ADVANCES IN THREE DIMENSIONAL PRINTING – STATE OF THE ART AND FUTURE PERSPECTIVES

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ABSTACT

This paper surveys the current state and capabilities of Three Dimensional Printing (3DP). Based on its technical background – the ink jet printing as known from the printer and plotter industry – a classification structure has been developed and proposed. Different printing techniques and process concepts, together with their advantages and limitations are described and analysed. A large variety of manufacturing applications such as rapid pattern making and rapid tooling using the 3DP process directly or as core technology, as well as further implications in design and engineering analysis, medicine, and architecture are presented and evaluated. Some research issues are also discussed. An attempt, based on the state of the art, to show weaknesses and opportunities, and to draw conclusions about the future of this important process wraps up this paper.

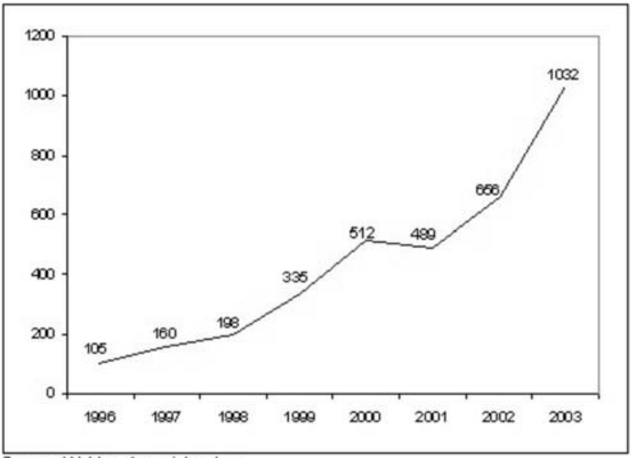
Keywords: 3D Printing, Ink Jet Technology, Concept modelling, Rapid Tooling, Rapid Manufacturing

1. INTRODUCTION

Layer Manufacturing (LM) technologies have expanded vastly over the 15 years of its history. Originally seen as mostly suitable for Rapid Prototyping (RP), these processes are not exclusively used for that purpose any longer. With the advent of new materials along with new processes, each technology has been contributing to the diversities in different fields of application. In the process of improvement, it is however critical to understand exactly, what the capability of each individual technology is in order to compare current processes and techniques, or even future improvements.

During the last decade intensive research efforts have been focussed primarily on the so called high-end additive processes, and above all on the Stereolithography (SLA) and the Selective Laser Sintering (SLS) technologies, exploring various issues mostly related to process control and material property improvement. In recent years Three Dimensional Printing (3DP) came to the foreground as a very competitive process in terms of cost and speed, and sales of related equipment have increased significantly compared to other RP machines (Figure 1) [1]. These devices were developed, and are still seen, mostly as a "concept modeller". However, with the larger selection of materials available today, as well as the wide variety of post treatment procedures, the scope for this technology is growing quickly – far beyond the original idea of generating design iterations or inexpensive metal parts directly from a CAD file.

This paper surveys the current state and capabilities of the 3DP as a Layer Manufacturing technology. Based on its technical background – the ink jet printing as known from the printer and plotter industry, where this technique involves shooting tiny droplets on paper to produce graphic images – a classification structure has been developed and proposed. Different printing mechanisms and process concepts, together with their advantages and limitations are described and analysed. Some process control issues are also discussed. A large variety of manufacturing applications such as rapid pattern making and rapid tooling using the 3DP process directly or as core technology, as well as further implication in design and engineering analysis, medicine, and architecture are presented and evaluated. Some of the most relevant research directions are highlighted. An attempt, based on the state of the art, to show weaknesses and opportunities, and to draw conclusions about the future of this important process wraps up this paper.



Source: Wohlers Associates, Inc.

Figure1: Growth of 3D Printer sales [1]

2. DEFINITION AND CLASSIFICATION

2.1 Three Dimensional Printing – background and definition

The birth of the Solid Freeform Manufacturing (SFM) can be traced back to 1988 when the first Stereolithography (SLA) machine was introduced. The development of the idea for RP started, however, a few years earlier. In the mean time many new proposals emerged and numerous patents on the subject were deposited. Some of the processes introduced earlier disappeared completely; while others are still in use, but without further development. Table 1 below, gives an overview about that matter.

As can be seen from Table 1 the rationale about 3D Printing – in its Drop-on-Bed (DoB) version - was one of the first developments and its continuous improvement is far from exhausted. Although a patent was filed at the end of 1989, it was granted only four years later. The commercial use had to wait for another four years to a time when other processes such as Stereolithography (SLA), Fused Deposition Modelling (FDM) or Laminated Object Manufacturing (LOM) were widely established and drew large crowds at international fairs.

Generally speaking the Three Dimensional Printing is an up runner of the Ink-Jet Printing technology, which was originally developed some 30 years ago. There are two types of Ink Jet Printing [2]:

- Continuous Ink Jet Printing uses a stream of charged droplets and deflects those, which are to be used for printing
- Drop-on-Demand (DoD) Ink Jet Printing positions the ink jet printing head over the place where printing is to occur before depositing a droplet.

The main characteristics of these two principle forms of Ink-Jet Printing can be summarised as follows:

- Drop formation velocity – very rapid droplet generation (60 kHz) by the Continuous printing; substantially lower – typically 5-6 kHz by DoD.
- Fluid viscosity – the continuous drop formation requires very low viscosity fluids; relatively low values by DoD
- The fluid must be able to conduct electricity (even if only weakly), while the excitation by DoD is assured by the pressuring device.

Name	Acronym	Development years
Stereolithography	SLA	1986 - 1988
Solid Ground Curing († = year of disappearance)	SGC	1986 – 1988 1999†
Laminated Object Manufacturing	LOM	1985 - 1991
Fused Deposition Modelling	FDM	1988 - 1991
Selective Laser Sintering	SLS	1987 - 1992
3D Printing (Drop on Bed)	3DP	1985 - 1997

Table 1: LM Technologies, acronyms and development years [3]

The ability for subsequent overprinting leads to the building of the third dimension, whereby each layer must solidify. This allows a multi-layer and multi-material construction, therefore also the name Three Dimensional Printing.

Obviously, there must be some target properties of the fluids, which make them "printable". These properties must allow to

- Maximise the solid loading of suspensions
- Keep fluid properties within a printable window
- Stabilise suspension against settling

Keep viscosity < 40 mPas [2].

These target properties are given by principles of the fluid mechanics. Hereby the key parameters are the Reynolds number (R_e) and the Weber number (W_e). Suitable fluids for DoD printing for example normally satisfy the condition $1 < R_e / \sqrt{W_e} < 10$.

2.2 Classification of the 3D Printing techniques

During the last 15 years a large variety of 3D Printing techniques were introduced into the RP industry. As mentioned above all these techniques have their roots in the ink jet printing technology and the use of a printer head is the only element, which they have in common. This printer head – in whatever version it might be applied – serves to shoot either droplets of binder, or of liquid-to-solid compound, and so forms a layer of an RP model. The shooting of droplets of the actual building material (liquid-to-solid compound) in DoD mode is known as Drop-on-Drop deposition, while the shooting of droplets of binder on the powder material is called Drop-on-Powder (DoP), or Drop-on-Bed (DoB) deposition. Depending on the ink jet method a thermal, polymer or physical phase change takes place.

Table 2 shows how different deposition techniques link up to the different technologies that make use of them.

Table 2: Summary of processes and corresponding technologies [4]

Aimed Deposition Process	Technology
DoD deposition	• 3D Plotting • Multi-Jet Modelling
DoP deposition	• 3D Printing
Continuous deposition	• Fused Deposition Modelling (FDM)

2.2.1 DoD Deposition

<u>Thermal Phase Change Inkjets</u>

The process, as introduced originally by Sanders Prototype, Inc. (now undertaken by Solidscape, Inc.), makes use of two print heads with single jets, one for depositing the thermoplastic building material while the other deposits supporting wax. The supporting wax material is deposited at the same time as the thermoplastic. The liquefied build material cools and solidifies upon contact with the previous layer as it is ejected from the print head. After each layer is completed, a cutter removes approximately 0.025mm from the top surface to provide a smooth, even surface for the next layer [5]. The build platform is adjusted to receive the next layer, and the process is repeated for the next cross-section of build and support material (Figure 2). Smooth cosmetic surface quality can be achieved by pre-tracing the perimeter of a layer prior to filling in the interior. Exceptional accuracy characterises further this method. The process can be considered as a hybrid of FDM and 3D Printing. Solidscape Inc. calls it "3D Plotting".

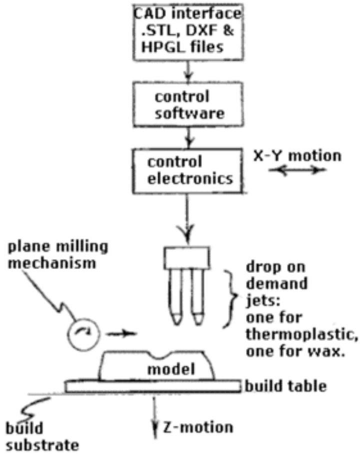


Figure 2: Schematic diagram of 3D Plotting [6]

Solidscape, Inc. makes use of this inkjet technique in their products as shown below (Figure 3). Their individual technical characteristics are displayed in Table 3.

(a) T612™ (b) T66™ (c) PatternMaster™

Figure 3: Solidscape products that make use of 3D Plotting technology [7]

Another example of the Thermal Phase Change concept is the Multi-Jet Modelling™ as introduced by 3D Systems. It utilises several hundred nozzles in a wide head configuration to deposit molten plastic for layering [6]. The system is fast compared to most other RP techniques, and produces good appearance models with minimal operator effort. The system is illustrated below:

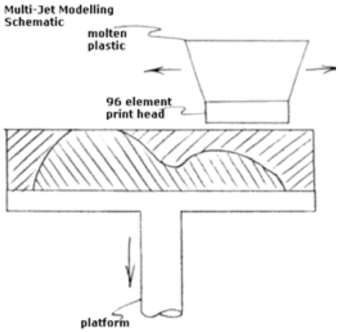


Figure 4: Schematic diagram of Multi-Jet Modelling [6]

The product that incorporates this inkjet printing technology is the ThermoJet Modeler as shown below (Figure 5). All thermal phase change inkjets have material limitations and make fragile parts. The applications range from concept models to precise casting patterns for industry and the arts, particularly jewelry.

Photopolymer Phase Change Inkjets

The concept is based on the use of photopolymers as building materials. A wide area inkjet head layerwise deposits both build and support material. It subsequently completely cures each layer after it is deposited with a UV flood lamp mounted on the print head. The support material, which is also a photopolymer, is removed by washing it away in a secondary operation.

Figure 5: 3D Systems' ThermoJet [8]

The process, called *PolyJet*™ was introduced by Objet Geometries Ltd., an Israeli company, some four years ago firstly on their Quadra machine. Meantime this company expanded its product range by introducing the EDEN models. A similar photopolymer-based system called InVision™ was introduced by 3D Systems in 2003 (Figure 6). The typical application of the Photopolymer Phase Change inkjets is the conceptual modelling, characterised by a high quality of the models built.


Figure 6: The InVision 3D Printer from 3D Systems [8] and Objet's Eden 260 [46]

2.2.2 Drop-on-Powder Deposition

The US Patent 5,204,055 defines the 3D Printing as "a process for making a component by depositing a first layer of a fluent porous material, such as a powder, in a confined region and then depositing a binder material to selected regions of the layer of powder material to produce a layer of bonded powder material at the selected regions. Such steps are repeated a selected number of times to produce successive layers of selected regions of bonded powder material so as to form the desired component. The unbounded material is then removed." [9]. This solution was developed and patented by MIT (Massachusetts Institute of Technology), and then licensed to different companies depending on the applications. Its work principle is illustrated on the diagram below.

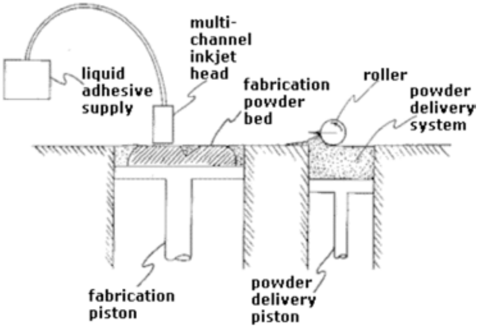


Figure 7: Schematic diagram of 3D Printing – Drop-on-Bed [6]

First Soligen, Inc. had commercialised it for building of ceramic shells for direct investment casting. Later Z-Corporation has utilised it in a variety of printers as displayed below in Figure 8 (a) ZPrinter 310 System, (b) Z406 3D Printer, and (c) Z810 3D Printer.

(a) (b) (c)

Figure 8: 3D Printers from Z Corporation [10]

Another application of the DoP concept was introduced by the ProMetal™ division of Extrude Hone Corporation. It provides the user with an ability to go directly from CAD data to steel moulding inserts. It uses an electrostatic inkjet printing head to deposit a liquid binder onto the powder metals. The part is built one layer at a time based on the sliced cross-sectional data. The metal powder layer is spread on the build piston and a sliced layer is printed onto the powder layer by the inkjet print head depositing droplets of binder that are in turn dried by the binder drying lamp [5]. The process is repeated until the part build is completed.

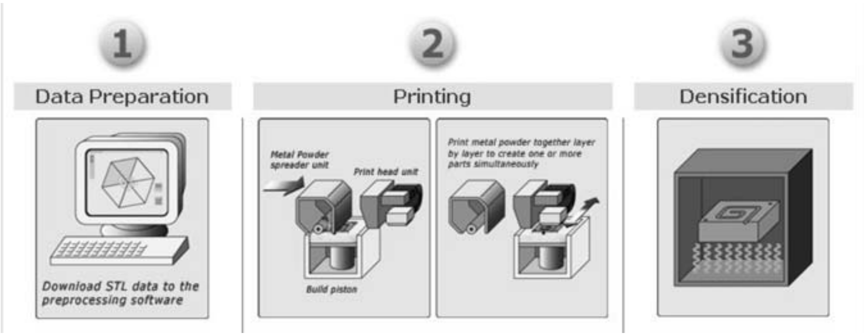


Figure 9: Three-step process for ProMetal 3D Printing [11]

ProMetal provides two printers, shown here in Figure 10, which makes use of this 3DP technology to produce metal parts. Their individual technical characteristics can be viewed in Table 3.

Figure 10: ProMetal equipment that utilises the 3DP technology (11)

2.2.3 Continuous Deposition

The Fused Deposition Modelling process in combination with the continuous inkjet printing technique is utilised by Stratasys in two of its low cost products - Prodigy Plus and Dimension.

Figure 11: Prodigy Plus and Dimension – FDM printers from Stratasys and Dimension Printing [47, 48]

Prodigy Plus makes use of ABS plastic as modelling material. It is equipped with the design tool called WaterWorks, which allows a designer to create mechanisms whose moving parts are built assembled. The Dimension and Prodigy Plus printers have similar specifications, with one of the most apparent differences being the support material used. While the Dimension printer makes use of the Break Away Support System (BASS™), Prodigy Plus incorporates the WaterWorks automated support system [5].

2.2.4 Classification

Based on the variety of applications utilising the 3D Printing process the following classification of the 3D printing techniques can be derived (Figure 12).

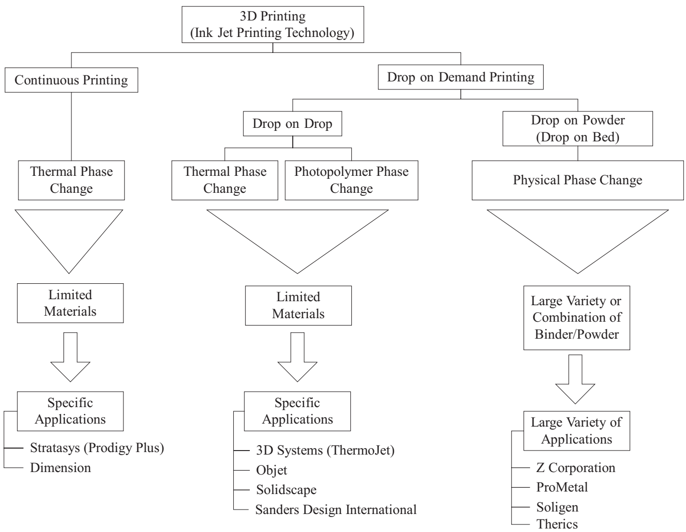


Figure 12: Classification structure of the 3D printing techniques as utilised in layer manufacturing applications

From the diagram above the nature similarities of the DoD and the Continuous Printing techniques can be seen, where the “printable fluid” and the building substance are one and the same material. This means that the building material has to meet two requirements – the first is related to the fluid’s printability as discussed above, and secondly to the purpose of building the model, i.e. the intended application. The necessity to fulfil this set of requirements puts substantial limits to the range of materials suitable for a particular application. In contrast, the Drop-on-Bed (Powder) version distributes the responsibility to meet the requirements to two different substances. In fact, almost every material can be brought in a powder phase – the starting point also of the SLS process. Hereby the task to make this material possible to process in a 3DP device is moved to the task to find a suitable binding liquid. This scenario predetermines a much larger variety of suitable combinations and thus, a much larger application range. The possibility to use infiltrating agents in a next stage of the model manufacturing process extends further the variety of applications.

3. TECHNICAL AND ECONOMIC CHARACTERISTICS

With the above classification, a framework is now established from which current and future technologies can be compared with regards to their individual technical and economic characteristics. Depending on the application, one technology will be more suitable than another to accomplish the task. As far as possible, this study has sought to identify all of the current commercially available 3D printing technologies that fall within the classification framework discussed above. The characteristics to each of the printing machines (printers) have been tabulated in Table 3 on the following page, and compares typical attributes such as geometry and size, materials, accuracy and model quality, build speed and price according to each core technology.

3D Printers		Core Tech-nology	Geometry and Size		Materials					Accuracy & Quality						Build Speed	Price
Company	Machine		Machine Size [cm]	Build Envelope [cm] (X, Y, Z)	Supports Required?	Building Material	Support Material	Binder	Infiltra-tion Agent	Reported Accuracy [mm]		Layer Thickness [mm]	Surface Rough-ness [µm]	Tensile Strength [Mpa]	Elon-gation at Break		
3D Systems	ThermoJet	MJM (Drop-on-Drop)	137 x 76 x 112	25 x 19 x 20	Yes	ThermoJet 88, ThermoJet 2000	VisiJet® (Wax)	N/A	N/A	??	Resolution [DPI] (X,Y,Z) 300 x 400 x 600	0.040	??	24	15.60%	??	$ 50 000
	InVision™ 3D Printer		77 x 124 x 148	29.8 x 18.5 x 20.3	Yes	Accura® VisiJet M100	VisiJet® S100	N/A	N/A	??	328 x 328 x 606		??			??	$ 40 000
	InVision™ HR 3D Printer		77 x 124 x 148	12.7 x 17.8 x 5	Yes	VisiJet HR-M100	VisiJet® S100	N/A	N/A	??	656 x 656 x 800		??	25		??	??
Stratasys	Prodigy Plus	FDM (Continuous)	69 x 86 x 104	20.3 x 20.3 x 30.5	Yes	ABS Plastic	Soluble Support Material	N/A	N/A	±0.127		Fine: 0.178 Std: 0.245 Draft: 0.330	??	35	>10%	??	$ 55 000
Dimension	Dimension SST		69 x 91 x 104		Yes	ABS Plastic	BASS™ Support Material	N/A	N/A			Std: 0.245 Draft: 0.330	??			??	$ 34 900
Z Corporation	Z406	3DP (Drop-on-Bed)	102 x 79 x 112	20.3 x 25.4 x 20.3	(No)	zp102; zp15e; zp250; ZCast™501	Same as build material	zb51; zb56	Elastomer; ZMax™; Wax; Z-Snap™; Z-Bond™10 Z-Bond™100;	**Own Study (Zprinter 310)**		0.076 - 0.254	**Own Study**	**Wohlers Report** / **Own Study**	**Own Study**	Colour: 2 layer/min Mono: 6 layer/min	$ 56 500
	Z810		241 x 114 x 193	50 x 60 x 40	(No)					zp102 (infiltrated with Zi580 resin) Axis: X / Y / Z Max: 0.405 / 0.179 / 0.189 Avg: -0.05 / -0.05 / -0.15 Min: -0.47 / -0.355 / -0.561			10.38-12.64 (R_a)	8.6 - 14.8 (zp100) / 0.127 (zp100)	0.19%	??	$ 180 000
	ZPrinter 310		74 x 81 x 109	20 3 x 25.4 x20.3	(No)											±4-5 layer/min	$ 25 900
Objet	Eden™260	PolyJet (Drop-on-Drop)	87 x 74 x 120	25.6 x 25 x 20.3	Yes	FullCure M720 (Photo-polymer)	FullCure S705 (Photo-polymer)	N/A	N/A	0.1 - 0.2		0.016	??	42.3	15 - 25%	Z-Direction: 12.5 mm/hr/pass	$ 94 000
	Eden™330		132 x 99 x 120	33.6 x 32.6 x 20	Yes					±0.20			??			??	$ 99 000
So idscape	T612	3D Plotting (Drop-on-Drop)	86.4 x 66 x 128.3	13.4 x 15.2 x 15.2	Yes	ProtoBuild™ Material (Proprietary thermoplastic)	Proto-Support™ Material	N/A	N/A	±0.025		0.013 - 0.076	0.8 - 1.6 (RMS)	Data not available SolidScape says the material provides mechanical strength abouth twice that of investment casting wax and has "plastic-like" structural and tactile qualities		??	$ 77 000
	T66		53 x 48 x 53	15.2 x 15.2 x 15.2	Yes		Proto-Support™ Material	N/A	N/A							??	$ 50 000
	PatternMaker		52 x 44.5 x 58.5	30.5 x 15.2 x 21.6	Yes		Proto-Support™ Material	N/A	N/A							??	??
Sanders Design International	Rapid Tool Maker	3D Plotting (Drop-on-Drop)	174 x 66 x 167.5	90 x 30 x 30	Yes	(Proprietary thermoplastic)	Wax	N/A	N/A	Model accuracy not stated but SDI specifies machine resolution as 5 x 5 x 3µm (X,Y,Z)		0.012	??	??	??	??	$120 000
Extrude Hone (ProMetal)	R2	Metal 3DP (Drop-on-Bed)	180 x 120 x 150	20 x 20 x 15	No	S3; S4; S4H (Stainless Steel, other metals)	Same as build material	??	Bronze	ProMetal states that the process is typically accurate to ±0.125 mm		??	??	406 - 765	3.8% - 8%	30-90sec/layer	$ 200 000
	S15	Sand 3DP (Drop-on-Bed)	330 x 300 x 200	150 x 75 x 75	No	Sand		??	N/A			??	??	??	??	12 - 24 mm/hr	$1 200 000

Table 3: Tecnical and Economic Characteristics of 3D Printing

Some observations that are apparent can be summarised by the following:

- The hybrid FDM technology from Stratasys is currently the only 3D printing process that uses a continuous material deposition technique.
- Machine sizes and build envelopes vary widely in accordance to the machine's intended application. ProMetal's metal and sand 3DP machines currently have the largest build volumes while the smaller build volumes can be found for 3D System's InVision™ 3D Printer, and Solidscape's T66 and T612 models.
- Apart from the powder-based (Drop-on-Bed) printing processes, all other techniques require some kind of extra support material that needs to be removed from the main build material. On the other hand, the Drop-on-Bed technologies are the only ones that make use of a powder binding material and require post-infiltration to increase model quality. This can be seen either as a drawback or a benefit. A drawback, since post-processing time increases overall lead time. Advantageous, since a suitable infiltration material can alter the model's physical properties and thereby increase its range of applications.
- Accuracy capabilities of each technology are not generally reported in great detail. An apparent tendency is that accuracy capabilities are in many cases reported only as some single "±" value. But research has indicated that achievable accuracy is strongly related, among other things, to the relevant build axes of the machine. The reported values do however give some measure by which a comparison can be made. It seems that Solidscape and Sanders Design International's 3D plotting machines are currently showing the best accuracy results, along with having the thinnest layer thicknesses (13 and 12 microns respectively).
- Other characteristics that are also poorly specified or reported are surface roughness of models and the build speeds of each technology. Consequently, in cases where information is given, it is not done according to a same-standard format. Surface roughness is for example reported as an RMS value for Solidscape's machines, while R_e values have been calculated in other cases.
- Objet's PolyJet technology currently provides material with the largest tensile strength (42.3 MPa), while Stratasys and Dimension's ABS parts show good tensile strength at a reported 35 MPa. An alarming discrepancy however exists between reported figures for zp100 material from Z Corporation. An in-house study of the same material and infiltration agent was done according to the same ASTM D638 test standard [12]. This study found that only a maximum tensile strength of 127 kPa was reached in contrast to the reported 8.6 – 14.8 MPa [1].
- The prices of 3D printing machines range between $25 900 to $1.2 million for the ZPrinter 310 and ProMetal S15 machines respectively. The increasing market share of Stratasys (Dimension) and Z Corporation’s Z 310 can be directly attributed to them being the lowest-cost systems available at the moment.

4. APPLICATIONS

As mentioned above, the Drop-on-Drop method is related mainly to one type of material and a specific application. Therefore they will not be discussed in this section. All examples presented below are produced on DoB type printers.

4.1 Design

4.1.1 Concept modelling (product creation - visualisation, design iteration)

The comparatively high speed and low operational cost of the 3D Printers means that a large number of models can be produced during the product development phase. Designers can go through several iterations having physical samples to evaluate each concept [13, 14]. The models are used further to enhance communication (between engineers and non-engineering departments) during the design phase; it also helps substantially with error detection.

Non-geometric product information can be efficiently communicated by using colour printed 3DP parts. Over moulded parts can have a realistic appearance for example [15]. It can also be used to present Finite Element Method (FEM) results or to highlight variations in wall thickness [16]. In the figure below the wall thickness information is critical to manufacturers. The colours make it much easier to evaluate the manufacturability of the part. The strength of colour printing comes to the fore in examples such as this where the colour pattern represents the result of an analysis and cannot be accurately painted on afterwards.

Figure13. Model of manifold displaying finite element analysis information [16]

4.1.2 Proof of concept (customer presentation)

3DP models are used in various ways to prove concepts during customer presentations. Thimany reports that DaimlerChrysler uses 3DP parts for wind-tunnel testing [14]. This saves the company as much as 90% in model making time.

A comparison of FDM with 3DP for making conceptual models for testing the aesthetic appearance of spotlight housings showed that 3DP are cheaper and faster to make and the details of the design were reproduced better. The models were used to evaluate the lamp shape and colour [17].

Combined with secondary processes, i.e. RTV silicone moulding, objects for customer presentations can be made in different type of resins that closely represent the end use materials. In this case transparent bottles were needed (see Figure 14). Surface defects such as the stair-step effect resulting from the nature of the LM processes had to be eliminated to ensure transparency. This required extensive hand polishing of the patterns before the silicone rubber moulds were made. A surface finish of R_a= 0.15μm was achieved, which took however, 32 man hours – a rather time consuming operation [18].

Figure 14: Transparent bottles produced for customer presentation. Uninfiltrated part and patterns are also shown [18]

4.1.3 Market research

The prototype of the mop dryer shown in Figure 15 was made for presenting the concept to potential customers. The part (312×194×98mm) is much larger than the build volume of the Z402 printer. It was printed in sections and glued together. The entire process took less than 48 hours. The low cost of this type of 3DP models allows small number of parts to be cost effectively built for market research purposes and sent to various potential customers.

Figure 15: Prototype of Mop Dryer (courtesy of USABCO) [18]

4.2 Manufacturing

According to Bak [19] the main advantage of 3DP for Rapid Manufacturing is its speed. Small production volumes can be produced much faster than with processes such as SLS and SLA. However, the variety of available materials and limited accuracy precludes the manufacturing of certain parts. Material and process selection is intrinsically linked and therefore new developments in extending the range of materials used are very important for the direct production of parts with 3DP.

4.2.1 Fit and functional models

The ability of 3DP to make functionally graded material (FGM) parts opens up new possibilities for designers to optimise their designs. An example of designing a pulley with more carbide near the hub and rim (to make it harder and therefore more wear resistant) is discussed by Jackson, et al. [20]. This heralds a completely new way in which parts can be designed.

FGM parts are made by depositing various binders and/or slurries onto the powder bed through several jets. This can be controlled to a resolution of 100µm (the size of the droplets) [20]. It is hereby pointed out that current CAD systems do not make provision for storing FGM information. Other design tools also need to be developed before products can be designed on a large scale using this technology, e.g. it will be necessary to develop FEM models, and designers will also need certain guidelines. They will need further specific information regarding the process capabilities such as the maximum and minimum allowable concentration of a material, the maximum allowable rate of change of the material composition and the dimensional capabilities of the machine [21].

It is now possible to make fully functional metal parts using the 3DP process [19]. Components having 60% stainless steel and 40% bronze can be made by a light sintering process followed by infiltration. One hundred percent dense stainless steel parts can be achieved after a heavy sintering.

Sun et al [22] developed a new 3DP process for making Ti_3SiC_2 carbide parts. This material has unique mechanical and electrical properties (high thermal and electrical conductivity) and is often used in diesel engine and aircraft applications. The parts are printed on a standard Z402 (Z Corporation) printer. This is followed by a cold isostatic pressing (CIP) and sintering stage. It is reported that 94% density was achieved after post-processing.

Rubber similar parts can be manufactured using starch based powder and infiltrated with a polyurethane rubber moulding system. The part shown below, a gear shift boot, was manufactured within five hours (growing, curing, infiltration and drying) with the clear purpose of noise testing on a vehicle [23].

Figure 16: Rubber similar part built on a Z Corp 3D Printer (left); compression moulded rubber part (right)
(courtesy of CAE – Stellenbosch Automotive Engineering)

Using a secondary RTV silicone moulding step, polyurethane (PU) parts can be produced efficiently in small volumes (typically 10 – 30 parts). The 3DP part is used as a pattern for making the mould. Normally the patterns will first be hand polished and painted so that the PU will have a good surface finish. This is necessary for de-moulding as well as the appearance of the components. Normally the stronger plaster based powder is used and the parts are infiltrated with an epoxy based material. This gives adequate strength for the finishing operations. Components with wall thickness down to 2 mm can be made in this way; however, intricate detail may cause problems during the finishing operations. The brush handles in Figure 17 is an example of this process. Note that the handles have an over moulded section. This required two patterns and two silicone moulds.

Figure 17: Brush Handles (courtesy of USABCO).

4.2.2 Pattern making for casting processes

Components printed in starch based powder and infiltrated with surgical wax are extensively used as patterns for investment casting. Two examples – a differential housing (264×236×281mm) and a gimbal (ø350×440mm) - are shown below in figures 18 and 19. Both parts are substantially larger than the build volume of the Z402 printer. These components were built in sections (4 and 11 respectively). Note the support structure used to prevent warpage of the sections of the gimbal. It was found that unfiltrated starch based parts tend to warp significantly. By adding ribs to close the geometry, this can be prevented to a large extent. The ribs are removed during assembly when the parts have cooled down after wax infiltration [24].

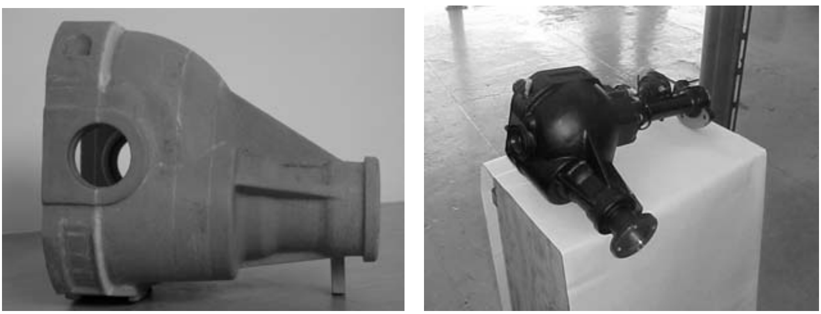


Figure 18: Differential Housing made with a 3DP Pattern and Investment Casting

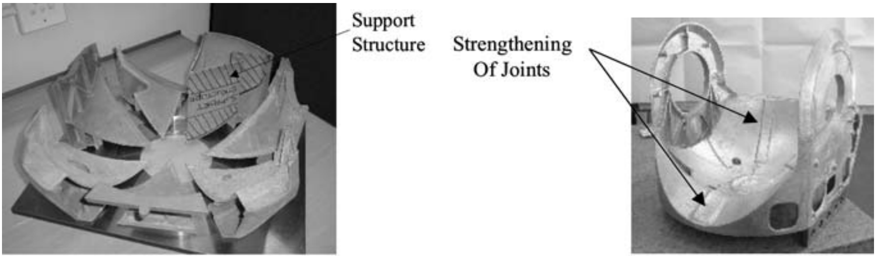


Figure19: Gimbal made with a 3DP pattern and investment casting

In general, using 3DP (DoB) patterns for investment casting are already an almost trivial process. If, however, certain requirements regarding accuracy or surface finish have to be met, especially when the size of the object exceeds the work envelope of the RP machine, then the task difficulty changes dramatically. The gimbal shown in figure 19, illustrates this argument. Its overall dimensions exceed the work envelope of the 3D Printer used by far. A process chain was needed to make only one functional prototype of this geometrically complex part, featuring several undercuts and internal cavities, with the single purpose of testing a new material – aluminium. The CAD model was divided into 11 sections (not all shown in Figure 19), 8 builds, for growing on the 3D printer. The gimbal had to be sectioned in such a way as to ensure the least amount of distortion to the geometry while at the same time facilitating the subsequent assembly. Support structures, usually in the form of ribs, were added to the CAD models as required.

The major challenge in making the pattern for the Gimbal lies in the 3 mm wall thickness. The combination, however, of thin walls and large size resulted in a complex assembly operation, which had to meet tight accuracy requirements (±0.2 mm). Using a conventional manufacturing process under these circumstances for producing a functional part, e.g. CNC machining a mould to make a wax pattern, would have been significantly more difficult, time consuming and costly. Another advantage of this process chain is to rapidly go through a number of design iterations, since both the 3DP method and investment casting can produce complex geometries without additional time and cost penalties.

3DP models can also be successfully used as patterns for developing tooling for sand casting (Figure 20). Essentially the method roots on printed parts as patterns for creating bridge tooling using sand mixed with epoxy as a low cost backing medium. This process chain was developed for producing large metal components such as gearbox housings, and demonstrated by making tooling for a marine engine gearbox and drive train enclosure respectively. Five, fully functional aluminium components were required for testing and marketing this design concept.

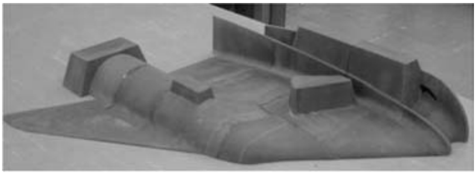


Figure 20: Pattern of Outer Surfaces (700×700mm).

The newly developed process chain was compared to the current approach of machining the tooling directly using the CNC option. Besides the time saving, an additional advantage is the ability of the 3DP route to allow testing of the core system and performing systematic checks along the process chain as required. The full scale check involving 8 printed cores specifically allows scrutinising the wall thickness and core prints (Figure 21), while the CNC-machining of the tooling precludes these tests [25].

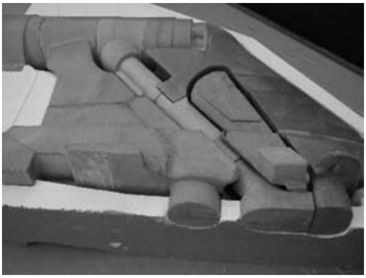


Figure 21: Core layout development

It has to be further stressed that the 3DP process aided enormously the design of a very complicated core system as shown on the figure above by allowing a half scale mock up of the pattern and core system to be made. This facilitated discussion and planning of the core system, ensuring that sufficient support was provided for all cores, checking the wall thickness, deciding on the core layout and the number of required cores. This is invaluable in bringing the designers, pattern maker and foundry personnel together as a concurrent engineering design team. Many potential problems can be ironed out early in the design phase by adopting this kind of design for manufacture approach. It further facilitates quotation and planning by the foundry.

Using the geometry independence of LM methods, the cooling layout of moulds can be designed to improve tooling performance and reduce cycle time [26]. This is referred to as conformal cooling and various researchers have published results using different approaches. A possible way is the fabrication of wax patterns on the 3D Printer for investment casting.

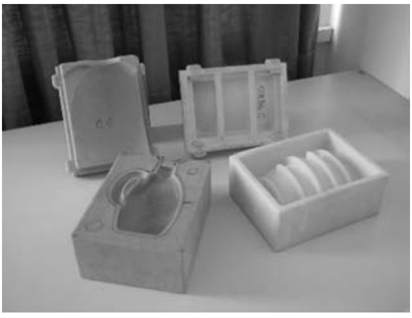


Figure 22: Wax patterns for investment casting with cooling channels and water jackets

Three conditions need to be met in order to widespread the application of this approach. Firstly, optimisation tools are needed to support the tooling designer in the analytical design approach. Current CFD (Computational Fluid Dynamics) tools are time consuming to use, requiring long run times for accurate results. This is counterproductive to the ideal of rapid tooling. Secondly, optimised process chains need to be developed for the manufacture of such tooling. Lastly designers need guidelines to point them in the right direction for designing optimised tooling. This is a new way of tooling design and experience gained by researchers needs to be encapsulated and transferred to designers.

4.2.3 Rapid tooling

The most important deterrents for using 3DP for Rapid Tooling (RT) applications are porosity, dimensional accuracy, surface roughness, mechanical properties and the fact that one or two post-processing steps (sintering and/or infiltration) are required which reduces the productivity [3, 21, 27]. However, all these researchers give examples of using 3DP technology for direct manufacture of tooling. In fact Karapatis [27] already identified 3DP in 1998, together with SLS and Laser Generating, as one of three RP processes most suitable for RT. Iuliano and Gatto [17] report that many companies are hesitant to implement RT before cost and time efficiencies are sufficiently proven. They further state that before RT will be widely used, its properties must be thoroughly understood and guidance must be given to companies as to when RT will reduce the product lead time and investment cost.

A distinction is made here between direct (DRT) and indirect manufacture of rapid tooling [3, 27]. By direct methods it is meant that the part coming out of the 3D Printer will be used, after suitable post-processing, as the tool. In indirect methods, the 3DP model will be used to manufacture the tooling using some secondary process, such as investment casting. Indirect methods as such are discussed under the heading “Pattern making for casting processes”.

Metal tooling can be made by printing in stainless steel powder, sintering and infiltrating with bronze. This gives a part with 60% stainless steel and 40% bronze. Heavy sintering can be done which gives a 100% dense stainless steel part. These machines have large build platforms (1000×500×250mm) which are another advantage. However, the tooling requires post-machining [5, 19].

Tooling for sand casting can directly be printed. Bak [19] gives two alternatives. In the first method the complete tooling - cavity, gates, runners and riser – is designed as a solid model in a CAD system and printed in ceramic powder. In the alternative method only the mould inserts are printed – typically as a shell. The rest of the casting system is added afterwards with the sand backing. This process integrates seamlessly with conventional casting processes and can provide a best of both worlds solution. Complex cores can be printed, exploiting the geometry independence of LM methods, and then combined with the rest of the tooling. A third process chain involves the printing of patterns (in plaster) and cores (in ceramic) (Figure 23). The combination of traditional approach and advanced techniques for making patterns and cores provides the opportunity for companies to optimise process chains for specific product families and required number parts during the different phases of the product development process.

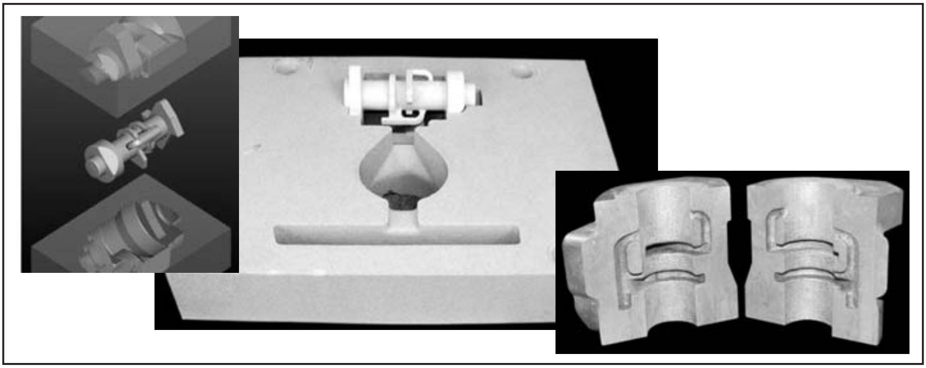


Figure 23: Tooling for sand casting produced with the help of 3D Printing [28]

4.3 Medical field

There is a lot of potential for the application of 3DP technology in the medical field, mainly in the areas listed below. However, some of these applications are still in the research stage. 3DP can be used for:

- Surgical aids
- Drug delivery systems
- Bone implants and tissue engineering
- Organ printing.

3DP models are already widely used as surgical aids, their cost being as much as 50% less than similar SLA parts. For example, the models are strong and accurate enough for pre-bending plates while planning surgery (Figure 24) [29]. Turnaround time for anatomical models is typically 2-3 days and models cost between US$500 and US$800. The models serve as pre-operative planning aids and surgical simulation, it facilitates communication between the surgeon and patient, it can be used for implant fitting and customisation. During the operation it can serve as a visual aid [30].

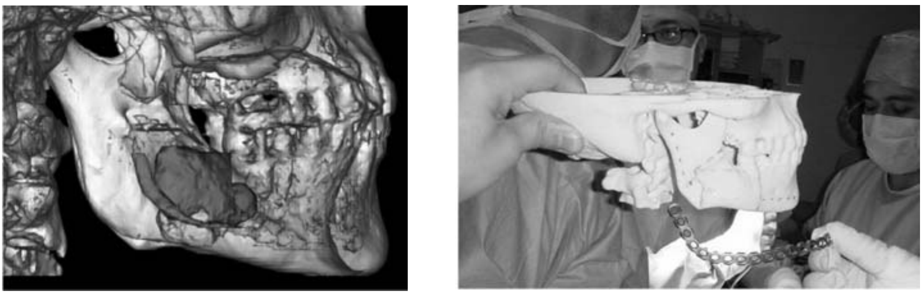


Figure 24: Skull section produced with 3DP for surgical planning and preparation [29]

Printers for making drug delivery systems are already commercialised and it can produce up to 20 000 tablets per hour, perhaps the first truly rapid manufacturing system [5]? LM offers a whole new way of designing drug delivery devices. According to Sharke [31] the local composition control capability of 3D Printers (also used for making functionally graded materials) means that the drug dosage can be controlled accurately. Alternate layers of powder can be of different material, thereby controlling the drug release time by adding inert materials.

Implants manufactured on 3D Printers are already a reality – both bone and soft tissue [5]. This has obvious major advantages in reconstructive surgery. When growing the implants, different polymer binders can be deposited at required locations, thereby encouraging cell migration into specific areas of the implant [31]. Lam et al [32] experimented with powders for growing scaffolds on a Z402 printer. The powder they successfully used is 50 wt% cornstarch, 30wt% dextran and 20 wt% gelatin. They used distilled water as binder. This has the advantage that biological agents or living cells can be included. According to them it is important to independently control the porosity and pore size of the scaffolds. By designing the pores as part of the CAD system and exploiting the RP system, this can be done. However, their system suffers from shrinkage problems and therefore accuracy as well. Their system is still in the experimental stage and they do not report any human or animal testing.

The ultimate goal for 3DP in the medical field is organ printing [31]. Mironov et al [33] reported some research in this direction. They developed a printer that can print gels, single cells and cell aggregates into a 3D gel. Their process consists of three stages: pre-processing (creating a CAD modelling which can be from scanned data), processing (printing) and post-processing (perfusion of printed organs and their biomechanical conditioning). Again, no human or animal testing is reported. Yan et al [34] are doing similar research.

4.4 Architecture

3DP models are used for visualisation tools in architecture [35]. However, they report difficulties in reproducing ornate details and free standing structures such as chimneys and railings. Their solution was to build small caps around this detail to ensure that it survives the de-powdering stage. Building a ground plane also helped to strengthen the structure and protect detail at ground level.

Figure 25: Architectural model printed in plaster based powder. Printing Time: 5.5 hours, dimensions: 200×240×120mm [35]

Another problem with architectural models is that 3D models of buildings cannot be uniformly scaled so that they are small enough for the build volume of standard 3D

Printers. The wall thickness will be too small. This means that CAD models must be specially designed for the prototyping stage. This is unproductive and there is the added risk in the human translation of the original CAD data into the prototype CAD data that information would be lost or transferred incorrectly.

5. MAIN RESEARCH ISSUES

The main research issues can be categorised in four groups, related to

- Material improvement
- Process improvement
- Expansion of application range and
- Customer satisfaction.

The first two categories can be seen as basic research, while the second two are representing applied research activities.

The research related to material improvement can be seen from two points of view. Firstly, the 3D printer producers strive to improve the properties of existing materials in order to lift the performance of their products. A typical example is the improvement of the starch powder used with the Z Corporation machines. Within the last four years this type of powder was “upgraded” three times – zp11, zp14, zp15e, and this again in combination with different binders and suitable infiltrants. On the other side is the attempt to introduce new materials, opening in this way new applications. Z Corp, with the introduction of the new ZCast material a year ago, again serves as an example. This material (ZCast 500) enabled the Z- Corp printers to expand their manufacturing application range by entering into the sand casting technology. In the mean time this material was replaced by the improved version of ZCast 501. Wohlers [1] gives a comprehensive update on new materials for the variety of 3D printers. Parallel to this, various universities are involved in numerous research programmes for development of suitable material combinations. In a leading position is the MIT. Its 3DP Laboratory is involved in several projects aiming at the development of materials for specific applications [36]. Large efforts worldwide are streamed into the development of biomaterials for medical applications.

Intensive research is conducted towards the improvement of the 3DP process. A large portion of this type of research is related to the improvement of the basic process capabilities with regard to the achievable accuracy and surface quality [37, 38].

Substantial efforts are focused on the development of advanced control strategies. One of the most important issues in this domain is the development of the Local Composition Control (LCC). The LCC represents basically the ability to create objects with composition variation within them. This indicates the great potential to produce parts whose material composition can be tailored within a component to achieve local control of properties (e.g. index of refraction, electrical conductivity, formability, magnetic properties, corrosion resistance, hardness vs. toughness, etc.) [36]. Another issue in this regard is the adaptive slicing control, which generates different slice thicknesses based on the local slope of the part [44, 45].

A large variety of applied research projects is related to the improvement of existing applications or to exploration of new challenges. One of the most actively researched areas is that of manufacturing. Relevant research topics include improved design aids with a particular emphasis on finite element analysis, development of optimised process chains for indirect and direct RT for casting and moulding processes, conformal cooling issues, combination with subtractive processes and with High Speed Cutting (HSC) in particular, rapid manufacturing. Intensive research efforts are canalised into the medical field with a particular accent on tissue engineering. A further big challenge is the architectural modelling.

Another major portion of applied research is related to the establishing of the true capabilities of working RP equipment. This is a prime task at colleges and universities, which go beyond the use of 3D printers for teaching purposes only. On this basis an intensive link with industry can be developed and maintained, proactively meeting its real needs. Usually, when reporting about 3DP in general, the focus falls on the incredible speed and low cost, which undoubtedly are strong characteristics of this emerging process. It is, however, remarkable how more specific questions related, for example, to accuracy, surface quality or strength even in most successful case studies are carefully avoided. On websites of equipment manufacturers this type of information is given also only in a vague form.

Indeed, for a large variety of applications the question i.e. of accuracy is irrelevant – conceptual modelling, certain medical applications, design aids, anatomical modelling to mention a few. Still, an adequate surface finish (for aesthetic appearance) and strength are most often strongly desired. For some of the most important manufacturing applications, however, such as fit and function, pattern making or tooling for a variety of moulding and forming processes, the question also of (guaranteed) accuracy is of prime importance. Investigations show that these properties relate to and depend on:

- printing technique
- material used
- binder and binding mechanism
- nominal dimensions
- build orientation
- geometric features and their topology
- post treatment procedures
- infiltration agent.

Therefore, in order to acquire the ability to meet adequately the needs of industry an equipment related capability profile needs to be established, taking into account the impact on the manufacturing characteristics of the factors as listed above, as well as their internal relationship [39, 40, 41, 42, 43].

6. CONCLUSIONS

Compared to the more established RP processes such as SLS and SLA, 3DP particularly in its DoB version, is a fairly new process. Apart from some specific applications, the first commercial system arrived on the scene in 1997 and then it was mostly used as a concept modeller. The focus was on helping designers make physical prototypes for design review and visualisation purposes so that they could go quickly through design iterations. Extensions into RT and RM naturally came later. Although a number of commercial RT and RM systems, using the 3DP principle, are available, it appears that not as much is published on this topic than is true for the older, high-end systems such as SLA and SLS. In this section two questions are addressed, namely: a) What are the main/unique strengths of 3DP in terms of applications in various domains? and b) What are the weaknesses preventing its application in other branches or limiting it in the areas it is already used? Based on the various application examples and case studies as discussed above the main points are summarised below. The objective is to demonstrate that the appropriate use of 3DP is an efficient tool for rapid product development.

6.1 Strengths of 3DP for Rapid Product Development

As stated in the beginning, significant growth of 3DP sales are forecast in the near future [1]. The following strengths of this technology may summarise the main reasons for this:

- Compared to most other RP systems, 3DP and the DoB concept in particular offers high speed. This can be attributed to the inkjet principle and also to the fact that apart of the physical, no other phase change is involved in the process requiring time for the material to melt and/or solidify [1, 13, 19].
- The combination of low cost materials and equipment together with speed means that 3DP parts typically cost less than halve as much as similar parts produced with SLS or SLA [1, 29].
- A significant advantage with much potential for the future is the ability to produce functionally graded materials and do local composition control. This technology is still in a development stage, but holds much promise for medical and manufacturing applications. It may push 3DP more and more towards RT and RM. It still requires developments on the software side, since standard CAD systems cannot model functionally graded materials and the STL file format does not support material definition at any level [3, 20, 36].
- 3DP was the first commercial colour RP system. Although the cost effectiveness of this technology is questioned in some applications, conveying non-geometric product information using colour can be a useful design communication tool. Other RP systems have since implemented colour technology, but in many of these systems this comes with additional capital cost and manufacturing time. The reason is that in SLS systems, for example, the colour for each layer is deposited in a separate inkjet printing step, different from the laser sintering process to bind the powder. With 3DP the binder fluid can be coloured and thus colour printing can be done at the same speed [15].
- 3DP shares with most other LM methods a high degree of geometric independence in the parts that can be made. In fact, unlike liquid based methods, 3DP parts do not need support structures for overhanging geometry since the models are supported by the unused powder. However, in some instances support structures are useful to limit warpage of green parts [24]. Investigations have shown further that substantial inaccuracies can occur due to squashing of the supporting powder. This problem was however, addressed and the new slicing software from Z-Corporation allows for optional support structures to be added automatically.

- Commercial 3DP systems have some of the largest build volumes (1000mm × 500mm × 250mm).
- 3DP printers are office friendly and are often found in design offices. According to Wohlers [1] this makes the turnaround time of 3DP often faster than other RP processes. High-end RP systems are often found in a central area or laboratory within the company which means that it will be a more cumbersome process to have parts made. It can typically take two days to have a component made.
- The 3DP part can be finished and painted by hand. Their appearance for customer presentation and marketing can be improved greatly in this way.

6.2 Weaknesses of 3DP for Rapid Product Development

- A major problem that stands in the way of the widespread use of 3DP for RM is the porosity [3, 27]. While most other RP systems also have the same problem, it must be acknowledged that 3DP also competes with material removal processes such as High Speed Cutting.
- Compared to other RP processes, 3DP – in its DoB version – is not very accurate. Dimitrov et al [39] compared it to LOM and SLS and showed that SLS is about an order of magnitude better. Ippolito et al [40] give accuracies for the other major RP processes (SLA, FDM and SLS) and they are all better than the reported accuracy of DoB 3DP.
- The surface finish is also poor compared to other RP processes. Surface roughness of more than 40μm is reported, which is much more than the roughness for processes such as SLS, SLA, LOM and FDM [27, 40].
- The materials available with 3DP – at least currently – are very limited compared to processes such as Selective Laser Melting [3]. Related to this is a limited range of mechanical properties.
- One or two secondary stages (sintering and/or infiltration) are needed to make most functional parts. This decreases productivity.

In conclusion it can be said that capabilities such as the geometric independence of 3DP and the possibility to produce FGM parts creates a new paradigm in product design as 3DP moves into true RM and RT. Development of new processes, such as printing FGM models and new materials promises to extend the capability profile of 3DP [20, 21, 22].

Designers, however, need suitable information to exploit the strengths of the technology. Detailed information of the materials properties are needed (e.g. strength, thermal properties, fatigue properties, etc.). Processes capability profiles have to be developed, recording characteristics such as accuracy, surface finish, strength, elongation, build time and cost [41, 42, 43]. An interesting comparison of the “utilisation value” of 3D printers from the view point of their use as concept modeller is shown in Figure 26. The low utilisation value of the Z-Corp printers contradicts drastically with their unit sales, which can be explained through their much wider application range. Product histories and case studies are needed so that designers can become familiar with the expected life of 3DP products and their behaviour under various environmental conditions.

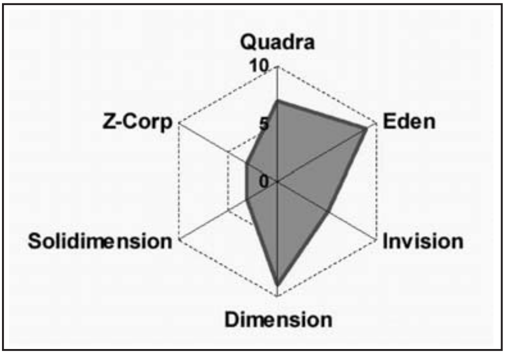


Figure 26: Utilisation value of 3D Printers as concept modellers [43]

Suitable software tools are needed, as alluded to in the discussion above. These must be able to aid the design and analysis of FGM parts as well as tooling with conformal cooling. Process chains must be optimised too. Combinations with various other manufacturing methods, e.g. CNC machining and casting technologies, have to be thoroughly researched.

Finally, where is the place of the 3DP technology among the other LM methods? A possible scenario is given in Figure 27. A firm place of this technology will remain during the design phase. The big potential, however, in the Rapid Manufacturing domain manifests its great future perspectives.

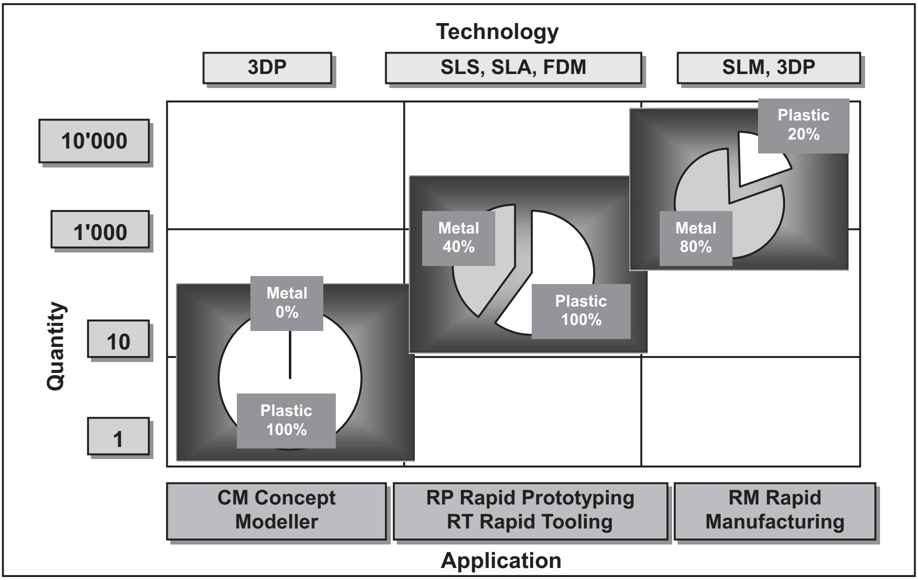


Figure 27: Consolidation forecast for the LM Technologies 2002 -2010 [3]

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