheets coated with a thermally activated adhesive. A new layer is glued to the previous layer using a heated roller. The contours of the cross-section are cut into the sheet with a laser. Portions of the layer not belonging to the part are crosshatched, and can be broken away upon completion of the part.

Paper Lamination Technology (PLT)

This process is similar to LOM; the only difference is that PLT used a computerized knife to cut the contours of the cross-section.

Solid foil polymerization (SFP)

The part is built up by binding layers of semi-polymerized foils. These foils are solidified by UV source. Those parts of foil which are not solidified acts as support material and a removed as they are soluble in monomer resin.

1.3.1.5.Electro-Setting Fluid

This process employs the property of electro-setting fluid that when a voltage is applied the fluid gets solidified. The layers are printed over a conductive materials , stacked an immersed in a bath of electro-setting fluid. When fluid is energized it solidifies thus generating the part.

1.3.2. Material Removal

This category has 2 processes namely Laser Manufacturing (LM) and Desktop Manufacturing (DM). The prototypes are created by removing the material rather then adding. The material removal process can be different ranging from conventional machining to laser ablation.

1.4. Applications of Rapid Prototyping

Engineering model making

Models are made to confirm that designs are correct in dimensions before expensive tooling is made for mass production runs. Rapid prototyping replaces the manufacture of metal prototypes from CAD drawings by conventional machining techniques, being quicker and cheaper. The rapid prototyping models can also be used for engineering analysis like visualization of flow patterns. photo-elastic stress analysis and thermo-elastic tension analysis.

Engineering manufacture

Rapid prototyping can make tools for vacuum casting, investment castings, etc. It is very suitable for one-off objects, or small production runs. There is a lot of research on manufacturing metal items directly that is without an intermediate casting stage. At the moment, only a very limited range of metals can be produced, with less than optimum material properties.

Industrial design

Accurate samples of objects like plastic boxes, instrument cases, door handles, etc can be made. The ability to handle very intricate shapes easily is a big advantage of rapid prototyping compared to standard techniques. The model can be sanded and painted if required to help the visualization of the final production-run version.

Medical procedures

Modern advanced medical imaging techniques, such as whole body scanners, can accurately map out the dimensions of bones or body organs of a living person. These measurements can be used to make computer models of the body parts from which full-scale plastic copies can be made by rapid prototyping. The plastic copies are used for planning surgery or shaping replacement joints. RP techniques can also be used for operation planning, surgery rehearsal, training and prosthesis design. SLA is one method which was used to make bone implant.

Architecture

Architects have always used models as a way of conveying their design concepts to the public. Increasingly they are also using CAD systems to generate building plans, so rapid prototyping of the building models directly from the CAD program is an obvious next step

Reverse engineering

Reverse engineering uses rapid prototyping to duplicate existing objects, rather than simply construct real versions of computer models. It has a whole variety of applications, from archeology to medicine. The object to be copied (perhaps at an altered scale) is digitized - the shape is mapped out by taking measurements over a complete mesh of surface points. This can be done by physically tracing over the object with a stylus, or by laser scanning, or by x-rays or CAT scans for living bodies. It is even possible to reconstruct the physical dimensions of an object from a set of photographs. Once the *cloud of points* has been acquired, the next stage is to generate a 3D computer model from the cloud. Special software is used for this. If any alterations are wanted to the object, for instance changing the size, or adding new features, it is done at this stage. Then the solid copy is made by CNC machining or rapid prototyping.

1.5. Limitations of Conventional RP Techniques

Conventional rapid prototyping techniques like SLA, SGC, LOM and FDM have produced a significant impact in design and manufacturing but the application is limited to producing non-metal parts only for visualization and form/fit purpose. SLS produce metal parts but porosity and post processing steps are a major drawback. The post processing methods alter the microstructure, properties and characteristics of the part and also produce significant part shrinkage. Thermal spraying is also an alternative for metal parts and has been used successfully. The application of thermal spray process to produce parts with high structural integrity and dimensional tolerances is also limited by the presence of porosity. Moreover due to the spray nature of deposition, the inter layer bonding is relatively weak with low interlayer remelting, geometric part with high aspect ratio are also difficult to manufacture. De-lamination due to thermal stresses is also big problem in application of thermal spraying to rapid prototyping.

1.6. Weld Base Deposition Methods

Welding based deposition has shown promise to produce form/fit/functional parts with high structural integrity and dimensional tolerances. Due to relatively high heat input and large remelting depth the bond between layers is very strong. The weld based deposition process can be broadly classified as non transferred mode e.g. Microcasting, Merz et al. [9] or transferred mode e.g. gas metal arc welding.

Microcasting

The process used for depositing material in SDM is called microcasting. Microcasting is a non transferred welding process in which the arc does not comes in contact with the substrate as shown in Figure 1-4

The plasma arc is used to melt the wire fed through a conventional MIG system. The arc heat creates a molten pool at the end of wire. A discrete droplet is formed which detaches when the gravitational force on the droplet exceeds the surface tension holding it. Individual droplets with size ranging from 1 to 5 mm fall freely on the substrate at several droplets per second. Due to high superheat available and large volume to surface area ratio's the droplets are deposited at very high temperatures, up to 2300° C, facilitating localized substrate re-melt and strong metallurgical bonding. In order to control the oxidation of droplets and the substrate the system is enclosed in a shroud which provide the inert nitrogen environment.

Development of microcasting process requires investigation of various thermal and mechanical issues like droplet temperature, re-melting depth, substrate temperature, residual stresses and deformations. As microcasting can also be used to create parts with multi material interface therefore it is necessary to investigate interaction between dissimilar materials.

The existing literature on the thermal modeling of microcasting process is very limited; some aspects of microcasting are similar to the thermal spraying. The research in thermal spray has been focused largely on the modeling of droplet spreading and solidification, i.e. droplet shape and solidification time, on the level of single droplet by Trapaga et al.[11], Bertagnolli et al.[11] and multiple droplets by Kang et al.[13]. Trapaga modeled droplet solidification heat transfer using a empirically determined substrate heat transfer co-efficient. Bertagnolli modeled droplet solidification by an interface heat transfer co-efficient to determine the heat flux in to the substrate. Similar modeling was performed by Kang for multiple droplets. Various processing, thermal and mechanical issues related to microcasting were discussed by Amon et al[14]. 1D Numerical simulation was used to model the microcasting process by schmaltz et al.[15] and the results were verified against experimental and analytical data. The model was simplified to the impingement of a single molten metal droplet on a solid substrate. The numerical result indicate that for a stainless steel droplet, temperature of 2300° C is required to cause substrate remelting of about 10μm, however substrate preheating will lower the required impact temperature. The thermocouple experiments indicate that for typical microcasting parameters a temperature of 2300°C is available and the metallographic examination confirms the remelting of substrate. Amon et al.[16], compared the relative features of a 1D and multi dimensional microcasting model. It was concluded that a 1D model can be used effectively for the prediction of remelting depth but for wider range of parameters a multi dimensional model is required. The 1D and 2D model gives similar result for initial part of cooling process up to about 0.2 seconds after which the multi dimensional effects becomes dominant. In order to incorporate the dynamic effect of droplet spreading the microcasting model was modified by using a effective liquid conductivity Zarzalejo et al.[16], obtained by multiplying the liquid conductivity by a conductivity multiplier, to account for the fluid motion near the interface of droplet and substrate. The multiplier was quantified by heat balance at the droplet and substrate interface. The model was verified by metallographic examination of remelting depth and thermocouple measurement was performed for the determination of deposited material temperature history. It was found that for stainless steel a multiplier of 5 gives good agreement with experimental measurement. A Parametric analysis conducted by Schmaltz et al.[17], shows that changes in the initial droplet temperature within the range found in microcasting have no effect on the droplet-cooling rate during solidification. On the other hand, it is found that a 2000 °C copper droplet induces a six-fold increase on the remelting thickness compared to an 1800 °C droplet therefore, metallurgical bonding between layers can be improved by increasing the initial droplet temperature without effecting the final microstructure. It is found that preheating the substrate decreases the droplet-cooling rate during solidification. However, this effect diminishes towards the droplet top. Numerical simulations also reveal that the region close to the droplet/substrate interface experiences cooling rates that are an order of magnitude higher than those at the droplet top region. Therefore, it is possible to control this rapid cooling and to obtain a more homogeneous microstructure throughout the droplet domain by increasing the initial temperature of the substrate. Numerical results also show that preheating the substrate facilitates the remelting process. The droplet solidification time is delayed when either the initial droplet temperature or the substrate temperature is increased. This is relevant for successive droplet deposition since a better interlayer bonding is achieved when a droplet is deposited overlapping a previously deposited droplet that has not solidified completely. Results for different combinations of copper and stainless steel show that droplets deposited on copper substrate experience higher cooling rates during solidification than droplets deposited on stainless steel. When using copper as a sacrificial material for building stainless steel artifacts, preheating the copper is desired to obtain homogeneous microstructure in the steel part. In addition, remelting is less likely to occur when steel is deposited over copper. It is recommended to use copper as a sacrificial material since copper can be easily removed while maintaining a good stainless steel surface quality.

Residual stresses and deformation are a major cause of concern in rapid prototyping processes. The principal detrimental effect of residual stresses is warping which is unacceptable for the manufacturing of functional parts. Droplet level thermo-mechanical modeling of microcasting for a single metal droplet of cylindrical shape, chin et al.[19], successive layer and columns of droplets, chin et al.[20], adjacent droplets chin et al.[21], were performed. 2D axis-symmetric analysis was performed with single droplet over a large substrate. Transverse Residual Stresses along the thickness of the droplet and substrate was discussed and the results were compared with a 1D model and it was found that both models gives comparable results along the centerline of the domain. The analysis was further extended to take into account the effect of preheating. Uniform substrate preheating results in reduction in magnitude of stress but is accompanied by an increase in the depth into the substrate to which residual tensile stresses are present. 1D model of successive layer deposition, was developed to understand the effect of new layer on residual stresses in previous layers and it was found that the final stress state after deposition of new layer is weakly effected by stress state of previous layers. It has also been indicated that the part constraining and material with limited strain hardening can reduce part warping. Results from simulations of droplets successively deposited in columns shows that, whether same amount of material is deposited as single droplet or multiple droplets the final residual stresses state does not vary. Moreover it was also indicated that localized preheating tends to increase the residual stresses rather then limiting it. Three dimensional modeling of droplets deposited in a row, shows that there is a limited thermal interaction between the droplet even if the droplets are in contact with each other. Periodic steady state is achieved when few droplets are deposited causing the temperature of the substrate to rise and providing the stress relief. Mechanical interactions will result in higher stress in the direction of deposition as compared to the transverse direction; this observation is consistent with the experimental observed directional dependent warping, Klingbeil et al.[22]

Welding

In the weld based deposition systems using gas metal arc welding has following advantages as compared to microcasting;

- Greater Interlayer bonding
- Less Porosity
- Large deposition rate, up to $15in^3/hr$
- Greater material utilization, up to 90%
- Less costly equipment
- High structural integrity
- Welding gives better controllability of the size, flux, velocity and thermal state of the droplet and the thermal state of substrate, making it a promising method to obtain metallic parts.

A number of different welding types have been tested for rapid prototyping application e.g. Gas Metal Arc Welding (GMAW), Gas Tungsten Arc Welding (GTAW), Electron Beam Welding (EBW), Laser Welding and Variable Polarity Gas Tungsten Arc Welding (VPGTAW). These processes have been used as a standalone 3D Welding system or as a hybrid 3D Welding and CNC milling system. A 3D welding system can give excellent mechanical properties but due to low resolution the parts are generally near net shape. This method is generally accepted for medium to large prototypes like the automobile casing. Baker in 1925 used welding for the first time to create 3D parts like receptacles and containers of ornamental. The earliest application of welding as deposition method for a solid freeform fabrication process was reported in Germany in

1960 where several free standing parts were built. Wilcox & Babcock and Rolls Royce tried welding to produce large components in order to save the wastage cost of high performance alloys. A number of different patents are present where 3D welding is being used for build up of free standing parts[22].

A double spiral overlay welding technique used generally for cladding application was employed to create parts with heavy sections by Spencer et al.[26]. This deposition scheme was employed to increase the penetration into the substrate and to the neighboring beads without increasing the welding current. The 3D welding system was used to create a horizontal slab and a vertical slab. Tensile testing and metallographic examination were carried out for samples cut from the parts welded. It has been found that for a vertical slab the samples cut from top of slab are 8.6% weaker in term of UTS as compared to samples cut from the bottom. The Yield strength and stiffness are also on the lower side for top samples. Tensile testing of horizontal slab shows that the strength in the direction of deposition is very good but across the welding the strength is reduced due to the presence of inclusions and voids. The metallographic examination shows that the root fill methods can give satisfactory penetration and the structural integrity of parts produced by this method is also good. The effect of operational temperatures on surface quality of parts produced by 3D welding was studied by Spencer et al.[27]. The parts produced were a vertical slab, horizontal slab and a hollow box. It was found that by controlling the substrate temperature at the start of each pass results in parts with good surface quality but at the expense of higher production time. This increase in production time was very severe in the buildup of vertical slab where the cooling time is twice the deposition time. The residual stresses measured for the samples show that it depends not only upon the controlled temperature but also on the geometry. It is concluded that a compromise must be achieved between the surface quality of part, production time and residual stresses to create fully functional parts. In order to prevent the metal deposition at high current level and to control the size of the droplet two different sensory feedback systems have been proposed by Kovacevic et.al.[28]. A laser beam placed through the arc can control the size of arc length so that the detached droplet is not out of the weld pool, thus ensuring precise positioning of deposition. The other system is a real time image processing setup based on the experimental setup proposed by Zheng et al.[29], in which the weld droplet detachment takes place at low current level, lower then the transition current of spray transfer. According to Zhang et al.[30]-[32] , in pulsed GMAW if the current is suddenly reduced, oscillation sets up in the droplet while it is hanging from the electrode. When the droplet is moving down, while oscillating, a pulse is applied which provides the required electro magnetic force, and this force along with the downward momentum of the droplet provides enough force to detach the droplet, since the pulse level is below the transition current level hence the droplet formed contains less amount of heat energy, enough to only re-melt the surface not deform it. The instant of pulsing also depends upon the required size of droplet and the instant is determined by using a real time image processing system. The above proposed methods not only control the heat input to the substrate but also give control over the instant of detachment, the size, flux and trajectory of the droplet. The above defined welding control system cannot guarantee high quality surface finish, therefore a hybrid gas metal arc welding and CNC milling system was developed. This hybrid system ensures good mechanical properties, excellent surface finish and dimensional accuracy. A new deposition process based on variable polarity gas tungsten arc welding, using 5356 Aluminum alloy was developed by Wang et al.[33] , for directly building cylindrical parts. GTAW has advantages over other welding process like it is capable of spatter free welding; precise control over welding parameters while the heat source and filler material are controlled independently. It was observed that due to high thermal conductivity of aluminum substrate preheating is required to decrease the temperature gradient between deposition and substrate. It was also noticed that for larger substrate the preheating temperature is higher. Choi et al.[34] , developed a hybrid rapid prototyping system by combining a laser welding system to a milling machine. Laser welding enables accurate deposition of metal while the milling operation provides the required surface finish and accuracy. The optimum basic process parameters like laser power, wire feed and table speed are determined. Metallographic examination, tensile testing and hardness testing were performed on parts fabricated by this method. A relationship between the process parameters and part properties was established. It was found that reliable bonding between layers exists and the parts have sufficient hardness and strength. The dimensional accuracy ensures that the process can be effectively used for production of tools like injection molds. A computer based process planning system coupled with the welding machine was developed by Zhang et al.[34] The software had the ability to slice and plans the torch path according to the specific needs of a 3D welding system. Problems like tolerances, speed, arc ignition, weld end and crater filling were incorporated into the planning algo. The system has the ability to vary the process parameter during buildup to ensure required accuracy of part. A low voltage electron beam welding has shown potential for space application. NASA Langley research center and Johnson space center have undertaken research to develop a solid freeform fabrication process based on electron beam welding which can be deployed in a long duration space mission [35], to supply the spare parts. The system consists of a electron beam power source and a wire feeder. The vacuum chamber is designed in such a way that it can take advantage of space vacuum. Testing of the process at 1-g level and microgravity environment is required for the determination of process variables. The control of weld deposition is essential for its development as a rapid prototyping tool. In order to control the droplet detachment time and size a welding wire feeder is designed which provides an additional mechanical force enabling deposition at low current level, Wu and Kovacevic [37]. This mechanical force is provided by the change in the direction of motion of the welding wire. At a higher feeding rate, 100mm/s and welding current ranging from 210 Ampere to 220 Ampere, a significant improvement in the weld quality is observed. However for feeding rate of 60 mm/s, an acceptable weld quality is obtained when the welding current is from 160A to 180A. The application of force at a frequency of 80Hz produces the best results with very uniform detachments of small droplets. High surface quality weld beads were produced with a uniform smooth spatter free appearance, moreover with wire oscillation the geometry of weld bead can be altered considerably. The weld width increases significantly while the reinforcement height and the bead plate wetting angle as well as the cross-sectional area of penetration decreases. A hybrid rapid prototyping system combining a welding machine, CNC milling and a process planner have been develop by Karunakaran et al.[39]. The process planner generates the code necessary for the deposition and machining. The mechanical and metallographic testing of the parts made for above setup shows that the system can be used effectively for the production of dense and strong components. Song et al.[40] , developed '3D Welding and Milling' system for rapid prototyping application. They combined the benefit of both the process to acquire high structural integrity and dimensional tolerances. The initial testing revealed that the parts made by this process give tensile strength and hardness equivalent to parts made by other direct deposition methods. The 3D welding process was optimized by statistical approach using Taguchi method by Song et al.[41] A number of bead on plate experiments were conducted and optimal values of parameters like welding voltage , wire feed speed, distance between the tip of welding gun and substrate and shielding gas composition were determined. It was observed that voltage and wire feed effect the bead quality while the gas and distance between the tip of welding gun and substrate do not have much impact. Tensile testing of samples shows that the strength is effected by alternating, with each layer, the direction of deposition. During weld based deposition the arc is in direct contact with substrate which results in large substrate remelting, which tends to destroy the geometric tolerances of underlying layers, therefore the management of heat input is important. Kovacevic et al.[42], proposed an adaptive controller for the welding parameters in order to manage the heat input. Using finite element simulation it was suggested that buildup of 3D parts was sensitive to heat input and heat transfer conditions. Vasinonta et al.[43], developed non dimensional plot termed process maps for the buildup of thin walled structures by LENS process to quantify the effect of wall height, laser power, deposition speed and part preheating on the size of melt pool and thermal gradients. The model was applicable for any rapid prototyping process using moving heat source. A link was created between the thermal gradient and residual stresses. It was concluded that uniform substrate preheating, up to 400°C, can reduce the residual stresses by about 40% but if the deposition is started on a substrate at room temperature than varying speed of heat source and power can reduce residual stresses by 20%. The melt pool varies significantly with power and speed. At large levels of base plate preheating, the reduction in residual stress is a very weak function of velocity and power. Thus at large levels of preheat, the full range of power and velocity can be used with minimal effects on maximum residual stress magnitudes. Preheating does not increase melt pool lengths significantly, any increase in melt pool size due to preheating can easily be eliminated by a small decrease in power or increase in velocity.

Nearly all manufacturing processes including forming process, machining processes, welding and heat/surface treatment process produce residual stresses in the components. A very detailed description of residual stresses and deformation in steel due to manufacturing process such as casting, rolling, hat treatment and welding etc. is given in, Totten et al. [44]. The research in welding as a rapid prototyping tool has been limited mostly to the development of equipment setup and possible applications. The control of metal transfer during deposition has also been investigated, as reviewed previously. The problems inherent to welding like residual stresses and deformation are a major cause of concern. The deformations results in tolerance loss, while the stresses may cause premature failure due to layer delamination and cracking. The research in determination and minimization of residual stresses and deformations with specific application to 3D welding is very limited. The previous research relies heavily on the use of finite element method as a simulation tool for the prediction of residual stresses and distortions. Finite Element simulation is the most widely used and acceptable tool for virtual prototyping Zorriassatine et al.[45].The influence of deposition patterns likes long raster and spiral on the deflection, of the metal part, was investigated by Nickel et.al.[45], using a combination of finite element analysis and experiments, for both beam substrate and plate type substrate. The finite element model assumed that the deposition pattern is such that it lies between two symmetry planes. It was found that for a beam substrate a short raster patterns produces lowest deflection but for plate type geometry, the outside to inside spiral path produces lowest deflection. A finite element model and experiments were used to examine the Christmas Tree Step development, Nickel [47]. In contrast to finite element model of deflection, the inter-layer surface defect, finite element model was sensitive to the heat transfer solution. Therefore, more accurate values for the thermal material properties and the heat flux absorbed by the substrate were necessary to predict the step sizes. Both the finite element model findings and the experiments show that the step is a result of the material deposited only in the vicinity of the part's edge. In addition, the results show that the deposition pattern does not significantly influence the step size. However, some patterns can produce a shift of the substrate that results in smaller than predicted step sizes. The results from experiments also show that the step size is dependent on the material deposited. Depositing 410stainless steel resulted in the lowest step size. Residual Stress driven delamination in Multi layers was studied by Bueth et al.[47]. The result showed that the steady state delamination energy release rate, G_{ss}, could be used to predict the critical interfaces where the debonding may occur. The Finite Element Method was used to show that G_{ss} could be used to determine the susceptibility of an interface to residual stress driven delamination. G_{ss} values and symmetry arguments have been used to show that the ordering of layers can change the location where delamination is most likely to occur and in doing so the susceptibility of part to delamination can be changed. Experimentation for estimation of residual stress induced warping, Klingbeil et al.[48], in specimen manufactured by microcasting and welding revealed that a combination of plate constraints and insulation results in low substrate warping. The experiments were conducted for various deposition path and it was found that those paths that take full advantage of substrate preheating gives least warping. The above experiments were compared against a 2D generalized plane strain (GPS) finite element model but the warping predicted by GPS model did not agree with experimental observations.

The modeling of metal deposition using gas metal arc welding have a number of features similar to conventional welding simulation like, moving heat source, accurate prediction of molten pool, determination of temperatures, deformations and residual stresses using , in most cases, sequentially coupled thermo-mechanical analysis. The buildup of a single layer in layered manufacturing is equivalent to multi pass welding, since a layer is created by the integration of a number of single pass welding.

The simulation of welding process was first appeared in early 1970's and so far various authors have written several reviews. The general trends in welding simulation can be found in Masubuchi [50] and Easterling [51] but the most recent and comprehensive review of developments in welding simulation is by Lindgren [52][51]-[54], which is compiled in three parts. Rosenthal's [55] model for moving point heat source is considered a first step towards the simulation of welding. The author presented an analytical model to calculate transient heat distribution in an infinite plate due to a moving point heat source. In the early simulations transient temperature determined by using this model was applied as thermal load and structure analysis was performed directly. In the subsequent experimental work it was found that this model predicts accurate transient temperature in the far field only. Later on some other heat source models such as multiple point heat source Debiccari et al.[56], gave a better approximation of transient temperature distribution. There are several studies in which a line heat source is used to model welding simulation Assumption behind this simplification was infinite welding speed. Some studies were also conducted to compare the results of different heat source models, Goldak et al.[57]. A Gaussian distribution named "double ellipsoidal heat source" was presented by Goldak et al.[58] and is considered better option for simulation of arc welding. Scheme presented by Goldak is most widely being used heat source model and will be discussed in detail in the next chapter.

Towards the numerical aspect of simulation a number of numerical experiments were performed to evaluate the effect of modeling techniques, mesh intensity, element types, numerical integration procedure and type of solvers. Lindgren describes the effect of all these parameters in detail in his review but some of the important observations are.

The degree of the finite element shape functions for the displacements should be one order higher than the thermal analysis due to the fact that the temperature field directly becomes the thermal strain in the mechanical analysis.

For determination of transient heat distribution, transient and residual strain and stresses a fine mesh with linear elements is preferable than fewer elements of higher order because linear quad, in two dimensions, and brick, in three dimensions, are the basic recommendation in plasticity.

Using a linear element requires that average temperature should be used to compute a constant thermal strain in the mechanical analysis. Then the volumetric strain is constant in the element It is also important to under integrate the volumetric strain when using linear elements in-order to avoid locking.

For proper estimation of temperature and residual stress in the fusion zone and heat affected zone the element size should not be more than 01 mm and time step size should be smaller than 0.1 Sec. If the objective is microstructure determination the element size and load step size should be much smaller than the above described limiting values.

Gradient dependant adoptive meshing significantly reduces the total number of elements in the model and therefore reduces the computational time required. L.E. Lindgren and his co-workers further improved the above-mentioned adaptive meshing. The adaptive meshing technique calculates the thermal and stress gradient after each load step and refines the mesh where these gradients are high and decreases the number of elements in areas where the gradients are on low side.

Level of accuracy in the modeling of residual stresses and deformations in welding was discussed by Lidgren [59]. The modeling was divided into different levels of accuracy and the geometry required; element type used and temporal discretization needed are compared.

The modeling of weld pool is an important parameter since the size of molten pool determines the size and accuracy of deposition. The remelting depth is also a function of the size of the molten pool. The cooling rate at the solid-liquid transient boundary determines the microstructure and the solidification process. The temperature distribution determines the thermal residual stresses and deformations. The changes of the weld pool shape like width, remelting and cross sectional area, by variation in the distribution of heat source was reported by Tsai et al.[60] An analytical model was developed based on closed form solution to a traveling Gaussian heat source. Due to few simplified assumptions the model cannot predict the actual size of weld pool but can give an acceptable relationship between size of weld pool and process, material parameters. A 3D finite element model was developed by Hu et al.[61], for a laser based deposition process; in order to predict the molten pool size and temperature of the processing zone. The model was tested for a single bead wall. The predicted molten pool agrees well with the experimental data. It was concluded that in order to control the fusion zone and temperature of the processing zone the molten pool must be regulated effectively at a constant transverse velocity.

1.7. Experimental Determination of Residual Stresses

Experimental determination of residual stresses, arising due to manufacturing process or due to service, is an area of great interest since the first quarter of the last century. Due to the efforts of Mathar and Soete a semi-destructive center hole-drilling technique for the measurement of residual stresses was in place till 1949. Since then, a lot of work has been contributed by a number of researchers, and several new techniques have been introduced. A brief introduction and theoretical background of the origin and measurement of residual stresses can be found in Withers and Bhadeshia [62]-[64] and Tuck [64], while the working principles and application methodology of these techniques can be found in Lu [[65]. A brief comparison of the experimental methods with tips for appropriate selection of a particular technique can be found in Kandil [[66].

Hole-drilling strain-gage method is the most widely used technique because of its established methodology, low equipment cost, versatility and reasonable accuracy. Keeping in view its affordable cost, suitability to our specific application and availability of standard procedure for stress measurement, center hole-drilling technique is selected for experimental verification of calculated stresses. Center hole-drilling strain gage method of residual stress measurement is semi destructive technique and is based on measurement of released strain due to drilling of a small hole at the center of the strain gage rosette. Mathar measured released strain by using mechanical extensometer while Soete used strain gauges to measure released strain. Kelsey, in 1956, first time used center hole drilling strain gauge method to determine variation of residual stresses with depth by drilling a through hole. He further developed methodology for blind hole-drilling for non-uniform residual stresses. Rendler and Vigness (1966) developed systematic and reproducible procedure for uniform residual stresses and developed geometry of strain gage rosette, and is used even now a days according to ASTM E-837 [67]

Beside the basic technique, another aspect was to develop equipment for stress-free drilling. In 1974, Beaney and Procter refined the use of air abrasion method to produce hole without inducing substantial drilling stresses. Flaman[68] used ultra high speed drilling for this purpose. Related fundamentals of center hole-drilling technique can be found in [69] by Vishay-Measurements Group, a reputed manufacturer of hole-drilling equipment and strain rosettes.

ASTM E-837 provides a standard procedure for measurement of uniform residual stresses through incremental hole-drilling method. According to this method a small hole is drilled (in successive increments) at the center of special rosette, pasted on the surface of stressed component. Stress profile changes due to hole-drilling and produce strain in the vicinity of hole. Measured strain corresponding to relieved stress is used for the determination of residual stresses with the help of data reduction equations and calibration constants. These calibration constants are calculated either experimentally or by using FE formulation. Over the time, several variations have been introduced in the hole-drilling method to cater the nature of stress profile.

The conversion of release strain data to residual stresses is referred as data reduction and can be categorized into following four types:

- Incremental Strain Method
- Power Series Method
- Average Stress Method
- Integral Method

Development of incremental strain method has already been discussed above. This method is based on the assumption that incremental strain relaxation measured during each successive hole depth is solely due to release of stress in corresponding hole depth increment. Scaramangas et al.[70] suggested corrections for the effect of surface preparation, plasticity induced during forming and machining stresses. Although incremental hole-drilling method is widely used but the basic assumption is not valid. Schajer[71] introduced an approximate method, called power series method, for the determination of non-uniform sub-surface residual stresses. This method is based on least square procedure to give best fit curve through the measured strain data. This method is best suited for gradually varying sub-surface residual stresses. Subsequently, Schajer[72] further improved his method of residual stress calculation.

According to [71] a new technique for stress calculation based on equivalent uniform stress was introduced by Nickola (1986). The equivalent uniform stress was assumed as uniform stress within the total hole depth that produces the same total strain relaxation as the actual non-uniform stress distribution. This assumption could be valid if the contribution to strain relaxation is the same by released stresses at various depths. Contrary to this assumption, stress released near the surface contributes more then those at higher depth. Subsequently Niku-Lari et al.[73], Flaman and Manning[74] reported calculation of calibration constants for integral method by using finite element technique. Schajer [75] reviewed different techniques and presented improved stress calculation procedure for power series method and integral method. He furtner presented practical implementation of integral method of center-hole-drilling technique. Later on, Wern[76]-[78] used wavelets to solve integral formulation. In his work numerical implementation was done with conjugate-gradient method. He was succeeded even to get solution of singular matrix. Zuccarello[79] suggested optimized hole-drilling steps to minimize measurement error and suggested depth distribution which gives diagonal coefficient of the coefficient matrix. Aoh and Wei [80]-[81] further improved the coefficient, determined by schajer, by using three-dimensional finite element model.

Towards the selection of proper technique for some anticipated stress profile Grant and Lord [82]-[83] compared all the four hole-drilling techniques and recommended the use of integral method for highly non-uniform stresses such as in the case of welding. Lord presented the results of round-robin exercise; "UK Residual Stress Inter comparison Exercise" in which results obtained from different laboratories were compared to develop a good practice guide for hole-drilling method and XRD. It was concluded that experimentally measured results may vary even if the same measurement procedure is used and accuracy of results strongly depend on operator's skill. NPL (National Physics Laboratory-UK) report [84] provides very useful information regarding estimation of uncertainties in the stress measurements using hole-drilling technique. The uncertainties present in the experimental procedure was discussed by Oettel [85].

1.8. Scope of Research

Modeling and Simulation are essential stages in the engineering design and problem solving process and are undertaken before a physical prototype is built. Computers are used to draw physical structures and standard mathematical models are used to simulate the operation of a device or a process like weld based layered manufacturing process. The Modeling and Simulation phase is often the longest part in the engineering design process.

As discussed earlier, during literature review, number of simplified efforts has been made to model the deposition process by targeting the thermal issues in [15-18] and [42-43], while the structural issues have been discussed in [19-22] and [46-49]. These attempts concentrate on modeling of few parameters while the modeling procedures is very simplified, as the effect material addition, moving heat source, temperature dependent material properties and 3D substrate clamping, has not been incorporated simultaneously. As a result the studies concentrating on mechanical effects cannot predict the parameters like remelting and transient temperature distribution correctly while those attempting to model the thermal behavior cannot altogether predict residual stresses and distortions. Moreover the structural models cannot predict the residual stresses and distortion correctly e.g. Klingbeil [49]. In view of the above discussed limitations, correct prediction of thermo-mechanical parameters requires extensive modeling of the deposition process using standard procedures of welding simulation and integrating them with the simulation of rapid prototyping process.

In this research an attempt has been made to model the deposition process extensively taking into account the time dependent material addition, moving heat source and temperature dependent material properties. The deposition of layer has been modeled by overlapping the weld beads and controlling the deposition torch motion, details of which will be presented in subsequent chapters. The thermal and structural results have been verified against experimental data and have been found to be in good agreement. Due to the limitation of computational resources the model is limited to the buildup of single layer.

The research has been divided into three phases according to the complexity of the model and the extent of the results required.

- In the first phase a single molten metal droplet deposited over a large substrate has been modeled in order to understand the physics of thermo-mechanical interaction between the droplet and the substrate. The simplified model was used to study the effect of deposition shape, thermal boundary conditions at substrate bottom, heat sink size and properties on the cooling rate and build of residual stresses.

- In the second phase a 2D model is developed, transverse to the deposition direction while

- A complete 3D model is developed in the third phase. The inability of a 2D model to capture the effect of 3D deposition and mechanical constraints are highlighted and the results are presented for penetration of fusion zone, residual stresses and deformations.

- A comprehensive parametric analysis has been performed using the 2D model for the optimization of basic process parameters, while a 3D model is used to study the effect of various mechanical constraints.

The research has deepened the understanding of the thermo-mechanical interaction of molten metal deposition, while the development of more complex 2D and 3D models provides a tool for obtaining optimal process parameters.

The thesis is organized with increasing modeling complexity starting from a droplet level model of deposition. Finally the 2D and 3D models are used to study the relative effect of various process parameters.

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1.10. Figures

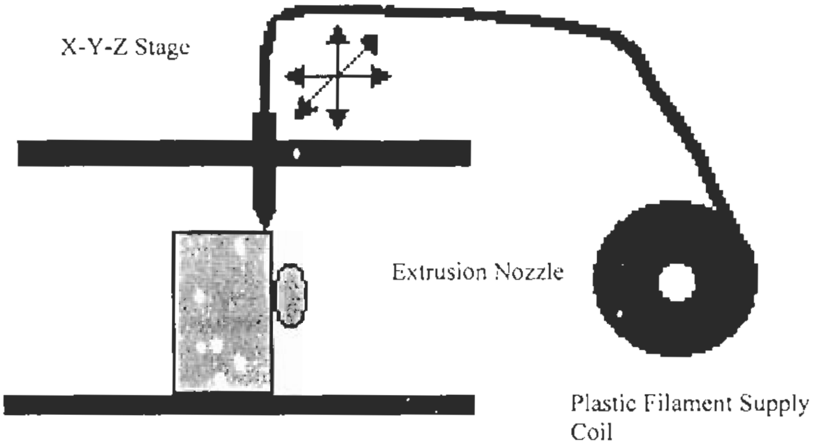


Figure 1-1: Schematic of FDM

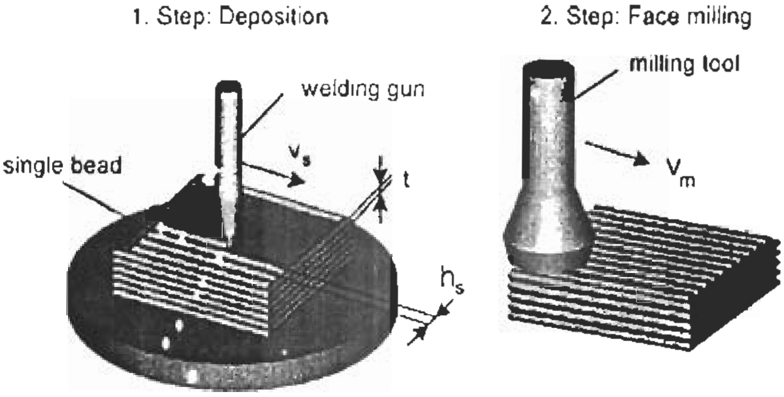
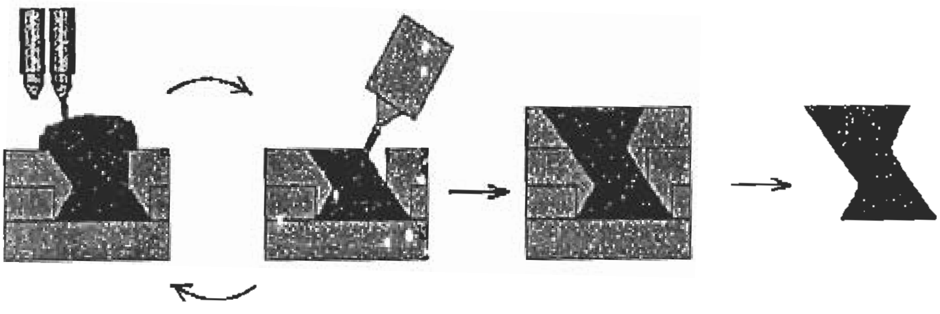


Figure 1-2: Schematic of Welding based rapid prototyping [40]



Deposition Machining Part with Support Material Final Part

Figure 1-3: Schematic of SDM

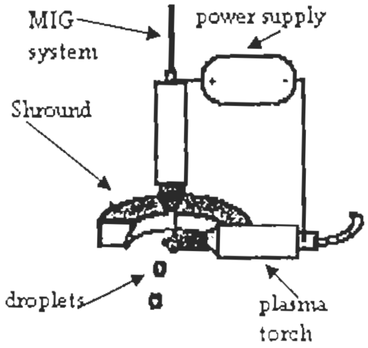


Figure 1-4: A Schematic of Microcasting Process [18]

S.No	1st Classification	2nd Classification	Process
	Material Addition	Liquid polymer	SL, LTP, Object, SGC, RMPD, HIS
		Discrete Particles	SLS, LST, LENS, LCVD, SLRS, GPD, SALD, LST, 3DP, DPS
		Molten Material	FDM, BPM, WBD, PDM, MJM, SDM, TS,HW
		Solid Sheets	LOM, PLT, SFP
		Electroset Fluid	ES
	Material Removal	Milling	Desktop (DM)
			Laser(LM)

Ballistic Particle Manufacturing (BPM)
Direct Photo shaping (DPS)
Electro-setting (ES)
Fused Deposition Modeling (FDM)
Gas Phase Deposition (GPD)
Holographic Interference solidification (HIS)
Laminated Object Manufacturing (LOM)
Laser Assist Chemical Vapour Deposition (LCVD)
Laser engineering Net Shaping (LENS)
Laser Sintering Technology (LST)
Liquid Thermal Polymerization (LTP)
Multi Jet Modelling (MJM)
Object Quadra Process (Object)
Precision Droplet Based Manufacturing (PDM)
Rapid Micro Product Development (RMPD)
Shape Deposition Manufacturing (SDM)
Selective Area Laser Sintering (SALD)
Selective Laser Reactive sintering (SLRS)
Selective Laser Sintering (SLS)
Solid Foil Polymerization (SFP)
Solid Ground Curing (SGC)
Stereolithography (SL)
Three Dimensional Printing (3DP)
Hybrid Welding and CNC Milling (HW)
Weld Based Deposition (WBD)

Table 1-1: Classification of Rapid Prototyping Techniques