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# Rapid Prototyping and Manufacturing: A Review of Current Technologies

Prof. Sandeep Karole[1], Prachi Rathore[2], Karuna Photphode[3] ,Roshan Rakse[4] ,Pravin Paradkar[5],Tanu Boharpi[6]

[1]*Professor, Dept.of Mechanical Engineering , Shri Balaji Institute Of Technology & Management,Betul ,Madhya Pradesh ,India*

[2,3,4]*Student , Dept.of Mechanical Engineering , Shri Balaji Institute Of Technology & Management,Betul ,Madhya Pradesh ,India*

***ABSTRACT***
*The idea to develop processes capable to produce physical components quickly and without requiring tooling,led to the development of the "free form fabrication" (FFF) or "rapid prototyping" (RP) technologies in the early 1980s. RP systems generally build up a prototype directly from the computer-aided design (CAD) data by using an additive "layerby layer" method. The RP technologies have brought several advantages to the manufacturing industry in such a way that these technologies are evolving toward the production of end- use parts. This paper presents a review of rapid prototypingand manufacturing (RP&M) technologies from their origins. The review includes commercially available RP systems and RP technologies that are still at the development stage or that have been proposed. The operating principles and the features of these technologies are presented. Process parameters suchas accuracy, layer thickness, operation speed are given. An extended classification of RP&M technologies is also includedin this paper.*

***Keywords****: rapid prototyping (RP), rapid manufacturing (RM),layer by layer.*

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## I. INTRODUCTION

The need for rapid physical construction of models before full-scale production has emerged as a consequence of the constant drive to reduce cost whilst demanding increasing speed, accuracy, quality and overall dimensions of the final product [1]. Rapid Technologies (RTs) have emerged to "allow" the fulfilment of this need. Two basic characteristics of RTs are: 1) their independence from the shape of the object to be manufactured, and 2) their dependence on physical principles, materials and target applications. Rapid Prototyping, as rapid technology, was introduced for the rapid construction of physical objects directly from digital data in a computer-aided design (CAD) system. The RP technologies were introduced to allow better visualization of forms during the conceptualisation and design stage of products, and consequently, to reduce the uncertainties that accompany the start of full-scale production. RP helps to shorten the design process by reducing the time required for building prototypes so that engineers can test and evaluate a design faster. The main advantage of RP is the fact that there is no need to define blank geometries, set-ups, consider material handling, jigs,fixtures and clamping, or to design moulds and dies.

The applications of RP technologies have been in the production of near net shape (NNS) prototypes, which arebrought into the required tolerance by a finishing operation. Some NNS products can be used directly (as a part requiring none or little finishing) others however require considerable post-processing. The RP technologies have brought several advantages to the manufacturing industry in such a way that these technologies are evolving toward the production of end- use parts. When this occurs, RP technologies are also referred to as rapid manufacturing (RM) technologies. On the other hand, when RP is used to manufacture production tools suchas molds, dies, etc., the RP techniques are also known asRapid Tooling (RT) techniques.

From the origin of the RP technologies, more than 25 years ago, several methods have emerged, some of them have become commercially available, other never became commercially available and others are still in development. During these years, there have been several research works regarding the review of those RP technologies [2]-[5]. These works have explained each RP technique, together with their main features, advantages, disadvantages and limitations.

RP technologies have still some limitations and problems which limit their use for the manufacture of functional parts. In general, the problems and limitations of RP processes can be summarized in nine categories as shown in Table 1. On the other hand, shape related limitations of RP technologies can be classified in seven categories [6]: cavities; distortion, shrinkage and warping; feature damage; feature size; overhangs; surface finish; and volume. Based on these limitations, the Design for Rapid Prototyping (DFRP) can be defined as the condition of optimal shapes and structures to satisfy functional needs while ensuring manufacturability inRP machines, [6]-[7]. In other words, the DFRP refers to the consideration of the problems and limitations of RP techniques during the design stage of a product, particularly if the product is intended to be produced by an RP technique.

The general procedure to construct a component in aRP&M technique can be described as follows: 1) a part is modeled by a CAD system to produce a 3D model of the component, 2) the CAD model is then decomposed (sliced) into a series of parallel cross-section layers, 3) the RP&M system reproduces the sliced data, and 4) a physical representation of the CAD model is obtained. Figure 1 illustrates this RP&M general procedure to construct a component.

| Category | Problems & limitations |
|---|---|
| Part accuracyand surface finishing | - Limited resolution along the build axis.<br>- Facet approximation and staircase effect.<br>- The dimensional accuracy and the surface quality is in general less than CNC machining and injectionmoulding processes.<br>- Shrinkage and distortion. |
| Cost of materials and equipment | - The costs of materials and RP machines are stillrelatively high. |
| Productiontime | - The build rate of RP systems is typically slow. Theproduction of an average-size model may take few hours. Large components are produced in many hoursor even days. |
| Range of materials | - The materials are limited to plastics, ceramics, heavy- duty paper, and a limited range of metals from stainless steel to titanium.<br>- RP systems build prototypes from basically just one material.<br>- The production of heterogeneous prototypes is limited. |
| Mechanical performance | - Depending on the RP method, prototypes tend to beweak and fragile compared to those made conventionally from metals and engineering plastics. |
| Size | - The maximum size of parts is relatively small. |
| Post processing | - Depending on the application and the RP technique, prototypes could require a post processing process. |
| Prototyping of assemblies | - The physical representation of assembly models that involve the assembly of multiple parts has not been addressed by RP technologies.<br>- Volume based construction is not commercially available yet. |
| Ecology | - Contamination for the use of toxic materials. |

**Table 1.** Problems and limitations of RP technologies.

This paper presents a review of the current state and capabilities of the rapid prototyping and manufacturing (RP&M) technologies from their origins. This review attempts to include the most important commercially available systems, no-commercially available systems and technologies that are still in development. The operating principles and main features of these technologies are presented. Process parameters such as accuracy, layer thickness, operation speed and costs are also provided. Also, an extended classification ofRP&M techniques is proposed in this paper.

The rest of the paper is structured as follows: section 2 describes with more detail the rapid prototyping and manufacturing technology principles; section 3 presents an extended classification of the RP&M technologies; section 4 presents the RP&M technologies reported in the literature together with a brief description of each of them; and last, section 5 draws some conclusions.

## II. RAPID PROTOTYPING AND MANUFACTURING

The proposal to develop processes capable to manufacture physical components quickly and without requiring tooling, led to the development of the “free form fabrication” (FFF) or “rapid prototyping” (RP) technologies in the early 1980s. RP systems generally build up a prototype directly from the computer-aided design (CAD) data by using an additive “layer by layer” method. When a part constructed in an RP technique can be used directly as an end-use part, the RP technique is also referred as a rapid manufacturing technique (RM). Thus, RP&M is a generic term that refers to a group of technologies that enable the construction of components directly from the computer and without the need of conventional tooling.

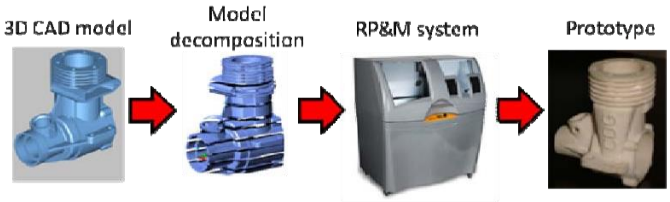

**Fig. 1.** RP&M general procedure to construct a component.

Most of the RP&M technologies build a component layer-by-layer from the bottom to the top until the final geometry is obtained. However, the materials and the way in which the layers are produced vary significantly among the different RP&M techniques. Depending on the particular case, a component produce in an RP&M system can be used as a concept model, a functional or semi-functional component, a master pattern, or even a tooling [5].

## III. CLASSIFICATION

There are many RP&M technologies which can be classified in several ways. According to the type of prototype being manufactured, the RP&M techniques can be classified in four groups [4]: visual prototype, functional prototype, material prototype and production prototype. Since this classification is defined by the type of prototype and not by the RP&M technique, it does not appropriate for the purposes of this paper. RP&M techniques can be also classified by the manufacturing process used [5]: curing process, sheet process, dispensing process, sintering process, and binding process. This classification is also limited to just the RP&M techniques that are based on the addition of material. A more general classification is based on two main categories [3]: process involving the addition of material and process involving the removal of material. Additionally, RP&M techniques can also be divided by the state of the prototype material before part formation [3]: liquid, discrete particles and solid sheets.

An extended classification of the RP&M techniques is proposed in this paper as shown Figure 2. This classification extends those presented in the literature by including new methods and by combining different methods of classifying the RP&M techniques. The proposed classification is based on four main groups: additive processes, subtractive processes, formative processes and hybrid processes. Additive processes are those in which the prototype is created by adding material, subtractive processes are those in which the prototype is created by removing material, formative processes are based on deforming the material to obtain the prototype, and hybrid processes are those which combine the addition, removal or formation of material to create the prototype. Additive processes may be subdivided into the following manufacturing processes:

- *Curing processes*. Those where a photo-sensitive material is exposed to a light source to harden it.
- *Sheet processes*. Those where thin sheets of material are cut to shape and stacked on top of each other.
- *Dispensing processes*. Those where a material is melted or vaporized and then deposited as a filament or droplets.
- *Sintering processes*. Those where a powdered material is sintered together using a heat source, typically a laser beam.
- *Binding processes*. Those where a liquid binder is deposited onto powdered material to bind the powder.
- *Assembly processes*. Those where a material or materials are assembled to construct the prototype.
- *Organism processes*. Those where live units such as live cells are assembled to make live tissues and organs.

On the other hand, the subtractive processes can be subdivided into two main groups: CNC machining and robotic machining. CNC machining refers to those systems that remove material from the workpiece as in traditional CNC machining (e.g. turning and milling). Robotic machining are those systems that use an industrial robot to move a cutting tool such as a mill to remove the material from the workpiece. Formative processes are those RP systems in which the prototype is created by deforming the raw material. Currently there is one RP system based on a formative process, robotyping. Hybrid RP&M techniques may combine additive, subtractive and formative processes to fabricate the component.

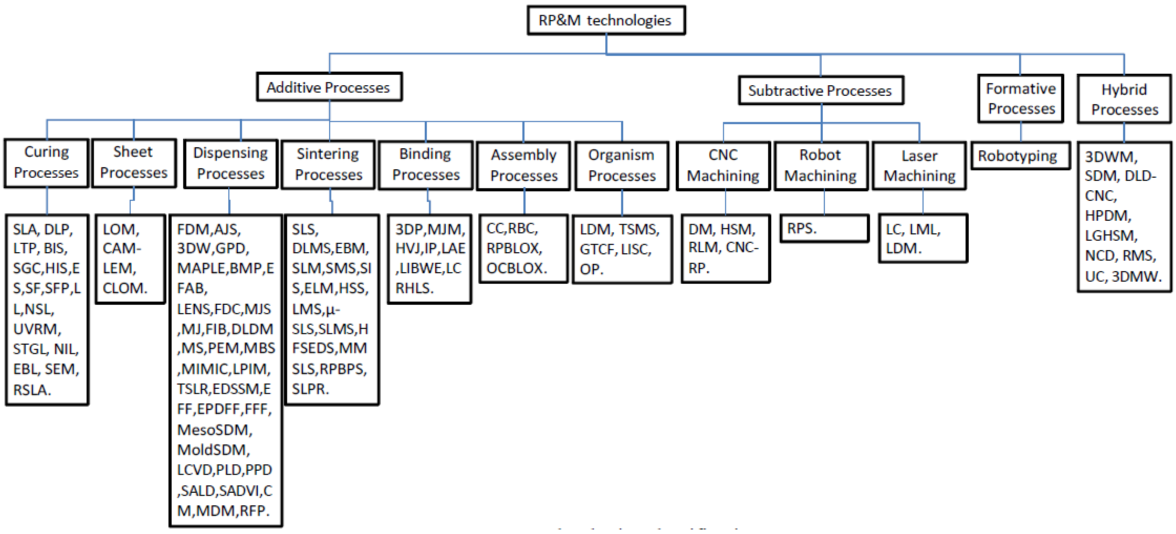

**Fig. 2.** RP&M technologies classification.

## IV. CURRENT TECHNOLOGIES

There are many RP&M technologies commerciallyavailable, others are under current development and some others have just been proposed. The following paragraphs provide a description of most of these RP&M technologies.

### ADDITVE PROCESSES

### Curing processesStereolithography (SLA)

Utilizing a UV laser and a vat of liquid UV-curablephotopolymer resin contains a platform on which the part is built [8]. The platform moves until it is just below the surface of the liquid polymer. On each layer, the laser beam traces a part cross-section pattern on the surface of the liquid resin. Exposure to the UV laser light cures, or, solidifies the pattern traced on the resin and adheres it to the layer below. After the pattern has been traced, the SLA's elevator platforms descends by a single layer thickness, then, a resin-filled blade sweeps across the part cross section, re-coating it with new freshmaterial and the laser draws the next slice on a fresh layer ofliquid polymer. This slice of the part solidifies and adheres ontop of the previous set slice. When all the slices have beentraced by the laser, the platform is removed from the vat andthe completed part is then finally cured in an ultraviolet oven.

### Direct Light Processing (DLP)

The process builds parts from an acrylate based photocurable resin, but it does so by using a two-dimensional matrix of mirrors rather than a '1D' array of print heads to selectively cure the material [18]. In order to selectively cure a layer, the process makes use of digital mirror devices (DMD) technology developed by National Instruments to selectively switch on and off mirrors that reflect UV light from a source on to the build area. With a build speed of 10–15 seconds per layer the process is well suited to building parts quickly, but the use of a single DMD with a finite matrix of pixels limitsthe process to small parts if a fine resolution is maintained.

### Liquid thermal polymerization (LTP)

This process is similar to SL except that the resin is thermosetting and an infrared laser is used to create the voxels. This difference means that the size of the voxels may be affected through heat dissipation, which may also cause unwanted distortion and shrinkage in the part. However, the problems are apparently no worse than those caused by SLand are controllable. This system is still being researched [19].

### Beam interference solidification (BIS)

This process uses two laser beams mounted at right angles which emit light at different frequencies to polymerise resin ina transparent vat. The fist laser excites the liquid to a reversible metastable state and then the incidence of the second beam polymerises the excited resin. To date, there are no commercial applications of this technology because there are still technical difficulties to be solved [19].

### Solid Ground Curing (SGC)

This system utilizes photopilymerising resin and light [19]. Data from the CAD model is used to produce a mask which is placed above the resins and surface. The entire layer can then be illuminated with a UV lamp. Once the layer has been cured,the excess resin is wiped away and any spaces are filled with wax. The wax is cooled with a chill plate, milled flat and chipsremoved. A new layer of resin is applied and the process repeated. The mask itself is a sheet of glass which is prepared whilst the current layer is being waxed, cooled and milled. The negative image of each subsequent layer is produced electrostatically on the glass and developed using a toner in a similar manner to laser printing. All the resin within a layer is completely cured by this method, and so no postcuring isrequired. The disadvantages of this system are that it is noisy, large and heavy and needs to be constantly manned. It wastesa large amount of wax which cannot be recycled.

### Holographic interference solidification (HIS)

A holographic image is projected into the resin causing an entire surface to solidify [19]. Data is still obtained from that CAD model, although not as slices. The build space is 300 x 300 x 300 mm. There are no commercial systems availableyet.

**Solidification of an electroset fluid: electrosetting (ES)** Electrodes are printed onto a conductive material such as aluminum [19]. Once all the layers have been printed, they are stacked, immersed in a bath of electrosetting fluid andenergized. The fluid which is between the electrodes thensolidifies to form the part. Once the composite has beenremoved and drained, the unwanted aluminum may betrimmed from the part. Advantages of this technology are that the part density, compressibility, hardness and adhesion may be controlled by controlling the voltage and current applied tothe aluminum. Parts may be made from silicon rubber,polyester, polyurethane or epoxy.

### Spatial Forming (SF)

It was developed to enable the formation of complex metallic microdevices using offset printing techniques. The CAD model is sliced into thin cross-sections, which are used for the patterning of a chrome mask by an E-beam pattern generator. The mask is then imaged to a lithographic printing plate, which is used for the printing of a UV curable organic ink. After printing a series of approximately 0.5 μm thick layers, inwhich each layer is individually cured with UV light, theresulting reverse structure is filled with a powder containingink by a knife. This material is also UV cured and the complete layer planarized. The entire process is then repeated until the desired thickness is reached. Finally the resulting green body is debindered and sintered in controlled atmospheres to obtain the final microdevice, [20].

### Solid foil polymerisation (SFP)

In this process the part is built up using semi-polymerised foils[19]. On exposure to UV light, the foil solidifies and bonds to the previous layer. It also becomes insoluble. Once the cross- section has been illuminated, a new foil can be applied. The areas of foil which do not constitute the eventual part are used to support it during the build process, but remain soluble and so are easy to remove. Once the part is complete, the non- bonded pieces can be dissolved to leave the finished part. No commercial systems are available yet.

### Laser lithography (LL)

This is the most straightforward approach to a maskless lithography. The lithography process itself remains the same; only the photomask exposureis replaced by a scanned exposure with a switched focused laser beam [20]. Still, a photoresist material has to be spun onto the wafer, prebaked, illuminated by the laser, developed and postbaked. For most wet chemical etching processes, the resist pattern has subsequently to be transferred into a previously deposited etch resistant mask. This leaves the maskless fabrication as the only benefit for laser lithography. The generation of sub- micron features on a single 4 inch wafer may take up to 1 day of scan time on a system with an X-Y table.

### Nanostereolithography (NSL)

Besides the application of the later described nanoimprinting techniques, the direct stereolithographic generation of submicron or nanosized structures is of particular interest especially for photonic or life science applications. The use of vapour pressure arc lamps or standard laser sources limits a further reduction of the accessible structural details due to the diffraction limit, [20].

### UV Reaction Molding (UVRM)

The UV process can be used for the fabrication of sensitive lens structures or deflecting prisms with low aspect ratios on silicon wafer substrates using a modified mask aligner [20]. The lens diameters range from 5 up to 300 μm, lens sag from 1 to 100 μm and with a smallest distance around 2 μm. Microstructured prototypes with an aspect ratio up to 5 can be realized with UV embossing technique using modified curableacrylates.

**Stereo-thermal-lithography (STLG)**

The process begins with the curing reaction of a photosensitive polymer characterized by chemical cross-linking reactions that create an infusible, insoluble and highly cross-linked three-dimensional network [34]. During this reaction, two main events occur: gelation and vitrification. The formation of a glassy solid material occurs due to an increase in both the cross-linking density and the molecular weight of the polymer being cured, and usually follows. From vitrification, the rate of reaction will undergo a significant decrease and the reaction becomes very slow as it becomes controlled by the diffusion of the reactive species.

**Other processes:** Nanoimprint Lithography (NIL), Electron Beam Lithography (EBL), Scanning Electron Microscope (SEM), [20]. Refrigerative Stereolithography (RSLA), [8].

**Sheet processes Laminated Object Manufacturing (LOM)**

A layer of material (generally paper) with plastic coating on the bottom side of the paper is placed on the platform, adhesive side down [8]. A heated roller passes over the material and sticks the material to the platform. A laser beam then traces the outline of one slice of the part by an optics system that is mounted to an X-Y stage, cutting through the layer of the material. The laser beam then crosshatches the material that does not form part of the cross-section, again cutting through the layer. The platform is then lowered one layer thickness, another layer of material is stuck onto the previous layer and the procedure is repeated with the next cross-section slice of the part. When all cross-section slices have been added, the solid block of material is removed from the platform and the crosshatched areas of the block are then broken away to reveal the final part. In general, the finish, accuracy and stability of paper objects are not as good as for materials used with other RP methods. However, material costs are very low, and objects have the look and feel of wood and can be worked and finished in the same manner.

**Other processes:** Computer Aided Manufacturing – Laminated Engineering Materials (CAM-LEM), Curved Laminated Object Manufacturing (CLOM), [8].

**Dispensing processesFused Deposition Modeling (FDM)**

Laying down material in layers, a plastic or metal filament of material is extruded out of a fine nozzle and deposited onto a platform [8]. The nozzle is preheated to melt the material and can be moved in the X-Y plane by a numerical controlled mechanism. The platform is then lowered relative to the nozzle and the next slice of the part is deposited on top of the previous slice. As the extruded filament is hot, it bonds to the material in the previous slice. The model or part is produced by extruding small beads of thermoplastic material to form layers as the material hardens immediately after extrusion from the nozzle. A second nozzle is used to extrude a differentmaterial in order to build-up support structures.

**Air-Pressure Jet Solidification (AJS)**

The system is an integration of NC control and proper building materials. The refined DS (denatured sucrose) is fed into two controllable jets and melted into a semi-molten state by heating systems. Each jet has a small nozzle on the tip, the diameter of the nozzle is0.2mm. The jet connects with an air compressor through a high pressure-resistant pipe on its top [11]. Fine filaments can be extruded through the nozzle by applying compressed air. Under the control of a computer, the on-off operation of the compressed air can be controlled by electromagnetic valves, and a 3D working platform movesaccording to the slicing data of the part.

**Cryogenic Prototyping (CP)**

The material is extruded out of a fine nozzle; the deposited material is solidified in a cryogenic chamber to avoid collapsing of scaffold structures [13]. Subsequent removal of ice crystals formed during the CP process with a controlled freeze drying process will result in controlled micro-porosity of the scaffold. Furthermore, this method allows the fabrication of temperature-sensitive polymeric scaffolds. The unique and novel method to control the formation of crystalline structures by rapidly frozen solvents to manipulate the formation of micro- and nano-sized pores; and the avoidance of porogens in processing make of this technique a feasible technology. The flow of materials is controlled by a pneumatic-based controller. In addition, the material is dispensed in a cryogenic chamber, in which the temperature is critically controlled and maintained by a refrigerated circulator.

**Three dimensional welding (3DW)**

This experimental system uses an arc-welding robot to deposit weld material on a platform as simple shapes which may then be built into more complex structures [19]. Unlike most RP technologies, therefore, the prototypes are not built using sliced CAD files. Parts with a resolution of a few millimeters have been made which may be used for sand casting or directly as tooling. Several problems still remain to be solved. Another system which is being researched deposits the weld material in layers. Feedback control is established by the useof thermocouples which monitor the temperature and operate an on-line water cooling system. There is a grit blasting nozzleto minimize the oxidization of the part and a suction system.

**Gas phase deposition (GPD)**

In this process, the molecules of a reactive gas are decomposed using either light or heat to leave a solid result of the decomposition then adheres to a substrate to form the part [19]. Three slightly different methods of constructing the part are currently being researched. In the first, called SALD (selective Area Laser Deposition), the solid component of the decomposed gas is all that is used to form the part. It is possible to construct parts made from carbon, silicon, carbides and silicon nitrides in this way. The second method, SALDVI (Selective Area Laser Deposition Vapour Infiltration), spreads a thin covering of powder for each layer. Then the decomposed solids fill in the spaces between the grains. In the third method, SLRS (Selective Laser Reactive Sintering), the laser initiates a reaction between the gas and the layer ofpowder to form a solid part of silicon carbide or silicon nitride. A resolution of 1µm is expected.

**Matrix Assisted Pulsed Laser Evaporation (MAPLE)** MAPLE DW (direct write) was invented by researchers at the Naval Research Laboratory, Washington. It uses a high-repetition-rate, 355nm UV laser beam which is focused on atransparent material or 'ribbon' that has a 1–10 mm thick layerof build material on the underside. As the laser energy is directed to the ribbon the build material transfers to the receiving substrate. This is analogous to a typewriter ribbon.

**Ballistic particle manufacturing (BPM)**

A stream of molten material is ejected from a nozzle. It separates into droplets which hit the substrate and immediatelycold weld to form the part [19]. If the substrate is rough,thermal contact between it and the part is increased which will reduce stresses within the part. The stream may be a drop-on- demand system or a continuous jet. In this process, the supports are usually made from a different material which facilitates their subsequent removal from the part. Advantages of the BMP are that it is cheap and environmentally safe and that metal parts made using this technology have a finer grain structure than the equivalent cast parts. A disadvantage is the small range of commercial material available to construct the prototypes.

**Electrochemical Fabrication (EFAB)**

This process is a repeated sequence of electroplating a patterned layer, deposition of a support material and planarization of the layer [20]. With EFAB, it is possible to fabricate very complex 3-D microdevices by stacking thinlayers which can have a thickness of only 2 to 10 µm in a high deposition rate. Each layer consists of a structural material e.g. copper and a sacrificial material e.g. nickel. Structural and sacrificial materials are deposited by electroplating. For the structural material a selective deposition process is used called "Instant Masking". In this process an initial photomask is created by standard lithographic methods. The photomask is then used to make the "Instant mask" formed by a metal anodeand a conformable insulator material. The Instant Mask ispressed against the substrate within an electrochemical bath. Now the structural material is selectively deposited on the substrate by an applied current. The mask is removed and the substrate is placed into a second bath where the sacrificial material is blanket-deposited over the whole substrate. Then both materials are polished to a planar layer with the desired thickness and the process is repeated as many times as required. Finally, after finishing the complete stack, the sacrificial material is removed in an etching bath. Timescaleof fabrication is in the range of a few weeks. However, due to the small size of microdevices it is possible to build a high number and a large variety of devices simultaneously on the same substrate. The features that can be built by EFAB can have a minimal size of 20 µm.

**Laser Engineered Net Shaping (LENS)**

The process is also known as Laser Cladding or Laser generating. In the process, the particles are fused together by alaser beam [20]. Unlike SLS the particles are not spread as a layer but fed through a nozzle in to the laser focus. Nozzles may be mounted on one side of the object or coaxially with the laser beam. In the focal point of the high power laser a molten pool of material is produced into which the powder is injected. The object to be built is moved below the laser beam to fabricate the desired cross-sectional geometry. The process is repeated by adding consecutive layers thereby producing a 3D-part. LENS is able to produce fully dense metal parts. Materials processed include steels, aluminum, titanium alloys, nickel based alloys and metal matrix composites. It is used for functional prototypes but it can also be used for repairing and modifying existing parts and tools. The extremely rapid cooling creates a fine grained microstructure, resulting in a high tensile strength and high ductility for most deposited metals. Parts fabricated by LENS are near net shape but generally will need surface finishing. The accuracy of theprocess is also in the range of 0.1–0.2 mm.

### Fused Deposition of Ceramics (FDC)

Based on the FDM where ceramic loaded polymer filaments are used to fabricate green ceramic components. This direct approach and the indirect method were particularly investigated to fabricate piezocomposite, [20].

### Multi-jet solidification (MJS)

Which is related to the FDM process and is able to build parts from a mixture of thermoplastic binders and metal or ceramic powders with solid contents of up to 50 vol.%. The powder- binder mixture is heated above the melting temperature and squeezed out through a nozzle. Using different nozzles with diameters between 0.5 and 2 mm, the process is suitable for producing medium sized parts, [20].Metal Jet (MJ) This is a method where patterned layers are formed bydroplets of a molten metal. This mechanism is similar to an ink jet printer. But unlike the 2D-printing, a 3D-structure is formed by the repetition of a layerwise deposition of patterns[20]. The molten metal drops are jetted out of a metal nozzleby a piezoelectric actuator which moves a diaphragm. Dropshave a speed of 1 m/s and a frequency of ejection of 4–20 Hz.With a 50 µm nozzle, droplet sizes of 80 µm were realized.This size is comparable with the ink droplet size ofcommercial ink jet printers. When the droplets collide with thesurface, they are still liquid. This reduces the accuracy of theparts but enhances the packing density of the deposited layer.

### Focused Ion Beam (FIB)

FIB is a versatile technique which enables imaging, maskless milling and the deposition of conducting and insulating material with high local precision [20]. It has the ability to fabricate structures which have a feature size below 1 µm. A FIB system operates similar to a scanning electron microscope (SEM). Both instruments use charged particles from a source, focus them into a beam through electromagnetic/electrostatic lenses and scan them across small areas of the sample. FIB differs from an electron microscope by using charged ions from a field emission liquid metal ion (FE-LMI) source. In thedeposition process, a precursor gas is sprayed onto the surface of the substrate by a fine nozzle, where it adsorbs. The adsorbed layer is hit by the ion beam which locally decomposes the precursor. By scanning the ion beam across the surface a layer of material with defined shape is createdand by depositing layers on top of each, a 3D-object is produced. In case of the deposition of metals, FIB is primarily used for making connections in integrated circuits.

### Direct laser deposition modeling (DLDM)

This process uses a focused laser beam as a heat source to create a molten pool on an underlying substrate [21]. Powder material is then injected into the molten pool through nozzles. The incoming powder is metallurgically bonded with the substrate upon solidification. The part is fabricated in a layer by layer manner in a shape that is dictated by the CAD solid model, which is sliced into thin layers orthogonal to the z-axis.

### Metal Spray (MS)

With metal spray, droplets of molten metal are sprayed on a master model [28]. Commonly used materials are zinc and steel. The largest problem with metal spray is thermal stress causing warping. In the UK, this problem has been investigated successfully and the results are patent pending. From the information currently available, it can be expected that metal spray has become a particularly interesting process, especially for larger moulds (small holes are difficult to fill with metal spray).

### Precise extrusion manufacturing (PEM)

By using different sprayers and software, PEM system allows the use of a variety of thermoplastic materials. The PEM process builds physical objects layer by layer directly driven by 3D CAD data [30]. The thermoplastic material feeds into a heated extrusion sprayer capable of moving in X-Y directions. The sprayer extrudes fine filament of the material onto a working platform capable of moving in the Z direction. A computer, based on the sliced data of the object, controls the moving of the sprayer and the platform so the material is extruded and deposited layer by layer in areas defined by CAD model to build a 3D object. Under the control of the software, the sprayer will not scan the contour but only scan the filling-in network of the object, which ensures the open porous architecture of the scaffolds.

### Laser chemical vapor deposition (LCVD)

A variant of chemical vapor deposition (CVD) is a process for generating solid deposits on the surface of a substrate by inducing chemical reactions in a suitable vapor reactant through the use of a laser beam. LCVD has the added advantage of geometric control of the deposit, by controlling the location of the laser beam. The feature size of the depositis dependent on the spot size of the laser, which ranges from approximately 5-500µm. Materials prepared by LCVD are typically of high quality, [42].

### Rapid freeze prototyping (RFP)

This is a method that uses water freezing into ice as its medium. The setup consists of a pressurized water containment unit, an X-Y table to control the plate to obtain the correct part geometry, a Z-axis elevator to raise the nozzle for the successive layers, a circuit driven nozzle and a freezer, [43].

### Multi-nozzle Deposition Manufacturing (MDM)

The MDM system is an RP system that performs extrusion/ jetting-based processes. Four nozzles at most can work orderly in the same system controlled by a computer. To ensure extrusion/jetting of the solid state scaffolding materials, they should be transformed into liquid state. For the liquid materials with high viscosity, the nozzle has a high-pressure- air-extrusion design. The MDM technology builds scaffolds, layer by layer, directly driven by three-dimensional digital models in the computer. It is accomplished in low temperature environment under 0 $^0$C in the refrigerator. The computer controls the nozzles to move orderly in X–Y directions and deposit liquid materials onto the platform in the area defined by the digital models. The layer of deposited materials is frozen on the platform. Also, under the control of the computer, the platform moves down one layer height in Z direction after the forming process of each layer. In this manner, the frozen scaffold is stacked up layer by layer. After the manufacturing process in the refrigerator, a freeze-drying process is necessary to get the solvent and water out of the frozen scaffolds, [38].

**Other processes:** Extrusion and Deposition of Semi-Solid Metals (EDSSM), Extrusion Freeforming (EFF), Electrophotographic Powder Deposition for Freeform Fabrication (EPDFF), Fast Freeform Fabrication (FFF), Mesoscopic shape deposition manufacturing (Meso SDM), Mold shape deposition manufacturing (Mold SDM), Laser chemical vapour deposition (LCVD), Pulsed laser deposition (PLD), Pointwise powder deposition (PPD), Selective area laser deposition (SALD), Selective area laser deposition and vapour infiltration (SADVI), [8]. Micromolding In Capillaries (MIMIC), Low-Pressure Injection Molding (LPIM), [20]. Thermal Spraying and Laser Remelting (TSLR), Mask Based Spraying (MBS), [26]. Compression Molding [40].

### Sintering processesSelective Laser Sintering (SLS)

In a controlled atmosphere, a layer of powdered material is deposited on a platform or substrate. Then a laser beam traces out the cross-section of one slice of the part previously sliced.

Where the laser beam hits the slice powder, the affected powder particles fuse (or sinter) together [8]. Another layer of powder is then deposited on top of the previous layer using a roller mechanism, and another slice of the part is fused (or sintered) onto the sintered material in the previous slice. The unsintered material in each layer can act as a support structure for the part itself. When the part is complete, the unsintered material can simply be blown or brushed off. Parts can often be built without additional support structures and parts in a range of materials can be obtained directly.

### Direct Laser Metal Sintering (DLMS)

A process that could produce metal parts without the need fora binder coating and the subsequent processing that would be required. Essentially the process involves either melting or liquid phase sintering of the metal powder, which typically is amixture of various components having different melting points. The initial goal of direct metal laser sintering was to produce tooling, but the process has been used for end-use Rapid Manufacture.

### Electron Beam Melting (EBM)

The process uses a similar approach to selective laser sinteringbut replaces a laser with an electron beam, this has interesting implications. Firstly, the electron beam may be directed by changing the electromagnetic field through which it passes. This eliminates the need for scanning mirrors and can significantly increase scanning speed (up to 1 km $s^{-1}$). Secondly, the power developed by the electron beam is very high, allowing the process to fully melt a wide range of metals including titanium alloy using a very fast scanning rate. However, the process is limited to conductive materials and surfaces, as with many other layer-based processes, often require extensive finishing, especially for tooling applications.Although the process uses a '0D' scanning approach, the speed of scanning coupled with no requirement for further furnace processing may make the process a leading contender for Rapid Manufacture.

### Selective Laser Melting (SLM)

The process uses a laser to fully melt stainless steel parts in a similar manner to laser sintering. The process is particularly adept at producing very small components, including ones with complex lattice structures. SLM machines of metals claim that 100% densities may be achieved.

### Selective Masking Sintering (SMS)

The process involves printing a mask of infrared radiation reflecting material on to a glass sheet and placing the sheet over a powder bed. Infrared radiation is then applied to the glass sheet and allowed to selectively pass through the mask in order to sinter the powder directly below. This process eliminates the requirement for a laser and in instances where a significant portion of the surface needs to be sintered. This should dramatically reduce processing times when compared with selective laser sintering. The SMS Machine claim that each layer can be fully processed in 10–20 seconds and that the use of a mask in place of a laser ensures that build times are easy to predict and independent of part volume. Consequently, this approach should have maximum benefits when being used for Rapid Manufacture in high volumes.

### Selective Inhibition Sintering (SIS)

The process seeks to combine the benefits of SLS (material properties) and jetting processes (build speed) to address two of the major concerns behind Rapid Manufacture [18].

However, SIS is likely to achieve better resolution and definition than the other process as the inhibiting material is printed directly on to the powder and uses no mask that might allow for light diffusion. The process uses a print head to jet fluid to inhibit sintering on to selected areas of the build volume. This is followed by using a radiating heat source to traverse the build area and sinter any powder that has not had the inhibitor printed on to it. Initial work used a single nozzle to print around the edge of parts but the process could easily be developed to simultaneously print the inhibiting material in a '1D' array or possibly a two-dimensional matrix. Unlike most of the other powder sintering processes, SIS does not require that the material comprising the part be elevated to a higher temperature than the material not to be sintered.

### Electrophotographic Layered Manufacturing (ELM)

The process uses electrophotographic methods to deposit a part powder and then a support powder for each layer [14]. Initial work focused around the idea of producing a green part by depositing separate part and support powders and then using a furnace operation to sinter the part material in a separate step; this required that the support material had a higher melt point than the part material. However, further work has experimented with the idea of sintering each layer before the next layer is deposited, as with other powder-based layer manufacturing processes. It seems that the process could be suited to very high production rates but limited to smaller parts such as electrical components.

### High-Speed Sintering (HSS)

HSS is aimed at taking advantage of the mechanical properties given by SLS while achieving an increase machine through put and reduced machine cost by eliminating the need for a laser [18]. HSS defines the geometry of each layer by printing a material that promotes absorption of radiation (and hence promotes sintering) on to the powder bed surface, rather like a negative of SIS. Research has shown that a high sintering rate results in minimal shrinkage and good edge definition but poor mechanical properties, while slow sintering achieves better mechanical properties but at a cost of definition and accuracy. By controlling sintering rates via techniques such as the use of greyscale and materials that absorb energy at different rates the goal of achieving good mechanical properties with good accuracy and surface finish is being pursued.

### Laser Microsintering (LMS)

A technique, based on SLS. It enables the fabrication of features with a structural resolution < 30 μm and aspect ratios > 10. It is important to control the gas environment, powder layer homogeneity and the sintering regime. The complete process takes place in a vacuum tight chamber (vacuum SLS) where sintering is performed by a Q-switched Nd:YAG laser in the pulse regime at a gas pressure in the range of 10−5 Pa up to 4 × 105 Pa, [20].

### Micro Selective Laser Sintering (μ-SLS)

A process based in SLS. The objective of the work is to obtain a resolution and a roughness in the range of the grain size and the size of the focused laser spot. To overcome the problems arising from the spreading of fine powders in a thin layer, a method is developed which deposits the powders from a liquid suspension. In this case, the liquid has to be evaporated prior to the sintering step to ensure that the laser interacts with the dry and compacted powder, [20].

### Selective Laser Micro Sintering (SLMS)

The process provides an improved resolution by a smaller laser beam spot. In order to fabricate microdevices, they use a Q-switched ND:YAG laser at 1064 nm and a power of 50W. In addition to that, a equipment was developed which performs frequency doubling by the external resonant ring cavity. With this equipment, the wavelength was shifted to the green light (532 nm). Compared to a laser spot diameter of 28.3 μm with the fundamental frequency of 1064 nm, at the second harmonic generation of 532 nm a laser spot of only 13 μm was measured. The maximum average power output was more than 10W with a conversion efficiency of 31%. For demonstration, micro Chinese characters were sintered from a Pb powder with a wall thickness of less than 100 μm and a height of about 2mm, [20].

**High frequency selective electrical discharge sintering (HFSEDS)**

This method is a layer-by-layer additive solid free form fabrication technique that directly creates 3D fulfilled objects from their CAD models [23]. In HFSEDS, an object is created by selectively fusing thin layers. Metal powders that are coated with polymers are used as raw materials. A computer- controlled scanning high frequency plasma arc, as a concentrated heat source that scans patterns, sinters the sequential layers corresponding to their slices in CAD model. Therefore, outer layer of the coated metal powders is melted after absorbing a small amount of heat from the high frequency plasma arc and then releases the heat during the re-solidification to form dense shapes. The manufactured fragile green part subsequently is postprocessed to fully dense condition by sintering and infiltration. Heat transfer processes have a significant influence on the final microstructure quality of the parts.

**Other processes:** Multimaterial selective laser sintering (MMSLS), Rapid pattern based powder sintering (RPBPS), Selective laser powder remelting (SLPR), [8].

**Binding processesThree-dimensional printing (3DP)**

The process starts by depositing a layer of powder at the top ofa fabrication chamber [8]. A feed chamber which contains a quantity of specially prepared corn starch, the vertical position of the upper surface of the build material can be varied by raising or lowering the feed piston. An adjacent build chamber operates in a similar manner whereby the vertical position of a piston determines the height of the build chamber. A horizontally reciprocating carriage, carrying a feed roller, the roller then distributes and compresses the powder at the top of the fabrication chamber; excess feed material is swept downan overflow chute. Also mounted on the carriage a binder cartridge travels over the surface layer of the build chamber material depositing a binder solution to match the current slice of CAD data. Once a layer is completed, the fabrication piston moves down by the thickness of a layer, and the process is repeated until the entire object is formed within the powder bed. After completion, the object is elevated and the extra powder brushed away leaving a "green" object. 3DP offers the advantages of speedy fabrication and low materials cost. In fact, it's probably the fastest of all RP methods.

**Multi Jet Modelling (MJM) (aka Thermojet)**

It works similarly to an inkjet printer. A print head containing 96 tiny nozzles in a linear array passes in the X-Y plane over a platform. Where material is to be deposited, a jet dispenses a droplet of a thermo-plastic polymer [8]. Any number of the 96 jets can be activated simultaneously, giving a rapid dispense rate when all jets are active. The hot droplets of material bond to the previous slice of the part that has just been printed. Thinsupport pillars must also be built-up slice by slice in the same material where they are needed. When the current slice of the part (plus slice of support pillars) is completed the platform is lowered relative to the print head and the next slice is printed. When all the slices have been completed, the part is removed from the machine and the support structure is broken off.

**High-Viscosity Jetting (HVJ)**

The principle involves continuous change in a layer’s pattern (negative image of the layer) according to a very thin slice of the object to be printed. This uses a mechanism based on displacing a small drop of a printable material (powder-filled polymer paste) to a desired location on a substrate. The fundamental unit consists of a single jet, which is controlled by air jet pressure, the distance from the substrate and the length of the jetting pulse. It also has flexibility in the degree of accuracy depending on the hole size being used for the jet. A production speed similar to existing high-volume production methods will be possible and the paste can be loaded with any powder.

**Inkjet printing (IP)**

Two main types of print heads are used for the inkjet printing: in continuous inkjet (CIJ) printers a continuous stream of droplets is formed, whereas in drop-on-demand (DOD) technology the droplets are only generated when required [20]. In CIJ printers a stream of an electroconductive fluid is delivered through a nozzle and is thereby subjected to vibrations by a piezoelectric actuator, which regulates the breakup of the stream into individual, uniform droplets with uniform spacing. As each drop passes through a charging electrode a controlled voltage can charge it. By passing high voltage deflection plates, the charged droplets are deflected in proportion to the charge carried and are used for the printing process, while uncharged droplets are unaffected and are collected in a gutter to be reused.

**Laser Assisted Etching (LAE)**
For this purpose a laser beam—frequently a green, blue or UV emission line from an Argon-Ion laser—is focused onto a silicon wafer through an atmosphere of e.g. molecular chlorine. The laser focus heats the silicon to near-melting or melting temperatures. In the following, the chlorine gas reacts with the heated silicon to form volatile compounds like SiCl2 and SiCl4. This complete transition of silicon into the gas phase allows a rapid, easy and complete removal from the wafer. The process takes additional benefit from the exceptionally high etch rate of molten silicon (up to 1000 µm s-1) in comparison to a very low etch rate of the unaffected material. Only the locally molten silicon will react with the chlorine thus providing a microfabrication technique for silicon microstructures, [20].

**Laser-induced backside wet etching (LIBWE)**
A nanosecond (ns)-pulsed UV laser beam passes through a photomask and a transparent plate to be absorbed by a dye solution located at the rear surface of the plate [27]. Due to strong laser absorption by the solution, the laser energy is initially confined to a photo-activated micron scale thin layer at the interface between the transparent plate and the solution, where the dye molecules are excited collectively. The photo- activated layer interacts with the surface of the plate, resulting in microetching. Typical etch rate is around 10 nm pulse-1, indicating that as large as about 1 µms-1 is possible with the repetition rate of around 100 Hz, about two order larger than ordinary plasma etching or HF etching.
**Other processes:** Local chemical reaction heat by laser scanning (LCRHLS), [8].

**Assembly processesContour Crafting (CC)**
It’s a construction process, which uses a computer-controlled crane or gantry to build edifices rapidly and efficiently without manual labor [9]. It was originally conceived as a method to construct molds for industrial parts. Using a quick-setting,concrete-like material, Contour Crafting forms the house's walls layer by layer until topped off by floors and ceilings set in place by the crane. The system calls for the insertion of structural components, like plumbing, wiring, utilities, and even consumer devices like audiovisual systems as the layers are built. With this system a complete home is probable built in a single day, and its electrically powered crane would produce very little construction material waste. Contour Crafting could significantly reduce environmental impact.

**Robocasting (RBC)**
It is a slurry deposition technique that has been applied to highly concentrated colloidal suspensions. The process is commonly used for the fabrication of alumina components from aqueous alumina-PVB gelcasting suspensions with solid volume fractions of about 0.5. The ceramic suspension and a cross-linking agent were separately pumped into a mixing chamber located directly in front of the nozzle with a diameter of 0.254–1.37 mm. The deposition of the suspension through nozzles with diameters of 200–400 µm was carried out under oil to prevent drying during assembly. The components were subsequently sintered to nearly full density. The deposition took place on a water-saturated plaster plate to prevent premature drying. During sintering the parts experienced alinear shrinkage of 17% and attained a final density of 98% of theoretical density, [20].

**RPBLOX**
RPBloX follows the use of conventional workshop machinery and technology, [35]. The RPBloX methodology involves a cellular approach to building up a part. Rather than slicing up the CAD model into numerous thin sheets, RPBloX segments the model into 3D cells (or Blox) of varying sizes. One of the main advantages of the RPBloX system over other RP techniques is the reduction of the build time especially when large and/or tick wall components are fabricated. Consequently, production costs could be significantly reduced without the forfeiting accuracy and timeliness.

**RPNNS also known as OCBLOX**
The RPNNS (rapid production of near net shapes) system [36] works by subdividing a 3D model into cubes of various sizes using an Octree decomposition approach. An optimisation method to reduce the number of cubes required to approximate the model is then performed. Once the Octree model has been verified for physical fabrication, the system automatically generates instructions for a robot assembly cell to construct the approximate prototype or NNS model.

## V. FORMATIVE PROCESSES

### Robotyping

There are two concepts for robotyping: first, the modelling of free form layers onto pre-adjusted modular forms and, second,the consolidation of form material by submerging tools [33]. The starting point for the modelling of free form layers is the production of ship propellers using flexible moulding boxes. At first, the form is roughly approached by modular elements which are either adjustable by rotating spindles or are put into the box by the industrial robot. Second, the free form layer is applied and modelled using specific robot tools. In contrast to this approach, where the form material has to be dosed before modelling, it works by filling up the box with form material and by submerging robot tools into the form material in order to consolidate the prototype below the surface of the form material. Here, the form material can be based on quartz sand or can be a hardenable liquid.

## VI. HYBRID PROCESSES

### 3D Welding and Milling (3DWM)

The process is based on the layered deposition of molten wire material using GMAW (aka Metal Inert Gas Welding MIGW) which is the most economic way of depositing molten metals [10]. The welding result is independent from the change of the relative movement between the wire nozzle and the X–Y table. First, a layer is built by depositing single beads side by side with bead offset. Combining the deposition with subsequent face milling enables us to make changes in the layer thickness between 0.1 and 1 mm. 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.

### Shape deposition manufacturing (SDM)

This still experimental layer-by-layer process involves spraying molten metal in rear net shape onto substrate, then removing unwanted material via NC operations. Support material is added in the same way either before or after the prototype material depending on whether the layer contains undercut features. The added material bolsters subsequent layers. If the layer is complex, support material may need tobe added both before and after the prototype material. Each layer is then shot-peened to remove residual which can position the workpiece to within an accuracy of ±5µm. Droplets of 1-3 mm diameter are deposited at a rate of 1-5 [19].

### Direct Laser Deposition and CNC (DLD-CNC)

In order to expand the applications of direct laser deposition processes, multi-axis capability is often needed. This process uses laser deposition for material deposition and CNC milling for material removal [21]. It includes two major systems: a laser deposition system and a CNC milling machine system. The laser deposition system and CNC milling machine workin shifts in a five-axis motion mode.

### Hybrid plasma deposition and milling (HPDM)

The process is based on the layered deposition of molten powder material using plasma arc [24]. The STL file of the 3DCAD model of the product is imported into the HPDM software system, then the processing path and NC instructions are automatically generated by the software. Based on these, the combination of plasma deposition and NC milling is realized by the hybrid machine. In the HPDM process, when a layer is deposited, its top surface is machined used planar milling to obtain a smooth surface with a certain thickness for further deposition, and the internal and external surface profile is machined used contour milling with T-slot cutters to removethe remaining stair steps on the surface and to attain finesurface state of the near-net shape metal part.

**Laser generating and high-speed milling (LGHSM)** Fraunhofer Institute and Fockele & Schwarze have developed a machine combining laser generating with high-speed milling[28]. According to them this should be the future for mouldmanufacturing. However, sharp inner corners will remaindifficult, due to the diameter of the milling tool.

### Nano Composite Deposition (NCD)

This deposition and machining system was constructed to offer high precision for micro-scale parts [29]. The nano composite was deposited into tens, hundreds micro-meter thin layers to form a near-net shape. Then net shape of the current layer was obtained by micro machining. By repeating the deposition and machining for each layer, final three- dimensional part with certain height (in z-direction) was obtained.

### Robot machining system (RMS)

The robot machining system uses an articulated robot with sixdegree- of-freedom mounted on a 2m long linear track [31].A rotary platform with clamping fixtures is installed for holding workpieces. The whole model is sliced into layers.The lower layer is machined first. Since the cavity on this layer is much shallower than that of the original model, no collision among the tool, the tool holder and the model occurs. After the machining of the lower layer, another layer is glued to it with homogeneity adhesive. Then the machining of a new layer can be repeated without collision. In layer based machining, there must be a small overlap of the tool path between the two consecutive stock layers. A machining layeris treated the same as that of conventional RP process. The cutting tool moves along each machining layer to cut the contour of the model.

**3D Micro Welding (3DMW)**

It consists of four components: a forming station, an arc control unit, system control computers, and a video- monitoring device. The forming station consists of an X–Y stage and a welding torch with Z movement. In the arc control unit, a micro-TIG welder is placed. All these components are controlled by the computer system. A metal substrate is placedon an X–Y stage under a tungsten electrode for arc welding. A small round metal bead of 0.4–1.0 mm diameter is formed by emitting a micro arc to the tip of a thin metal wire of 200µm diameter. A fused bead is welded to a metal substrate or previously formed beads. By continuing this process and building up beads layer by layer under the control of the computer system, a 3D metal object can be produced. The 3D-CAD data source is converted to a set of thin layers of 120 µm in thickness by commercial slicing software, [39].

**Ultrasonic consolidation (UC)**

This process was developed for fabrication of metallic parts from foils. The process uses a high frequency ultrasonic energy source to induce combined static and oscillating shear forces within metal foils to produce solid-state bonds and build up a near-net shape part, which is then machined to its final dimensions using an integrated, three-axis CNC milling machine. UC combines the advantages of additive and subtractive fabrication approaches allowing complex parts to be formed with high-dimensional accuracy and surface finish, including objects with complex internal passageways, objects made up of multiple materials, and objects integrated with wiring, fiber optics, sensors, and instruments, [41].

## VII. CONCLUSION

RP&M technologies have considerably evolved from their origin, more than 25 years ago. Several new RP&M systems have been proposed during these years. RP&M research has been focused on the development of systems to support new materials, e.g. organism processes, systems to support micro and nano fabrication, systems to fabricate end-user parts, systems based on new fabrication methods, and systems combining different RP&M techniques. Although there are many new proposed systems, few of them are commercially available; most of them are in development or have been proposed without commercial success. However, the original goal still remains as a key factor; reduce design and manufacturing costs and leads times to increase competitiveness.

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