Material Incress Manufacturing by Rapid Prototyping Techniques

Prof. J. P. Kruth, Katholieke Universiteit Leuven/Belgium

SUMMARY:

The paper gives a state-of-the-art overview of so called rapid prototyping techniques, like stereolithography, selective laser sintering, ballistic particle manufacturing and others. These are new manufacturing techniques in which the part is produced by gradually growing material to the required shape. A tentative classification and nomenclature is proposed. It is shown that those new processes are ideally suited for CIM. The paper tries to compare the different processes and discuss their application and performances.

Keywords: Manufacturing, Material Incress Manufacturing Rapid Prototyping, CIM

The author wishes to thank following persons and organizations having provided information for this keynote paper:
Prof. D. Allen, CIT, Cranfield (UK)
Prof. O. Bjorke, NTH, Trondheim (N)
Dr. Ir. D. Dauw, Charmilles Technologies (CH)
Prof. W. Koenig, WZL, Aachen (D)
Prof. E. Sachs, MIT (USA)
Dr. Ing. B. Schumacher, AGIE (CH)
Ir. R. Visman, Centrum voor Produktietechniek (NL)
Ir. B. Van der Schueren, KUL, Leuven (B)
Ir. R. van Trier, TNO, Delft (NL)
Rapid prototyping companies.

A NEW GROUP OF PRODUCTION TECHNIQUES: MATERIAL INCRESS MANUFACTURING

Until now, manufacturing techniques could be classified in two sets, according to the way the product's shape was generated:

1. **Forming processes:**
   Those processes start from the right amount of bulk material and deform it to the required shape. 'Deforming' in this context could be understood as 'deforming in solid state' (forging, stamping, drawing, extruding, etc.), as well as 'deforming in liquid or semi-liquid state' (casting, injection moulding, etc.). In all those cases, no material is added nor removed.
2. **Material removal processes:**
   Those processes start from a larger amount of bulk material and remove all excess material, be it in a conventional way (turning, milling, grinding, etc.) or in a non-traditional way (EDM, laser machining, ultrasonic machining, etc.)

Today we are facing a new group of manufacturing techniques, in which the shape is produced by adding, rather than removing or deforming material.

Several names are used to refer to those manufacturing techniques:

- **Rapid prototyping**
  This term refers to the original application field: the fast production of prototype models. Yet, these parts were initially to brittle to be applied as functional components. Today however, the same technique can produce small series of components (200...500) having sufficient mechanical properties to be used as functional parts in larger assemblies. The term 'Rapid Prototyping' no longer covers the applications.
- **CAD-Oriented Manufacturing**
- **Design Controlled Automated Fabrication (DesCAF)** [19]
- **Direct CAD Manufacturing (DCM)**
  Those terms refer to the intrinsic close link to CAD modelling: all these techniques have to start from a CAD model of the object to program the manufacturing equipment. When compared for instance to injection moulding, forging or classical powder sintering, the term 'direct CAD' emphasises that the intermediate fabrication of moulds or dies is eliminated.
- **3D Printing (TDM)**
- **Desktop Manufacturing (DTM)**
- **Instant Manufacturing**
  Those names refer to the futuristic idea that rapid prototyping techniques may become as popular and easy to use as laser printers: CAD stations would be provided with small peripheral devices standing on the designers desk and allowing to produce a push-button 3D plot of the design displayed on the screen. Today, we may not yet speak of desktop techniques and 'instant' is hardly applicable when production times are still of the order of a day.
- **Layer Manufacturing**
- **Laminated Object Manufacturing (LOM)**
  This term only refers to a limited number of techniques that add material in a layer-by-layer fashion (see 'Classification' below).
- **Solid Freeform Fabrication (SFF)**
  This term emphasizes the freedom to create very intricate shapes, which can not be produced with most other manufacturing techniques (e.g. hollow parts that can only be cast with destructible cores).
- **Material Deposit Manufacturing**
- **Material Addition Manufacturing** [48]
- **Material Incress Manufacturing (MIM)**
  The author like to suggest the later term. "Increscent" means "becoming gradually greater" (Webster Dictionary) and is more general than "deposit" or "addition": some techniques use direct 3D solidification (e.g. Holographic polymerization) and do not really deposit (lay down) material in successive layers. 'Material Incress Manufacturing' (MIM) clearly identifies those techniques as the antipode of 'Material Removal Manufacturing'. The acronym MIM may however cause confusion with Metal Injection Moulding.
  Other similar names include: **Material Increase or Material Grow Manufacturing.**

All those techniques apply a kind of selective solidification or binding of liquid or solid particles by glueing, welding (i.e. melting and resolidification), polymerization or chemical reaction.

Undoubtedly, the advent of 'material incress manufacturing' techniques may represent a major breakthrough in production engineering. Future books on history of manufacturing may quote the early nineties and the advent of those techniques of equal importance as the development of numerical control in the fifties and sixties, or as the advent of non-traditional machining processes in the last decades.

CLASSIFICATION

Two possible classifications of material incress manufacturing techniques are given in Fig. 1 and 2. The first relates to the way material is created or solidified. The second to the way the shape is built. The names of individual techniques are listed under the appropriate class. Those names are followed by references to companies or institutions developing corresponding manufacturing equipment. Twenty-nine (29) equipment builders are listed on Fig. 2, eight of which are already selling machines. Few others limit their activities to subcontracting and servicing using in house equipment, while many others are still in a development phase.

Classification according to material creation (Fig.1)

Raw material can be applied in three different states (Fig. 1): liquid, powder or solid. The present processes depositing material in **liquid** state, can be further classified in two groups:

- those using liquid polymers as base material and solidifying it by impact of light from lamps or lasers (Stereolithography, Interference Solidification) [2] or by heating (Thermal polymerization) [3],
- those based on melting, deposition and resolidification of material. They allow to use metals (Shape Melting Technology), as well as plastics or resins (Fused Deposition Modeling, Ballistic Particle Manufacturing).

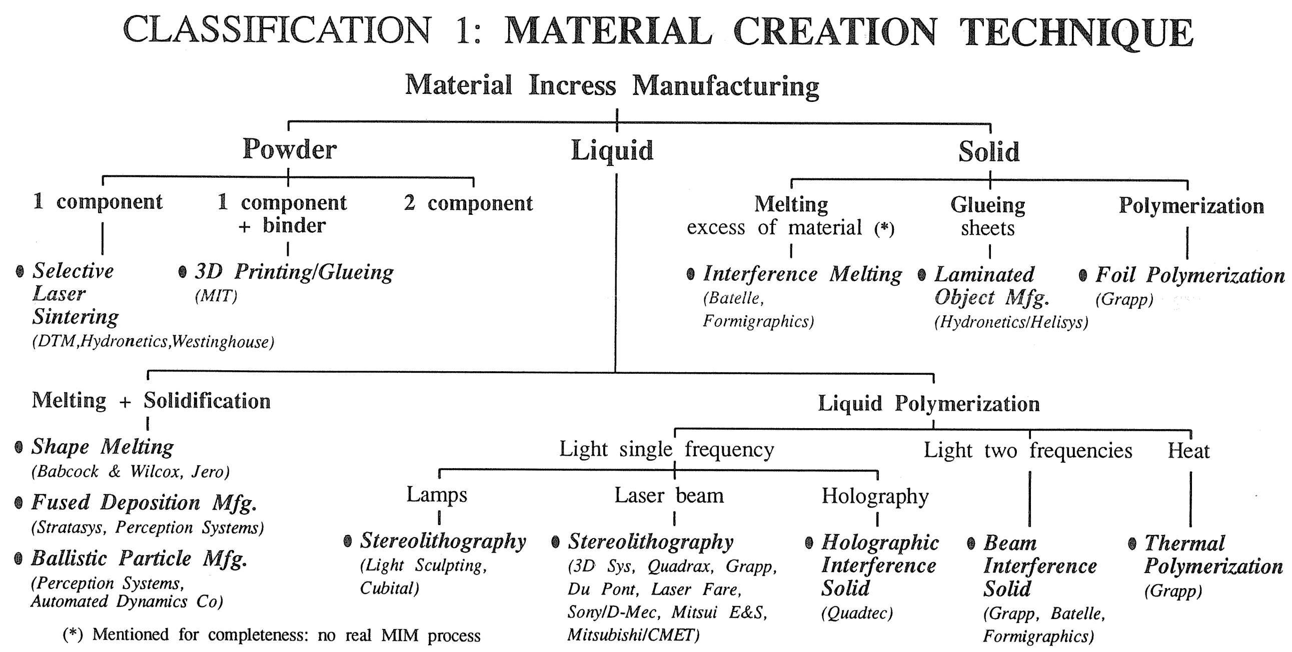


Fig.1. Classification of processes according to material creation.

Other processes use **powders**. Binding the grains can be obtained by melting together the interfacial grain contact area of a one component powder (Selective Laser Sintering), or glueing the grain together by selectively adding a binder or glue (e.g. MIT's 3D Printing process). A future alternative could be to start from a two component powder (as for carbides) and selectively activate the bounding (e.g. by laser sintering).

Finally, some processes start from bulk **solid** material, mostly thin foils. Several processes glue or weld foils on top of each other in order to produce the required shape [15,33]. Another process applies semi-polymerized plastic foils. The foils are bounded together by further photo-polymerization [2].

<u>Classification according to shape building</u> (Fig. 2)

Building up the shape can be done directly in 3D space (Fig. 2). However, most techniques build up parts in successive 2D layers created on top of each other (Fig. 7a).This is done by taking a CAD model of the part and first slice it in a large number of horizontal layers, normally at distances of a few tens of millimetre (one hundredth of inch). At manufacturing, all lower layers have to be created first before the next one can be deposited on top of it. A single layers can be created at once (layer by layer - one layer at a time). Most processes, however, create a solid layer by 'scanning' and solidifying it in a point-by-point fashion, e.g. by means of a laser beam (point by point - one point at a time). This scanning can be done in a continuous mode (Continuous creation of material - Fig. 12) or discontinuously (Voxel by voxel - Fig. 6).

Direct 3D techniques do not require the lower part of a product to be fully created before a higher part is manufactured. This gives even more flexibility in shape creation, but puts a great burden on programming the manufacturing equipment. This is why 'Fused Deposition Manufacturing', 'Shape Melting Technology' and other processes, which theoretically can be used as direct 3D techniques, are in practise used in a 2D layer mode. This greatly simplifies the CAM software: less CPU power needed, faster and easier programming of machine. For 3D techniques too, distinction can be made between processes creating a whole 3D surface at once (surface by surface manufacturing) and those producing the object point by point in a continuous or discrete mode.

<u>OVERVIEW OF TECHNIQUES</u>

This overview follows the classification given in figure 2. Characteristics of individual processes or machines are listed in table 1.

<u>Beam Interference Solidification (Liquid Two Photon Polymerization)</u>

This technique applies to a translucent liquid plastic (photo-sensitive monomer) contained in a translucent vat. Part creation occurs by a point-by-point solidification of the liquid at the intersection of two laser beams having different wave lengths: resp. frequency 1 and 2 (Fig. 3). All liquid hit by beam 1 is excited to a reversible metastable state that polymerizes upon impact of light with frequency 2.

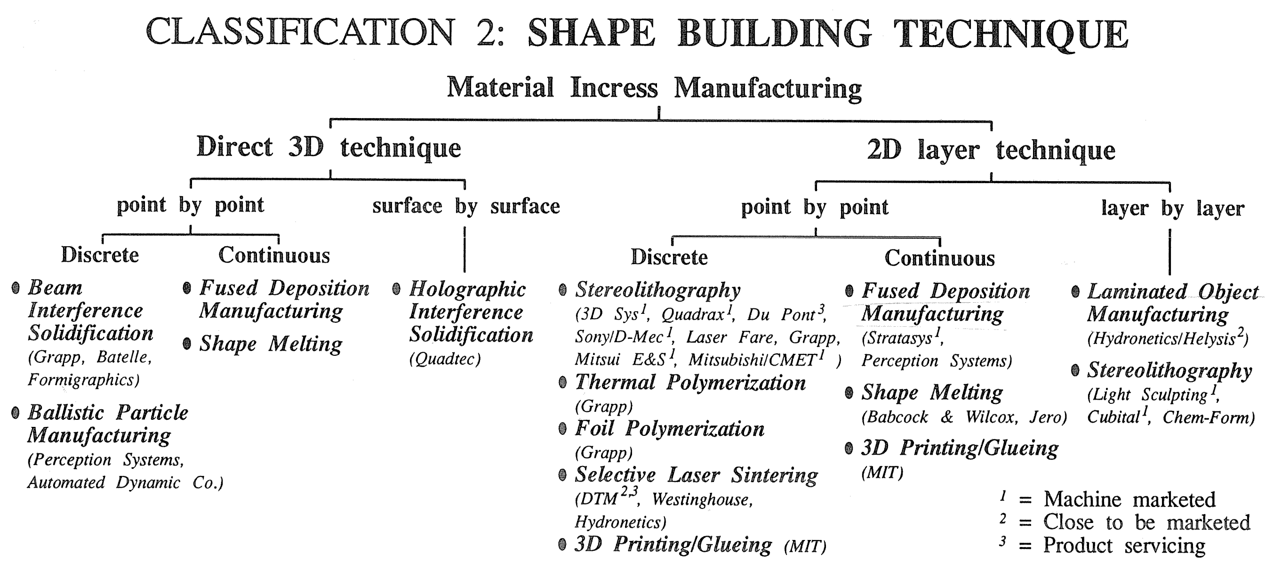


Fig.2. Classification of processes according to shape building.

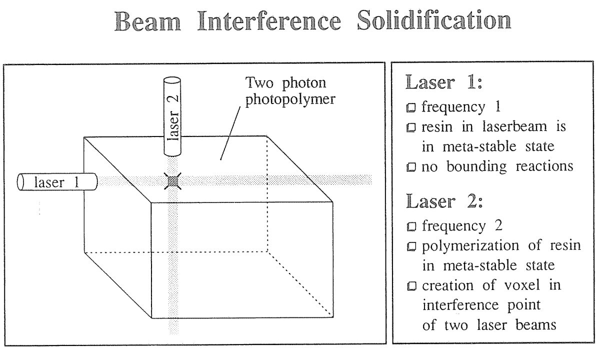


Fig.3. Beam Interference Solidification.

This process, developed among others by Batelle and Formigraphic in the sixties and GRAPP [2,9,19,34,45], didn't find industrial applications yet, because of problems with:

- light absorption (drop of intensity with depth),
- shade effects of parts already solidified,
- beam intersection problems due to light diffraction caused by local temperature variation or solidification.

Ballistic Particle Manufacturing (Inkt-Jet Mfg.)

Ballistic Particle Manufacturing produces parts by shooting droplets of molten material on top of each other (Fig. 4). Perception Systems Inc. has developed several prototype machines so far. The droplets are produced by piezo-electric inkt-jet printing nozzles generating droplets of about 50 μm diameter. The technique has already been applied for creating wax models for investment casting without need for dies [43]. However, the technique could be easily extended to other materials that easily melts and solidifies: e.g. thermoplastics and metals. Automated Dynamics Co. has built a prototype machine suited to deposit up to 1 kg of aluminium droplets per hour [23]. Allusion is also made to refined plasma spray for metallic parts [54].

The first prototype machine of Perception Systems still applies a 2D layer technique. The part is created on an elevator plate. A layer is created by moving the droplet gun in X and Y direction. Each time a layer is formed, the elevator moves downward (Z) and a new layer can be created on top of the previous one. The use of inkt-jet printing heads with an array of 32 parallel nozzles operating at 10,000 Hz each allows for high layer deposition rates. This machine requires horizontal overhangs within the part to be supported. This is presently done by creating plain supports from a water soluble synthetic wax (polyethylene glycol): see Fig. 19a. The supports are generated by droplets generated with a second inkt-jet gun and removed by dissolution in water. A six axis robot gun machine is under study. It should allow to shoot droplets from any direction, thereby eliminating the need for supports and the limitation to a 2D layer technique.

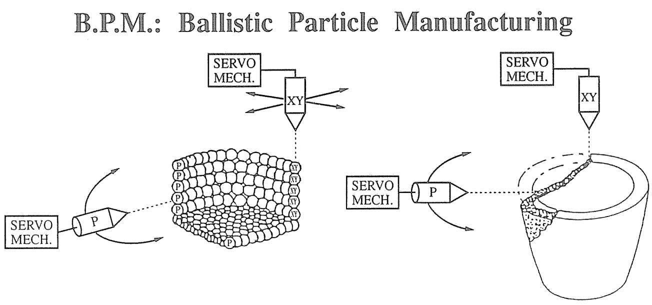


Fig.4. Ballistic Particle Manufacturing.

A major advantage of ballistic particle manufacturing is that it allows to apply different materials or colors within a single part.

Holographic Interference Solidification (Liquid Holographic Polymerization)

This process, as many other ones, is based on photo-polymerization. The idea is that projecting a holographic image in a vat of liquid photo-sensitive monomer could solidify a whole 3D surface at once, rather than having to build it up point by point. The holographic projection is obtained with a negative transparent holographic film created with a CAD system [23,20].

The process has been developed by Quadtec Pty, Melbourne, Australia (Rapidmodel machine, 300x300x300 mm workspace). Until now, little is known about the process. Reported applications include the production of lost-wax models and of copper electrodes for EDM.

Stereolithography (Liquid One Photon Polymerization)

Stereolithography is a typical example of a layer by layer manufacturing process based on photo-polymerization [7,31]. It was the first material incress manufacturing process commercially available (3D Systems' SLA-250 machine, 1988) and is still the most popular one (over 250 SLA machines sold by beginning of 1991).

Today some ten different developers or trade-marks of stereolithography machine are known (Fig. 2). They all rely on the same basic principle (Fig. 5) [4,20,24,25,27,30,34,36,48,54]. The part is built on a horizontal platform, dipped in a liquid plastic monomer. Solidification happens by photo-polymerization resulting from the impact of light on the upper surface of the liquid. (Mitsui illuminates the lower liquid surface through a glass-plate: fig. 5b). The monomer is chosen such that a single UV or visible light frequency can initiate polymerization: see table 1 [14,24,28,39]. Light absorption in the liquid limits the polymerization to a few tenths of millimetre below the surface. This approximately corresponds to the layer thickness. Illumination of the liquid surface is restricted to a pattern that corresponds to the part's cross section (see fig. 5 and next paragraphs).

Once a layer is solidified, the part is flooded with a new thin layer of liquid monomer and a new cross section of the part is solidified. The whole cycle is repeated until the part is totally formed. Examples of parts are depicted in Fig. 17a,b,c,d.

The fact that photo-polymerization only occurs over a few tenths of a millimetre below the liquid surface eliminates many problems encountered in 'beam interference solidification': it allows for less translucent polymers and for lower light intensity (Maximum laser powers on 3D Systems' SLA-190 machine is 12mW).

The range of photopolymers applicable today is still limited, but progress in this field goes very fast. For

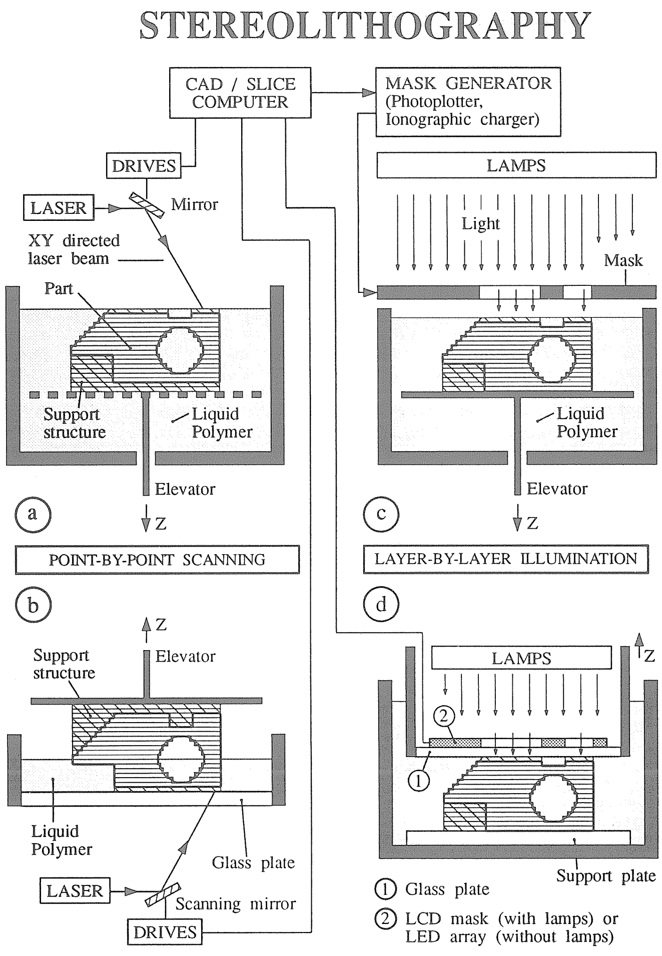


Fig.5. Different lay-outs for stereolithography.

example, only five acrylates with different mechanical and thermal properties are yet available for 3D's SLA machines. Some of the new acrylates have low melting temperatures that allow them to be used directly as lost-wax model for investment casting [49]. Others have great elasticity and may be applied for springs. Polymers with high impact strength are under development and were demonstrated to be suited to produce plastic hammers.

a) Point by point layer solidification

Most stereolithography machines apply a point-by-point solidification (Fig. 5a-5b). A laser beam scans the liquid surface in order to solidify a series of voxels (3D pixels or points): Fig. 6. In case of low power lasers, voxel formation is obtained by a point to point NC control that causes the laser beam to stop at each voxel point. The laser beam itself is not switched off between points: the beam travelling speed is too high to engender polymerization. Higher power lasers require reduction or shut off of the power between voxels. The voxels should have a size large enough to ensure connection with neighbouring voxels and with the under-laying layer (Fig. 6) [5,26]. The size of voxel overlap is controlled by adjusting the distance between voxels, the layer thickness, the laser power and the stay time of the beam on a voxel (scanning speed) and, on some machines, the laser spot size or focus [24,54].

To save time, the workpiece's cross sections are often only partially scanned and solidified: i.e. the laser only scans the outer and inner contour of the parts' cross section together with some cross hatching pattern giving the part a sufficient initial stiffness (Fig. 6 and 7c). Obviously the top and bottom faces have to be fully solidified by means of close overlapping scan lines in order to avoid leakage through those faces (Fig. 7b). Solidification of the liquid polymer still contained within the cross hatching patterns is done after all layers have been generated on the laser scanning machine. This happens by further exposing the "green part" to light. A special lighting device (post-curing 'oven' - Fig. 18) is provided for fast post-curing, but normal day light may do as well. Part accuracy is influenced largely by the ratio of initial laser curing to post-curing, the way of scanning, the type of cross hatching pattern, the density of cross hatching, the speed of post-curing (light intensity) and many more process parameters (about 30 parameters in total). Optimal adjustment of all parameters still needs a lot of research [8,32,44]. Such research is carried out among others by Bjorke and is reported in Volume one of the present CIRP annals [8].

b) Layer by layer solidification

Some more recent equipments use to solidify a whole layer at once. Hence, those systems may avoid the need for post-curing.

Illumination of a whole layer often happens through a mask representing the cross section of the workpiece (Fig. 5c). The Light Sculpting machine uses a photoplotter placed upstream of the machine in order to generate masks made from translucent photo-sensitive plastic foils (similar to those used for PCB copper path etching). A new mask is made and deposited for each different layer to be solidified [19]. Cubital and MAHO commercialize a machine in which the masks are generated by charging electrostatically a glass plate with a toner, as done in photocopy machines (Fig. 8) [42]. This allows the glass plate to be reused for successive masks. Compared to other liquid photo-polymerization processes, Cubital's system is special in such that the whole part is embodied in wax: after lighting a layer, the unsolidified polymer is first wiped off and replaced by wax that is cooled in order to solidify in turn. The wax serves as a support structure for hangovers and isolated parts of the product (Fig. 19a). It is also claimed that it reduces product distortions. Each layer of solidified polymer and wax is first milled to the right thickness before a new layer is applied. After the whole part is created, the wax is removed by using either hot water (e.g. dish washer), hot blown air, microwave energy or solvent.

Fudim [19] describes two systems that eliminates the need for creating the successive masks in a separate line (Fig. 5d):
- the first one applies a flat-pannel liquid crystal displays similar to those used for overhead projection of computer screens. The CAD computer directly controls the translucence of the LCD, put between the lamps and the liquid monomer.
- The second system applies a rectangular array of light emitting diodes put directly above the polymer vat.

Those programmable masks or lighting arrays can be put in direct touch with the liquid monomer, provided they have a special anti-addhesion coating. This allows to speed up the formation of a new layer by squeezing the liquid between the programmable mask and the part, rather than relying on free surface flooding. Free surface flooding of a layer generally takes 1 to 3 minutes, even when a scraper is used. This is much more than the time needed for solidifying a layer: solidification of a layer generally takes around 10...60 seconds in case of a partial point-by-point scanning and only few seconds when the whole layer is solidified at once. Squeezing the liquid could thus reduce the total production time by a factor of 100.

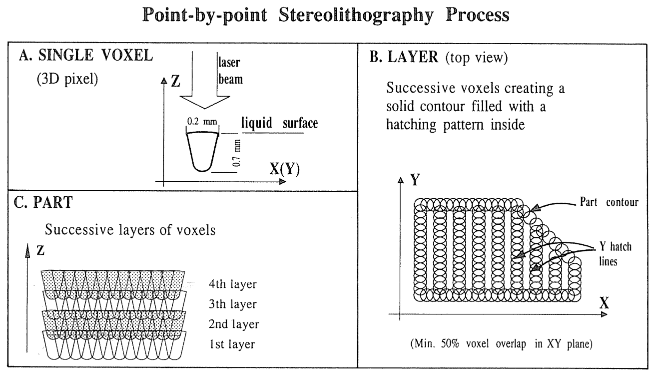


Fig.6. Point-by-point Stereolithography process.

Moreover, the fact that the whole cross section of a layer is illuminated and solidified on the machine eliminates the need for post-solidification of encapsulated liquid in a light oven. Other types of post-processing may however still be required: removing the supports or wax, thermal annealing, post-machining.

Liquid Thermal Polymerization

This process is very similar to stereolithography: successive layers of liquid polymer are solidified by laser scanning [2]. The differences lie in the type of polymer used (thermosetter instead of photopolymer) and a solidification based on heat, rather than light. Heat dissipation might cause difficulties to control the voxel size and the accuracy. According to Prof. André, this phenomenon can nevertheless be controlled. Thermal shrinkage and distortion may be another problem, but this one is surely not more severe that with stereolithography, were polymerization shrinkages of 6% in volume or 1.8% in dimension are common.

Solid Foil Polymerization

This process applies solid-to-solid polymerization, rather than liquid-to-solid [2]. Raw material consists of semi-polymerized plastic foils progressively stacked on top of each other. Each newly applied foil is illuminated locally. This causes the illuminated parts to polymerize further and kit to the foil underneath. Illuminated parts also become indissoluble. This allows the not illuminated parts to be dissolved afterwards, leaving the desired product.

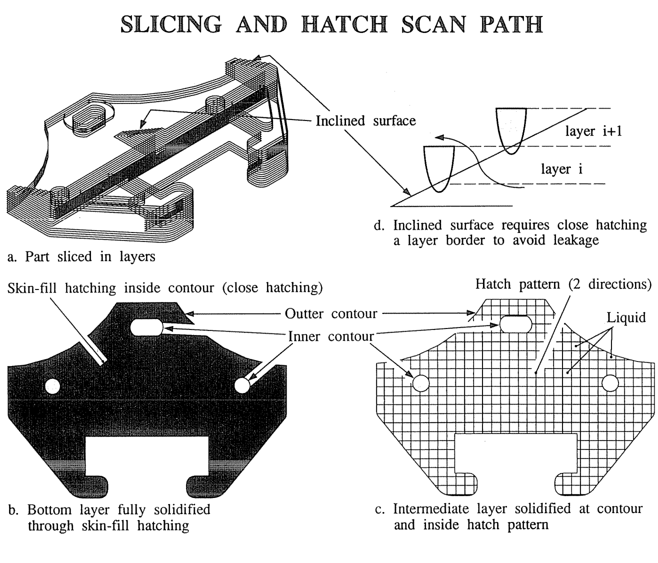


Fig.7. Stereolithography : slicing and scanning layers.

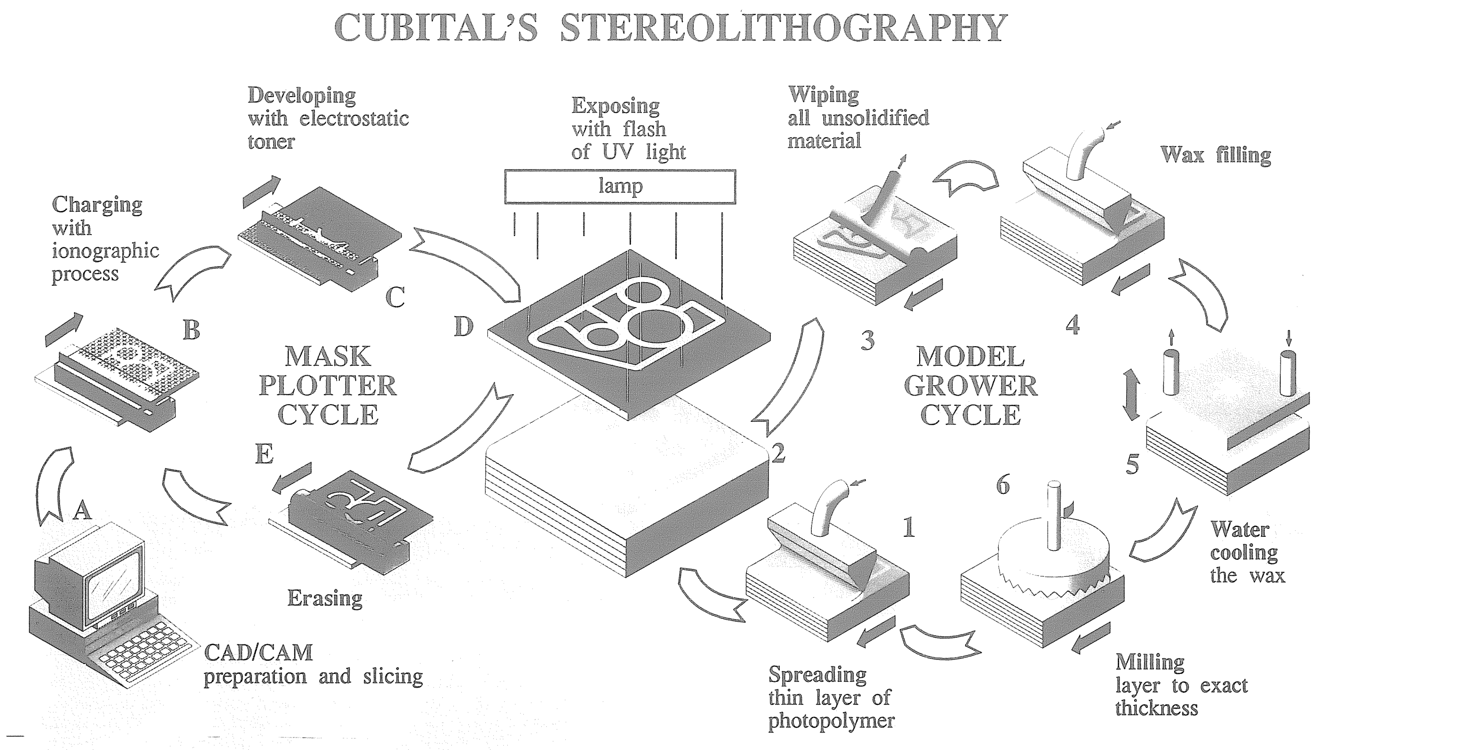


Fig.8. Cubital's layer-by-layer stereolithography process.

<u>Selective Laser Sintering (SLS)</u>

The layout of a selective laser sintering machine looks similar to the point-by-point stereolithography process: a laser beam scans and solidifies successive layers of the product (Fig. 9) [13,41]. The liquid polymer is replaced by bulk powder material preheated to a temperature slightly below its melting point. Selective solidification happens by further heating, up to the "sintering temperature", by means of the XY controlled pulsed laser beam. Sintering occurs when the grain viscosity drops with temperature, thereby causing the surface tensions to be overcome and creating an interfacial kitting of the grains without full melting (However, DTM's SLS process seems to cause full melting of the grains, rather than sintering [34]). The powder that is not scanned by the laser is unaffected and remains in place to support the next layer of powder and possible overhangs of the product.

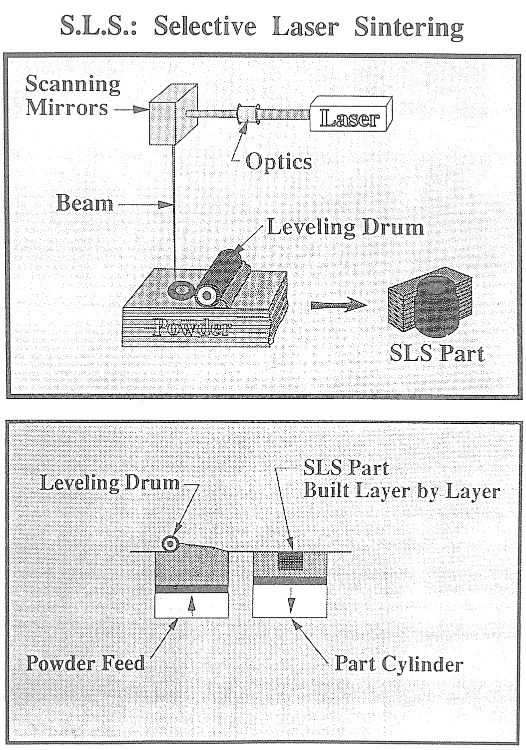


Fig.9. Selective Laser Sintering.

No binder material should be added as in 3D printing (see below) and no post curing is required as in point-by-point stereolithography, unless for ceramics. The later application requires polymer coated ceramics and post sintering in an oven (Compare to metal injection moulding). Today's industrial applications involve thermoplastics: PVC (Fig. 17e), polycarbonate (Fig. 17f), ABS, nylon and investment casting wax. Some successful laboratory tests were carried out with brass, copper and phosphate coated ceramics at the university of Texas and with steel at the University of Leuven. Westinghouse developed a similar process that applies a laser or electron beam for sintering/melting (50 to 18000 W). The equipment has been used for tests with powders of cobalt, iron and nickel alloys, titanium and ceramics [34].

<u>3D Printing/Glueing (Powder binding)</u>

3D Printing/Glueing is developed by MIT [45,46,47]. Up to now the process has been used by MIT for the fabrication of:
- ceramic moulds and cores for metal casting (Fig. 10)
- porous ceramic preforms, which when infiltrated by liquid metal will form metal-ceramic composite parts.

The process should be appropriate for powder metal parts as well, but no real applications are reported to date.

The process combines features of Selective Laser Sintering (SLS) and Ballistic Particle Manufacturing (BPM): see Fig. 11. Raw material consist of powder material that is deposited in successive layers, as in SLS. However, the laser beam, sintering the powder grains, is replaced by an inkt-jet printing head as in

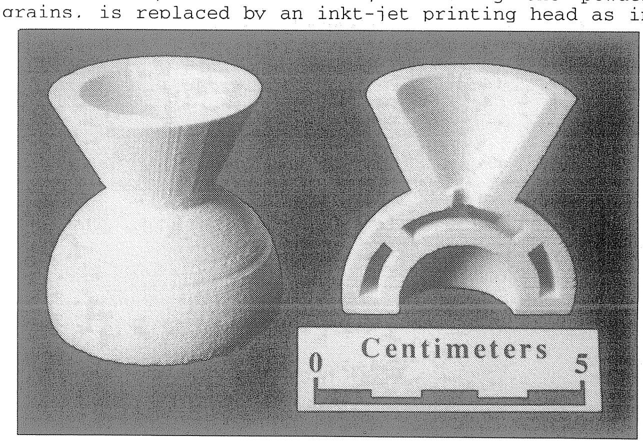


Fig.10. 3D Printing: Powder binded Ceramic Shell and Section [Material: Norton 320-mesh alumina powder. Binder: Nyacal 830 colloidal silica (30wt.% SiO_2). Part: 284 layers x 178 μm thick].

BPM. This head projects droplets of binder material onto the powder at those places where solidification is required. After building up the whole part, a heat treatment is applied: e.g. curing at 120°C for two hours. The unbound powder is than removed, leaving the fabricated part in its "green state". In case of ceramic parts, used as cores for lost wax models, a final firing at 1000-1500°C is required to give the part its full mechanical and refractory strength.

Two types of inkt-jet printing systems has been explored by MIT:
- the drop-on-demand system suited for discontinuous point-by-point solidification of a layer.
- the continuous-jet system in which a continuous cylindrical stream of binder emerge from the nozzle. This stream spontaneously breaks down into a succession of droplets as it moves towards the part.

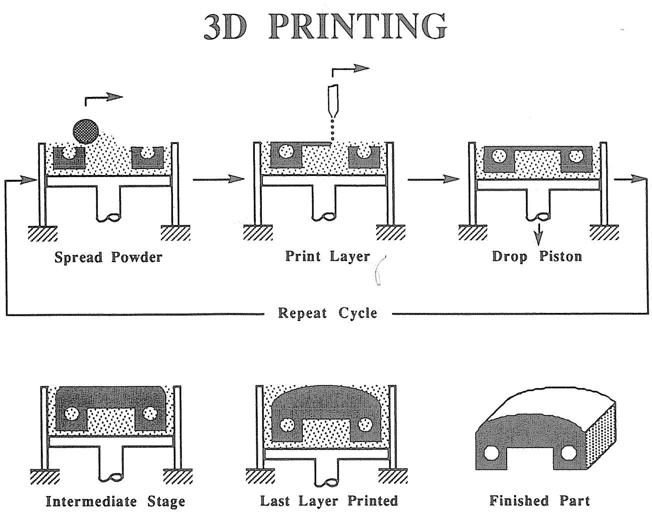


Fig.11. The 3D Printing or Powder Binding Process.

Printheads with over 100 jets are envisaged to speed up the solidification of a layer (Printheads with 1600 jets, 120 jets/inch, are commercially available). This is expected to reduce the layer solidification time to 5 sec/layer for a drop-on-demand system and a .5x.5 meter layer, or to 0.025 sec for continuous-jet systems [45].

MIT already gained quite some experience with alumimum-oxide and alumina-silica ceramic powders, bound with amorphous or colloidal silica. Other candidate powders are: zirconia, zircon and silicon carbide. There is no information available yet on applications with metal powders. Systematic tests are performed to study the insidence of processing parameters (binder volume, print line spacing) on shrinkage, dimensional accuracy and strength [46].

Fused Deposition Modeling and Shape Melting Technology

Those two processes build up a part by deposition of molten material onto a base plate or onto previously solidified material. Solidification happens by cooling of the molten material on the colder underlaying layers.

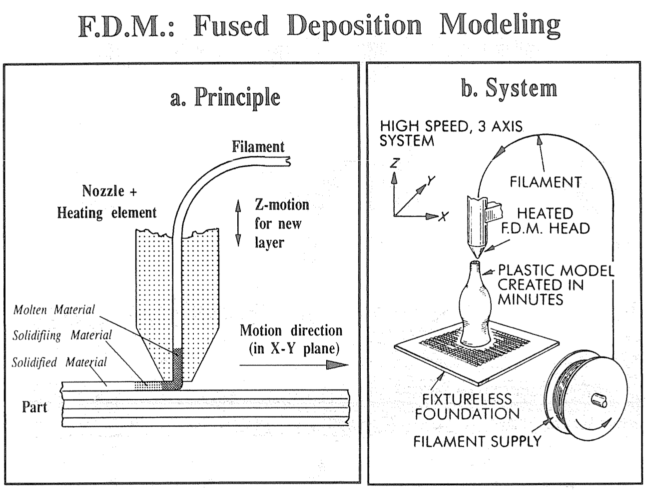


Fig.12. Fused Deposition Modeling.

In Fused Deposition Modelling [10], the molten material is obtained from a solid filament of thermoplastic material (1.25mm diameter size), fed into a XY controlled extrusion head (Fig. 12). The material is brought to 1 degree above melting temperature. This ensures resolidification by natural cooling within 0.1 seconds. The flow rate of the outcoming molten filament is controlled accurately by precision volumetric pumps. It should be adapted to the head travelling speed (up to 381mm/s), to the layer thickness (0.025 to 1.25mm), to the desired laminate width or wall thickness of the part (0.25 to 5mm), etc. Overall X, Y and Z tolerance of 0.125mm over a 305mm cube are claimed (0.04%), but some parts still seem rather rough and the process is less suited for small details (Fig. 13).

This process may theoretically be applied to any thermoplastic material. Parts built up of different materials or colors may even be produced easily. Today, three raw materials are available:
- an investment casting wax
- a wax-filled plastic adhesive material (machinable wax)
- a tough nylon like filament.

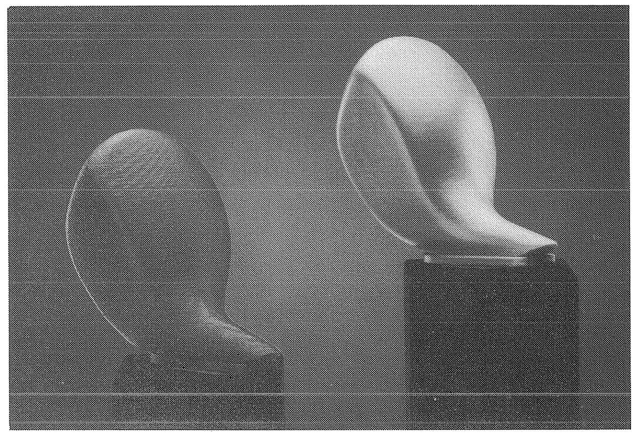


Fig.13. Fused Deposition Modeling : golf club driver in investment casting wax (left) and machinable wax (right).

A similar process, called Shape Melting and developed independently by Babcock & Wilcox [12] and Jero [34], allows to produce near net shape metal parts. A band or thread of metal is melted and deposited by arc welding. B&W uses a controlled cooling device to ensure fast solidification [34]. At this time there is still a strong limitation on accuracy: the parts exhibited by both companies are very rough and accuracy is not better than 1mm. Jero predicts problems for producing geometries smaller than 7mm in size. This contrasts strongly with the 0.5mm details that can be produced with most other material incress processes. However, this continuous point-by-point building process may produce parts with higher strength, higher toughness and more uniform and isotropic properties than parts produced by bulk casting or by metal removal from ingot raw material. Materials applied so far include Iconel

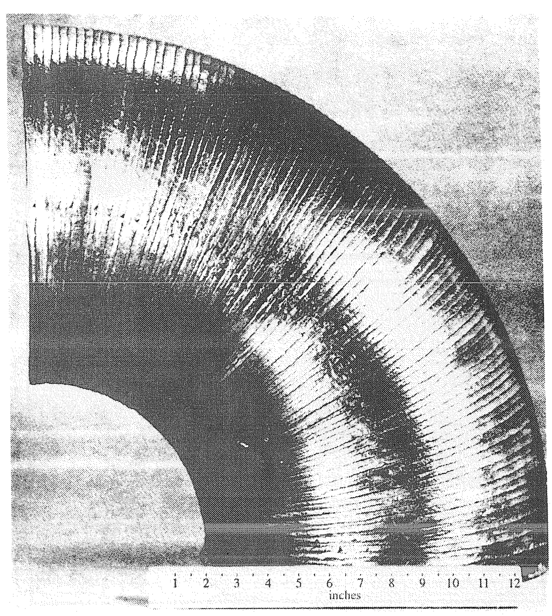


Fig.14. Shape melted alloy 625 elbow.

(Alloy 625), tungsten carbide, and other alloys. Figure 14 shows a part in which the layer thickness was varied with position by continuously adjusting the welding parameters.

Laminated Object Manufacturing

Parts produced by laminated object manufacturing consists of a stack of foils cut to shape and glued to each other (Figure 15) [15,16]. Each foil is first glued to the stack (Fig. 15a), before the part's cross section is cut out by a laser beam (Fig. 15b). The velocity and the focus of the laser beam is adjusted so that the cutting depth exactly corresponds to the thickness of the foil and that the underlying layer is not damaged.

Selective glue activation may then be obtained by scanning with a UV laser or by first printing a mask onto the foil and than illuminating with UV lamps thru a glass plate pressing the foil on the stack (Fig. 15).

The idea of laminated object manufacturing is not really new. Kunieda [33] already reported of a technique to build moulds by laser cutting, stacking and welding together thin sheet plates. However, Hydronetics' system may be considered the first really promising implementation.

COMPARISON OF PROCESSES

Table 1 compares various processes and machines in terms of materials, layer thickness, accuracy, speed, etc. It is mainly based on data obtained from literature and brochures. Data should be handled with care. Some processes could not prove to reach the claimed accuracy: see below. This is often due to lack of experience and inappropriate tuning of the equipment: the processes are still very new, complex (up to 30 adjustable parameters) and not well controlled. Optimizing the process can still bring tremendous improvements [8,32,43,46]. For example, connectors (similar to those depicted in Fig. 16) were produced in series of some hundred components at the university of Leuven. The machine used was an SLA-250 stereolithography machine. An accuracy of 0.02mm over 60mm was obtained in a repetitive way (0.03%) [49]. This is far better than the claimed machine accuracy of 0.1mm or 1%.

L.O.M.: Laminated Object Manufacturing

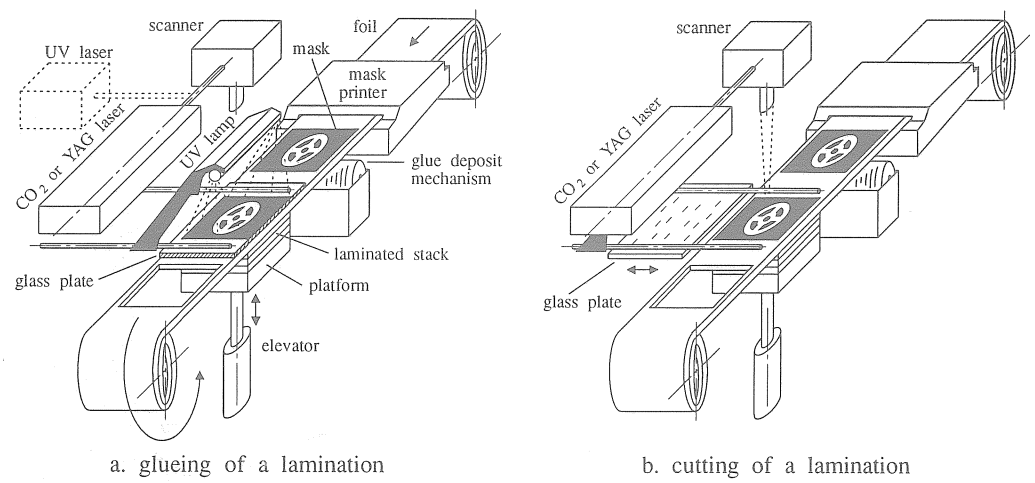


Fig.15. Laminated Object Manufacturing.

Virtually any foil material can be applied: paper (cellulose), metals, plastics, fabrics, synthetic materials, composites. The products supplied by the service bureau of Hydronetics/Helysis are made from cellulose foils and have a wood like aspect (Fig. 17g). This process uses foils that are pre-coated with glue, but a glue deposition mechanism is envisaged on future machines (Fig. 15).

Glueing occurs at present over the whole foil area: i.e. unneeded parts of the foil are glued as well and remains inside or around the product until the whole part is created. However, techniques are studied to glue only within the part's cross section. This may be obtained by applying heat sensitive glue all over the sheet and scanning the cross section area with a laser (Only the scanned area is glued). Using the initial cutting laser at high scanning speed could initiate glueing without cutting. Lower speed would then be used to cut out the contour of the cross section. UV sensitive glue is envisaged for transparent foils.

Connectors made by Stereolithography

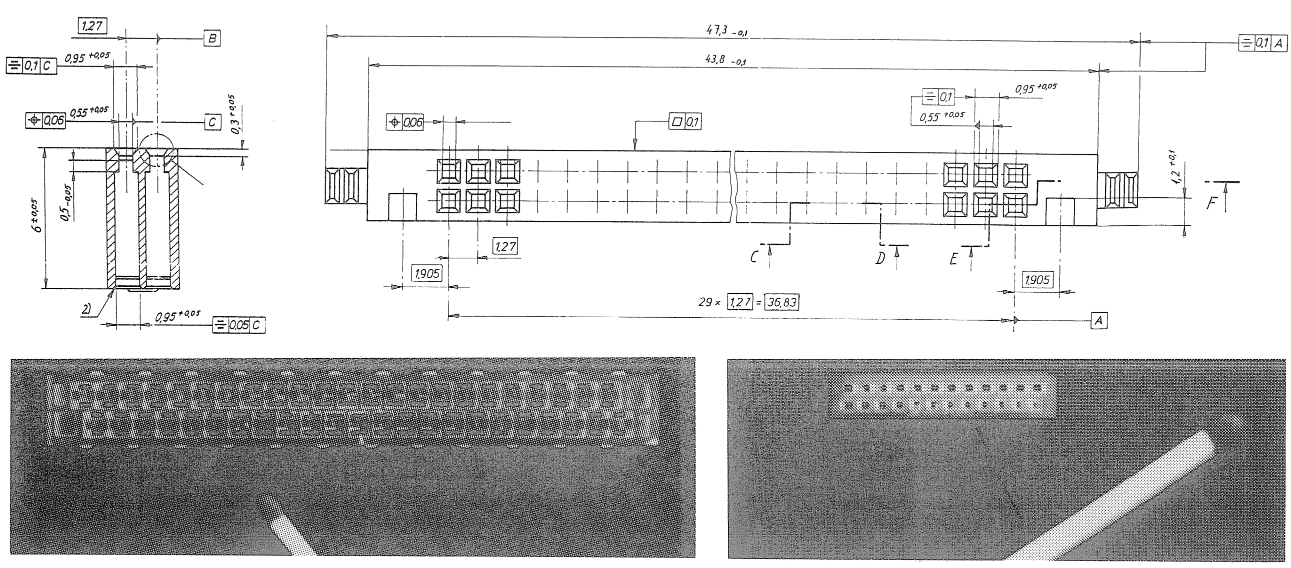


Fig.16. Examples of connectors produced with stereolithography.

TABLE 1 : CHARACTERISTICS OF MATERIAL INCRESS MANUFACTURING PROCESSES.

	PROCESS NAME / CHARACTERISTICS	Beam Interfer. Solid.	Ballistic Particle Manufact.	STEREOLITOGRAPHY – Point - by - Point: 3D Systems	Dupont	Quadrax	Sony/D-MEC	Mitsubishi CMET
MATERIAL	Materials applied so far [possible in future]	Photo-poly -mers (2photon): -Acrylates	Thermo-plastics: - Wax [Metals]	Photo-Polymers (UV): -Acrylates	Photo-Poly-mers (UV): -Acrylates	Thermoset photopolymer ($\lambda \approx 500$ nm) -Acrylates	Photopolymer (UV): -Acrylates	Photopo-lymer (UV): -Acrylates
	Raw shape	Liquid	Liquid (solvent)	Liquid	Liquid	Liquid	Liquid	Liquid
MACHINE	Max. work-piece size (mm)	300x300 x300	350x350x350	SLA190:191x191x249 SLA250:254x254x254 SLA500:508x508x610	305x305x305	305x305x305	M1:240x240x150 M2:500x500x150 M3:1000x800x500	530x360x350 830x600x500
	State of development	No break thru yet	Development; Sale:1993	Sales: ± 250 units	Service; No sale plan	Service = Early sales	Sales in Japan	Sales ?
	Approx. price (US $)	n.a. (not applicable)	50,000	SLA190:95,000 SLA250:185,000 SLA500:385,000	n.a.	195,000	?	?
LIGHT/HEAT SOURCE	Type	2 lasers	n.a. (Inkt jet nozzles)	SLA190:He-Cd laser SLA250:He-Cd laser SLA500:Ar-ion las.	Ar-ion laser	Ar-ion laser	M1:He-Cd laser M2:Ar-ion laser M3:Ar-ion laser	He-Cd laser
	Wave length	2 UV wave length	n.a.	(UV) He-Cd: 325nm Ar-ion 351+364nm	UV - 365 nm	Visible light 500 nm	UV	UV
	Power	?	n.a. (32 nozzles x 10 kHz drops)	SLA190: 12mW SLA250: 15mW SLA500: 200mW	300 - 500 mW	5 W (modulated)	Ar-ion 400mW (Acoustic optic modulat.)	?
PROCESS	Need to build supports	no supports	5-axis:no supp. 3-axis:yes wax	yes	yes	Yes	Yes	Yes
	Post curing process		no	UV-oven 3x400W	oven at at 93°C	Ligh oven 400W	UV oven	No claimed
ACCURACY	Layer thickness (mm)	n.a.	0.09	0.1 to 0.7	0.13 to 0.5	0.05 to 0.38	0.1 to 0.3	?
	Grain, Voxel or Focus size (mm)	?	0.05 .. 0.1 droplets	0.1 to 1.2 Focus	0.13 Focus	0.13 to 0.31 F (modulated)	0.1 to 0.3 Focus	?
	Overall Accuracy (mm)	?	± 0.1mm	± 0.127mm/25.4 mm (0.5%)	± 0.1mm xy: 0.2% z: 0.6%	± 0.13 mm	xy:±0.3mm z:±0.5mm	?
SPEED/TIME	Scan speed(pt/pt) Layer solid time (layer/layer)	?	up to 32 nozzles x 10 kHz	SLA250: 503mm/s SLA500: 2540mm/s	?	1400 mm/s	250 to 1500 mm/s	?
	Time in between layers	n.a.	0	20 sec to 3 mm	?	±15 sec	?	?
	Total time/layer (roughly)	n.a.	-	variable with size	variable with size	..15sec..	variable with size	variable with size
	Build rate (typical)		Al: 1 kg/h or 370,000mm3/h	SLA250-continu 65,548 mm3/h				

The "Centrum voor Productietechniek" and TNO, Netherlands, have carried out a comparative study [51]. They put orders to produce the part shown on figure 17 with 7 different processes. The results are given in table 2 and may be summarized as follows:

- **Stereolithography - 3D Systems**: most accurate process, with all dimensions within about + or - 0.1 or 0.2 mm (except one, difficult to hold because of distortions on large U-shape, but which is still better than 0.5%).
- **Stereolithography - Quadrax**: errors up to 4 mm on large dimensions in X and Z direction, but quite precise for small details in XY plane (few hundredths mm).
- **Stereolithography - Du Pont**: 0.1 to 0.8 mm accuracy; difficulties to handle complex parts (product produced in 3 parts).
- **Stereolithography - Cubital**: accuracy ranges from few hundredths (0.02) to few tenths (-0.45).
- **Selective Laser Sintering**: 0.1 to 0.5 mm accuracy.
- **Laminated Object Manufacturing**: it must be possible to reduce the deviations of up to 7 mm in vertical and Y direction. X accuracy is -0.04 for 100 mm.
- **Fused Deposition Modelling**: part not yet produced, six month after order; problems expected with details and complexity.

Repetitivity analysis was carried out by producing 12 parts as shown in fig. 17a on a 3D SLA-250 stereolithography machine. It proved that the deviations on dimensions are rather repetitive or deterministic. Compensation for the deterministic deviations would reduce the inaccuracy (average deviation) from typically 1% to 0.2%. The very high accuracies (0.02%) obtained by the university of Leuven (see above) are greatly due to a very precise compensation of shrinkage, laser beam diameter, etc.

The repetitiveness tests also showed that 75% of the deviations already occurred before post-curing. Those observations are confirmed by Bjorke [8]: see also [50,22].

MATERIAL RESEARCH AND PHOTO-POLYMERIZATION

Many material incress manufacturing techniques use common raw materials: e.g. metal or ceramic powders, thermoplastics, wax, etc. Several other techniques uses photopolymers, which until recently were not readily available on the market. Stereolithography, for example, required the development of new photopolymers. The range of available photopolymers is limited and often bound to a specific machine (a.o. wave length of light source). Today, the most popular stereolithography machine can only be provided with some five different polymers having still limited performances regarding strength, fatigue, aging, etc. A lot of R&D is yet needed to extend the range of photopolymers and their characteristics, but rapid progress is made.

The fact that many popular material incress manufacturing techniques are based on photo-polymerization and that this phenomenon and the related materials are not yet well know to many production engineers, justifies special attention to this chapter.

Photo-polymerization requires three chemical components: a monomer, a photo-initiator and a reaction terminator. The monomer and the photo-initiator are mixed in the initial liquid resin. The terminator normally comes from the oxygen in the atmosphere. Impact of light activates the photo-initiator, which is decomposed in radicals having a free electron. Those radicals react with a monomer chain to form a larger

TABLE 1 (end)

	Layer - by - Layer		Selective Laser Sintering	Three Dimensional Printing	Fused Deposition Modeling	Shape Melting Technology	Laminated Object Manufact.
Mitsui -ES	Light Sculpting	Cubital					
Photopolymer (UV): -Acryl.	Photo-polymer (UV): -Acrylates	Photo-polymer (UV): -Acrylates	Powders: -Thermplastics (ABS,PVC,PC, Nylon) -Wax -Metals (wider variety) -Polymer coated ceramics	Powders: -ceramics (Al_2O_3, Al-Silica) + Binder: Silica (30% SiO_2)	Thermoplastics: -Investment wax -Machinable wax -Wax filled plastic addhesive -Though nylon-like material [Metal Powder]	Metals: -Iconel -WC [Metals]	Paper, Cellulose Plastics, Metals, Fabrics Synth. Mat. Any sheet precoated with heat active addhesive (PE)
Liquid	Liquid	Liquid	Powder	Powder	1.25mm wire	Wire	Sheet, foil
300x300 x300	152x152 x229	480x480x330	Ø350x380	350x350x350	305x305x305	-	M1:325x250x375 M2:750x500x500
Sales ?	Service + Early sales	Service + Early sales	2 service co. Sale plan:1992	Sale plan: 1993	Early sales	Developm.No sale plan	Services + Close to sale
?	100,000	490,000	350,000	n.a.	156,000 (214,000 incl.W.S.)	n.a.	M1:75,000 M2:100,000
He-Cd laser	UV lamps	Mercury UV lamps	Pulsed CO_2 laser	n.a. (Inkt jet nozzles)	Welding nozzle	Welding nozzle	CO_2 laser (Alt YAG) (Opt. UV lamp/laser
UV	UV broad	UV broad	10,6 µm	n.a.	n.a.	n.a.	IR (Opt.UV for glue active)
40 mW	200 W	2500 W	50 W	n.a. (1..100 nozzles x 10..1000kHz)	-	-	M1:CO 25 M2:CO_2=50W
Yes, at top (hanging supp.)	Yes, but not at bottom	no (Autom. full wax support)	no (Autom. full powder support)	no (Autom. full powder support)	sometimes	no supports	no (previous sheets= support)
oven	no claimed	30 min	no, except for coated ceramics	Curing at ±150°C Firing at ±1200°C	none	post-machining for accuracy	none
?	0.013 to 1.3	0.05 to 0.15	0.13 [0.08 tentative]	0.18 [46] 0.05 [53]	0.025 to 1.25	?	0.01 to 0.15
?	n.a.	n.a.	±0.1 grain 0.5 Focus	0.01 to 0.1 Grain 0.02 binded	0.25 to 5 width of laminate		0.25 Focus
±0.1mm	xy:0.03-0.064 z:0.05	0.1 % (up to 0.5mm)	1 % or 0.1mm [23] ±0.03mm [53]	0.06 to 0.13%	0.08% (±0.125mm on 305mm cube)	± 1mm	xyz:±0.1mm per 100mm (0.1 %)
400 mm/s	10s/layer	?	1016mm/s	100 to 20,000 mm/s	381 mm/s	?	381 mm/s
3 sec	<40sec	waxing,mill time (Fig8)	compare depos. time 3D Print.	Wait for binder action:0.1-1sec Deposit:0.1-1sec	0	0	?
variable with size	<1min	110 sec	..15sec..	For 500x500 size: 5sec drop/demand 0.13sec cont.jet	variable with size	E.g. 10 min	?
	<1min/layer	24,581 mm^3/min	12-25 mm/h thickness	20mm/h (drop/d) 270mm/h (contin.)	?	?	10mm/h thick (100 layers/h)

molecular chain still having a free electron. Further reaction with monomer molecules lengthens the chain causing polymerization to proceed. The reaction can be stopped by binding the last free electron to an oxygen atom. As long as light remains, the formation of radicals will supersede the availability of free oxygen molecules in the liquid. As light disappears, the lack of new radicals will leave free way to the oxygen to react with the remaining free electrons and prohibit further polymerization. The presence of oxygen at the liquid's surface and its diffusion within the surface layer are thus essential for a controlled solidification.
Photo-polymerization is thus basically a light-based process; not a thermal process. This explains the low laser power required (Table 1) and the potential to produce highly accurate parts. The absence of heat diffusion and the well controlled termination of the chaining reaction avoids any polymerization outside the beam spot and allows a very precise control of the voxel size. Shrinkage has not to do with cooling down, but is due to volume reduction by polymerization (greater imbrication of molecules).

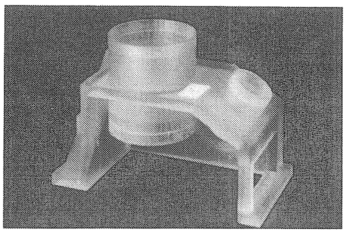
REAL CIM PROCESSES

One of the major reasons for the success of material incress manufacturing in future is expected to be its basic CIM nature: MIM is developed for and fully dependent on CAD and CIM [13].

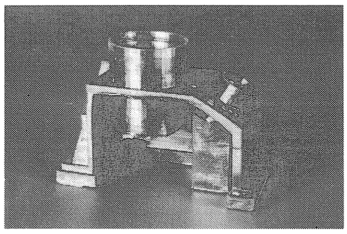
This drastically opposes to CIM as applied to material removal and forming techniques. Those techniques were developed long before computers entered the manufacturing environment and it has been (and will remain) a hard business to adapt those techniques to CIM, CAD and CAM. Automating the whole process from design to manufacture causes tremendous problems, such as knowledge capture and computer handling of knowledge (expert systems), planning (CAPP), interfaces (STEP, MAP,...), communication.

The fact that material incress manufacturing only creates material where needed and without any tooling, makes it very suited for CIM and eliminates most of the problems encountered with other processes:
- no need for feature-based design: a 3D surface or solid model of the product is sufficient, because the manufacturing process has not to be adapted to the type of geometry or feature;
- no need for conversion from design to manufacturing features: the design contains all geometrical information needed for manufacturing, because there is no difference between the part's material and the material to be machined;
- no need to define a blank geometry;
- process and operation planning are reduced to a minimum;
- no need to define sequences of operation (CAPP) and complex routings: the part is produced in one operation;
- no problem of defining different set-ups: part made in one set-up;
- no need for clamping, jigs or fixtures (However, some processes may need that a support structure is built up together with the workpiece);
- toolless process: no need for tool selection and management, no need for design and manufacture of moulds and dies.
- etc.

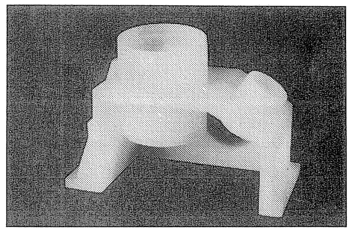
Material incress manufacturing allows a direct and very simple interface from CAD to CAM. It almost completely eliminates the need for CAPP. CIM simplifies to the following scenario (Fig. 18):



a. Stereolithography - 3D System

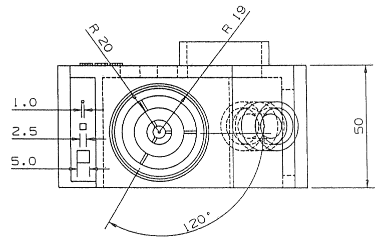


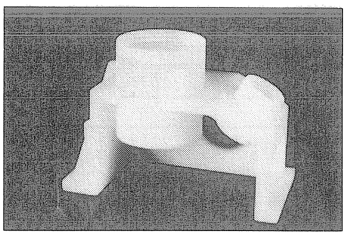
b. Stereolithography - Quadrax



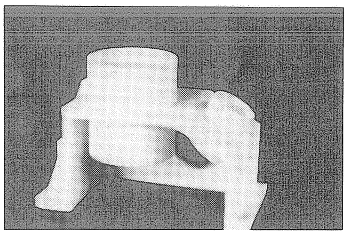
c. Stereolithography - Du Pont

TOP VIEW



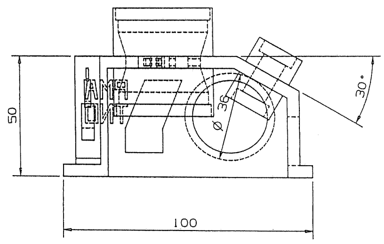


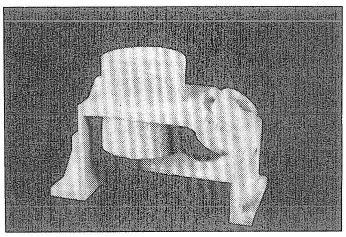
d. Stereolithography - Cubital



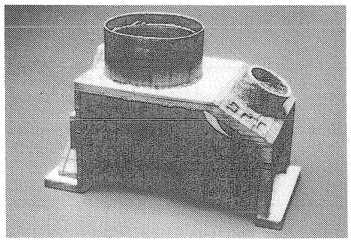
e. Sel. Laser Sintering: DTM (PVC)

FRONT VIEW





f. Sel. Laser Sintering: DTM (PC)



g. Laminated Object Mfg.: Helisys

h. The Part

Fig.17. Same part produced with different techniques.

a) Start from a good and complete geometrical description of the product:
A 3D surface or solid model is required. This is in opposition with NC turning and milling where 3D or even 2D wire-frame systems are most commonly used. However, there is little need for additional information (features, attributes, etc.). 3D surface models should be such that they are fully closed: a small gap in between two surfaces can make the model corrupt.

b) CAD/CAPP preparation:
The workpiece should be oriented properly with respect to the machine: the orientation is selected with regard to the production time (proportional to the workpiece height or number of layers), the accuracy (differential shrinkage, distortions), part geometry (avoidance of overhangs and trapped liquid or powder), etc. Next, the machining parameters are selected. This is one of the most difficult tasks, because the processes are still not well understood and have many adjustable parameters. Those parameters influence the machining time and accuracy (shrinkage, warpage). The model may be modified to compensate for shrinkage, although this may also be done at the CAM stage. In some cases, a support structure has to be designed to support overhanging parts. This structure generally consists of full material or a grid of vertical walls (Fig. 19). CAD programs to generate this structure automatically may be common in the future. With several processes, the support structure is created automatically during

TABLE 2 : COMPARATIVE ACCURACY TESTS

MANUFACTURING PROCES	MATERIAL	ACCURACY (deviation from nominal volume)						REMARKS
		HORIZONTAL				VERTICAL	COMBINED	
Company name: machine		Lenght (100mm)	Width (50mm)	Cylinder inner/ outer ø (ø 19/20mm)	Square details (1,0/2,5 /5,0mm)	Height (50mm)	Vertical Cylinder (ø 36mm)	
Point - by - point stereolithography 3D-System : SLA-250	Acrylate	-0,44	-0,12	-0,21/±0,04	+0,14	+0,25	+0,15	-Most accurate of processes tested by SPT
Point - by - point stereolithography Quadrax : Mark 1000	Acrylate	+3,00	-0,85	-0,60/-0,76	0/+0,07/ -0,02	±4,30	+0,85 -1,30	-Details are very accurate
Point - by - point stereolitography Du Pont : SOMOS	Acrylate	-0,68	-0,77	-0,46/-1,55	-0,02/ -0,12 -0,12	-0,62	-0,54	-Inclined cylinder made separately -Very soft material => deflections while measuring
Layer - by - Layer stereolithography Cubital : Solider	Acrylate	-0,09	-0,45	-0,02/-0,38	-0,23	-0,06	-0,20	-high vertical accuracy is due to the post-milling of each layer -Inhomogenities and wax inclusions between layers
Selective laser Sintering DTM: SLS System 125	PVC Polycar-bonate Wax	-0,23 -0,86 -	-0,10 -0,38 -	-0,52/+0,26 -0,58/0,51 -	+0,36 -0,13 -	+0,23 -0,20 -	±0,04 -0,34 -	-granular surfaces -Polycarbonate shrinks more then PVC no date available
Laminated Object Mfg Hydronetics/Helisys: LOM	Wood-like paper (cellu-lose)	-0,04	-7,00	+0,7/-0,7	-0,33 (2)	-7,05	-3,97 -0,27 (1)	-Process can do better -Low accuracy is due to problems -Cylinders are unround (1) -Details 1,0 and 2,5mm not present (2)
Fused Deposit. Mod. Stratasys: 3D Mod.								-Product not delivered (after 6 months)

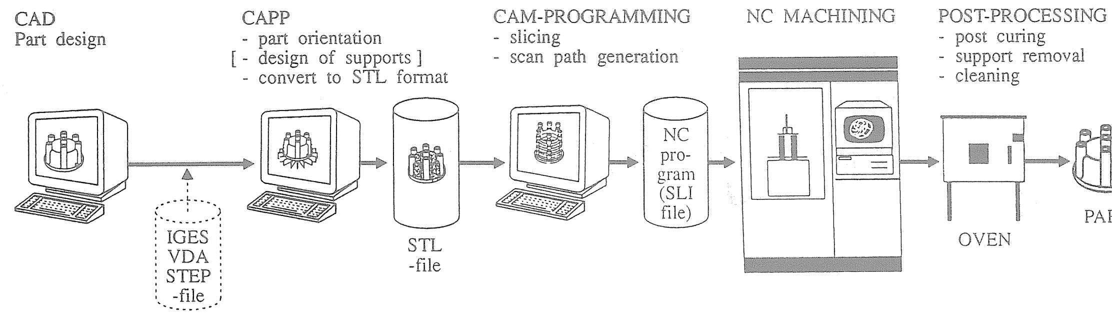


Fig.18. Typical CIM scenario for material incress manufacturing.

manufacturing and doesn't need any preliminary design: see Cubital's stereolithography machine (Fig. 8: full wax support), selective laser sintering and powder binding or 3D printing (Fig. 9 and 10: powder support), solid foil polymerization and laminated object manufacturing (Fig. 15: foil support), 5-axis ballistic particle manufacturing.

c) CAD-to-CAM interface:
Although MIM is very new, the 'STL interface' developed by 3D System for the stereolithography process has already become a standard de facto taken over by nearly all vendors of MIM machines. This PHIGS-based format, approximates the part's outer and inner surfaces by a set of triangular flat patches. Each patch is described by its three vertices and a vector pointing out of the material.

d) CAM software or slicing processor:
All layer-by-layer manufacturing processes require slicing of the product model and support structure at distances equal to the layer thickness. The slicing is made easy by the STL format, containing only flat triangular faces. A scan path is generated for each layer. Laminated object manufacturing only requires the cross-section's contour to be scanned. However, most other processes also need some scanning of the inside of the cross-section: e.g. all point-by-point processes or the mask preparation for layer-by-layer manufacturing. Different scanning patterns are used for scanning the inside of the sections: parallel paths, honeycomb structure, etc. The scanning pattern greatly

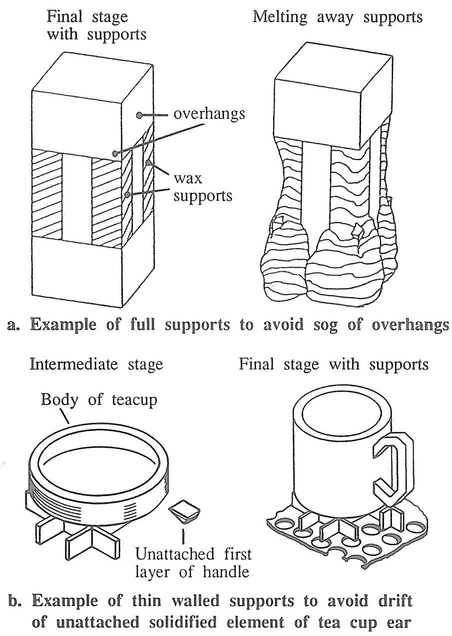


Fig.19. Supports for material incress manufacturing.

influences the accuracy (shrinkage, warpage) and production time. Different scanning techniques may be applied to different layers. For instance, in stereolithography, all bottom and top surfaces are fully scanned by close parallel paths, while intermediate layers are only scanned at their contours and filled with cross hatching lines some millimetre apart (Fig. 7).

e) Machining file interface:
The results of the slicing and the vectorization process (i.e. scanpath generation) are transmitted to the controller of the machine, where the part is produced layer after layer. No standard, like the ISO NC code for conventional NC machines, exists yet at this level. Most vendors use binary formats, which they even do not disclose. This hampers the possibility for the user to optimize the actual NC programs. The part creation on the machine may, for some processes, still be followed by a post-processing operation, as described earlier.

APPLICATIONS AND PERFORMANCES

Table 1 already summarized the applications in term of materials and accuracy. Efforts are still required to get the accuracy at the level of traditional manufacturing techniques. However, fig. 16 shows that accuracies are yet possible that are comparable to the best ones obtained in injection moulding (0.02mm).

The real advantages of material incress manufacturing are of another nature. Some of those advantages have been mentioned before, but other need more comment:
- **Freedom in shape:**
There are almost no limitations to the complexity of the parts. Fig. 10 shows the unique possibilities to produce parts with intricate internal shapes: no problem of accessibility, no need for cores and no problem of demoulding cores and dies [33]. The process is also very suited to produce very tiny details (Fig. 16), thin walled products (Fig. 20), as well as sculptured surfaces (Fig. 13), provided a suited CAD model is available.
- **Multi-material and anisotropic parts:**
Most processes allow to change material during the building process. This allows to create parts combining different materials, colors, mechanical or thermal properties.
- **Perfect CIM matching:** see above.

Other advantages become clear when looking at the applications:
- **Fast prototypes:** no need to develop special tools, moulds or dies.
- **One-off-a-kind functional parts:**
The present material characteristics (strength, elasticity, etc.) allow to produce functional parts as well, rather than prototypes of reduced strength.
- **Small series of parts:**
This mainly applies to plastic products, where the break-even point justifying a mould still requires series of several thousands of components. Series in the order of several tens or hundreds can be produced economically by material incress techniques [49], mainly when different parts are produced simultaneously. The latter allows to divide the relative long layer formation time over several products.
- **Soft tools and other derived applications:**
Many processes proved to be very suited for producing

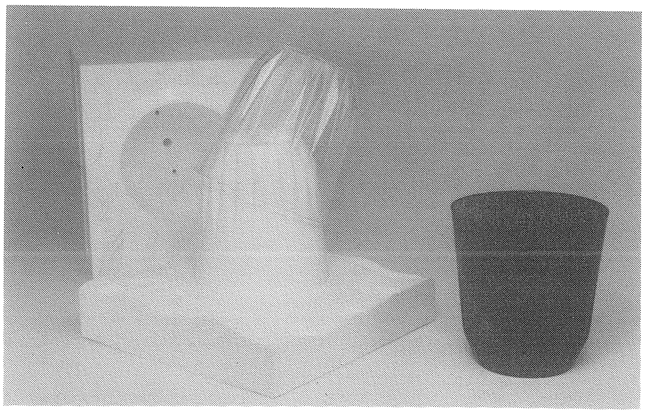


Fig.20. Silicone mould made from stereolithography model of cup wall thicknes 0.6 mm.

wax models for investment casting: stereolithography, ballistic particle manufacturing, selective laser sintering, fused deposition modeling and other polymer-based processes. Several companies also use stereolithography models to produce small-series injection moulds (Fig. 20) [49] made from silicone [38], epoxy or ceramics [52]. The silicone, epoxy or ceramic powder is cast around the stereolithography model in order to form a mould. The mould is then split in two and the model is removed, leaving the desired mould cavity behind. Those low cost moulds can be produced in a couple of days and may be used for thermoplastic moulding of few tens to hundreds of components. Plastic injection moulding in silicone moulds has to be done on vacuum injection machines.
Several derived applications are based on metal spraying of stereolithography models. Spraying the model with metal alloy (Kirskite or Zinc alloy) allows to produce a hard shell which, when backed with epoxy in an aluminium dieblock, forms a die cavity suited for 1000 to 2000 injections [6]. Stereolithography also found applications to produce EDM electrodes. Graphite electrodes can be shaped with abrading dies on orbital presses. The abrading die consists of a stereolithography model covered with a silicon-carbide bearing epoxy [27. Studies to use copper coated models as EDM electrodes were envisioned (BRITE-INSTANTCAM project [8]).

- Models for non-engineering applications:
The capabilities of rapid prototyping makes it very suited for all kind of model making applications. The Academic Hospital of Leuven uses CT-scan images to produce skeleton models prior to operations. Other examples involve wind-tunnel models [29], architectural etc.

CONCLUSION

A set of new and promising manufacturing techniques are breaking through. They are based on material deposition instead of material removal or deformation (forming). It is not yet possible to evaluate the full insidence of those techniques on the manufacturing and engineering environment. However, it will undoubtedly revolutionize the present design and manufacturing practise in a wide range of applications. A lot of research, development and standardization (a.o. nomenclature) work is still needed to bring those techniques to maturity.

REFERENCES

1. André, e.a., 1990, "Synthèse de formes par laser", Les microtechniques dans l'Industrie, Micronora 90, Besançon, September 19-20, p.115-136.
2. André, J.C., e.a., 1991, "Computer aided manufacture of three dimensional objects", to be published, J. of Intelligent & Robotic System.
3. Andre, J.C., Grisoni, B., Corbet, A., 1986, "Polymérisation induite thermiquement", French patent 86 02 237 (20.02.86).
4. Arita, K., 1991, "Development and application of optical stereolithography for the big size model introducing solid creation system of Sony", 2nd Int. Conf. on Rapid Prototyping, p.23-38.
5. Ashley, S., 1991, "Rapid Prototyping Systems", Mechanical Engineering, April, p.34-43.
6. Bak, D.J., 1990, "Quick path to prototype tooling", Design News, June 25.
7. Benedict, G.F., 1989, "Stereolithography - the new design tool for the 1990s", Proc. 6th Int. Conf. Lasers in Manufacturing, p.249-261.
8. Bjorke, O., 1991, "How to make stereolithography into a practical tool for tool production", CIRP Annals, Vol.40/1, p.1-12.
9. Brody, I.H., 1983, "Laser Sculpts Molds for Complex Parts", High Technology, Aug., p. 70-71.
10. Crump, S., 1991, "Fused Deposition Modeling (FDM): Putting Rapid Back in Prototyping", 2nd Int. Conf. on Rapid Prototyping, p.358-361.
11. Deckard, C.R., Beaman ,J.J., 1987, "Solid freeform fabrication and selective powder sintering", Proc., 15th NAMRC-SME.
12. Doyle, Th.E., 1990, "Shape melting technology", Nat. Conf. on Rapid Prototyping, p.55-62.
13. DTM Corp., 1990, "The Selective Laser Sintering Process, Third Generation DeskTop Manufacturing", Nat. Conf. on Rapid Prototyping, p.5-10.
14. Fan, R. N., 1990, "A Unique photoliquid for SOMOS solid modeling application.", Nat. Conf. on Rapid Prototyping, p.87-91.
15. Feygin, M., 1990, "Laminated Object Manufacturing", Nat. Conf. on Rapid Prototyping, p.63-65.
16. Feygin, M., 1991, "LOM system goes into Production", 2nd Int. Conf. on Rapid Prototyping, p.351-357.
17. Fudim, E.V., 1986 ,"Sculpting Parts with Light", Machine Design, March 6, p.102-106.
18. Fudim, E.V., 1990, "Fast accurate prototyping by simultaneous irradiation of whole layers of constrained polymer", Nat. Conf. on Rapid Prototyping, p.23-30.
19. Fudim, E.V., 1991, "Three-dimensional prototyping by simultaneous contact imaging of whole slices", Nat. Computer Graphics Association Conf., Chicago, April.
20. Fudim, E.V., 1991, "Photosoldification of Three-Dimensional Objects by simultanious contact imaging of whole layers of Photopolymer", 2nd Int. Conf. on Rapid Prototyping, p.369-381.
21. Fussell, P.S., Weiss, L.E., 1990, "Steel shape Fabrication by Spray Deposition", Nat. Conf. on Rapid Prototyping, p.49-53.
22. Gargiulo, E., e.a., 1991 "Stereolithography Process Accuracy User Experience", 2nd Int. Conf. on Rapid Prototyping, p.311-325.
23. Heirbaut, W., 1989, "Prototypes zonder werktuigbouw", Industrie Magazine, Oct., p.3-7.
24. Heller, T.B., 1990, "Rapid Modeling using visible-light lasers", Nat. Conf. on Rapid Prototyping", p.19-22.
25. Hirsch, J.L., 1990, "Du Pont SOMOS Solid Imaging System", Nat. Conf. on Rapid Prototyping", p.11.
26. Hull, C., 1991 "Rapid prototyping in the 1990's", 2nd Int. Conf. on Rapid Prototyping, p.211-218.
27. Hull, C., 1991, "Stereolithography : looking forward - looking back", The Slate, Januari 1991, p.1.
28. Hunziker, M., Bernhard, P., 1990, "Development of Resin Systems for StereoLithography: Holographic Cure Monitoring", Nat. Conf. on Rapid Prototyping", p.79-81.
29. Jamieson, R., 1990, "New options in aerodynamic modelling: CAD, CFD, stereolithography and shading in a workstation environment", Computer-Aided Engineering Journal,June, p.75-79.
30. Kobayashi, A., 1991, "Application of Solid Creator system of Engine Components Design", 2nd Int. Conf. on Rapid Prototyping, p.334-341.
31. Kodama H., 1981, "Automatic Method for Fabricating a Three-Dimensional Plastic Model with Photo-Hardening Polymer, Rev.Sci. Instrum., 52(11), Nov, p.1170-1773.
32. Kruth, J.P., Van Brussel, H., Pauwels, J., Van Rickstal, F., 1991, "Karakteriseren van het Mechanisch en Fysisch gedrag .. van het Stereolithografisch Process", Thesis 91EP18, K.U.Leuven, Belgium.
33. Kunieda, K., e.a., 1989, "Laser Application to Die Making - Laminated injection Molds by Bonding Laser Cut Sheets", Proc. of Intern. Symp. for Electro-Machining (ISEM-9).
34. Lumbye, K., 1990, "Desk Top Manufacturing, The next Industrial Revolution", Report of BRITE/EURAM project Instantcam, DTI, Denmark.
35. Masters, W.E., 1990, "The ballistic particle manufacturing process", Nat. Conf. on Rapid Prototyping", p.39-48.
36. Medler, D.K., 1990, "Stereolithography : a primer", Atomitive Eng., vol.98/12, Dec.,p39-41.
37. Miller B., 1991, "Fast prototyping makes models sooner and better", Plastic world, Feb., p.44-47.
38. Mueller, T., 1991 "Applications of Stereolithography in Injection Molding", 2nd Int. Conf. on Rapid Prototyping, p.327-333.
39. Murphy., E.J., Krajewski, J.J., 1990, "Some characteristics of steric polymerization", Nat. Conf. on Rapid Prototyping, p.67-71.
40. Nakagawa, T., Kunieda, M., Liu, S., 1985, "Laser Cut Sheet Laminated Forming Dies by Diffusion Bonding", Proc. 25th MTDR Conf., Birmingham, p.505-510.
41. Nutt, K., "The Selective Laser Sintering Process", DTM Corp.,Austin, Texas.
42. Pomerantz I, 1990, "Precision and resolution in physical imaging", Nat. Conf. on Rapid Prototyping", p.31-34.
43. Richardson, K.E., 1991, " The Production of wax models by the ballistic particle manufacturing process", 2nd Conf. on Rapid Prototyping, p.15-22.
44. Richter, J., Dr.Jacobs, P., 1991, "The present state of accuracy in stereolithography", 2nd Int. Conf. on Rapid Prototyping, p.269-293.
45. Sachs, E., e.a., 1990, "Three Dimensional Printing: Ceramic Tooling and Parts Directly From a CAD Model", Nat. Conf. on Rapid Prototyping , p.35-37.
46. Sachs, E., e.a., 1991, "Three dimensional Printing: Ceramic shells and cores for casting and other applications", 2nd Int. Conf. on Rapid Prototyping, p.39-53.
47. Sachs, E., Cima, M., Cornie, J., 1990, "Three-Dimensional Printing: Rapid Tooling and Prototypes Directly from a CAD Model.", CIRP Annals, vol.39/1, p.201-204.
48. Schätti, T., 1991, "Rapid prototyping etabliert sich", Technische Rundschau, 20/91, p.36-43.
49. Van der Schueren, B., Kruth, J.P., 1991, "Stereolithografie een materiaalgroeitechniek", MB-Produktietechniek, Jrg.57, Nr.7/8, July/August
50. VanPutte, D., 1991, "A Study of stereolithography uniformity and repeatability", 2nd Int. Conf. on Rapid Prototyping, p.295-309.
51. Visman, R., 1991, "Private Communication".
52. Wise, S., 1991, "Chemically Bonded Ceramic Tooling for Rapid Prototyping", 2nd Int. Conf. on Rapid Prototyping, p.152-161.
53. Wohlers, T.T., 1991, "Make fiction Fact Fast", Manufacturing Engineering, March, p.44-49.
54. -, 1990, "3D Prototypes Shot from Nozzle", Machine Design, June 21, P.60-62.