A comparative study of rapid prototyping techniques

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This paper provides a comparative study of Rapid prototyping techniques presently available in industry and/or under development in research laboratories. These techniques emerged during the last decade with the purpose of building physical models of products in the shortest possible time. These models are used for early verification of product designs and quick production of prototypes for testing. A CAD graphic model of the prototype model is sliced into layers and a post processor translates the boundaries of these layers into equivalent movements of servo drives of a rapid prototyping machine. Rapid prototyping technologies are based on manufacturing processes that are mainly additive in nature. These processes build models by joining particles or layers of raw material rather than machining or forming it; they are based on the layer-manufacturing concept. The components of rapid prototyping systems and their interrelations are reviewed while shedding light on the advantages, disadvantages, applicability and limitations of these techniques.

تقدم هذه الورقة البحثية دراسة مقارنة لأساليب النمذجة السريعة المطبقة حاليا بالصناعة أو التي مازالت في طور التطوير بالمؤسسات العلمية المختلفة. أساليب النمذجة السريعة تطورت خلال العقد السابق بسرعة كبيرة بهدف بناء نماذج للمنتجات في وقت قصير. هذه النماذج ضرورية لاختبار المنتج في مراحل التصميم وتحت ظروف التشغيل المختلفة. تبدأ عملية النمذجة السريعة ببناء النموذج على الحاسب باستخدام برامج التصميم والرسم ثم يتم تقسيم النموذج إلى شرائح وتعرف كل شريحة من خلال حدودها. تم تحول المعلومات عن حدود الشرائح إلى حركات مكافئة على أنظمة الحركة لما كنيات النمذجة السريعة. وتقوم الورقة البحثية بدراسة أنظمة النمذجة السريعة من حيث طبيعة تكوينها وتلقى الضوء على مميزات وعيوب أساليب النمذجة السريعة المختلفة.

Keywords: Rapid prototyping, Layered manufacturing, CAD modeling, Stereolithography.

1. Introduction

Manufacturing processes fall mainly into two main categories: subtractive and compressive. In a subtractive process, a block of material is carved out to produce the desired shape. A compressive process forces a semi-solid or liquid material into the desired shape, and then the material is processed to harden or solidify. Most conventional manufacturing processes fall into the subtractive category. They include machining processes such as CNC and high speed milling, turning and grinding. Machining processes are not suitable for manufacturing parts with very small internal cavities or complex geometry. Compressive processes include casting and molding. They are suitable mainly for high production rates when tight product tolerances are not needed [1-5].

Rapid prototyping (RP) is a group of modern manufacturing technologies that are used to generate a three dimensional prototype of a product from a CAD representation of the product. These technologies are also referred to as Solid Free Form fabrication (SFF). RP technologies involve manufacturing processes that are additive in nature, that is an object is built by joining particles or layers of raw material rather than machining or forming it [6-8].

RP technologies emerged in 1987 with the presentation of the concept of layered manufacturing by Charies Hall of 3D Systems Incorporation. Since then, RP technologies have been improving and several RP systems

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were commercialized. The principle of layered manufacturing is that a solid 3D CAD model of an object is sliced into several cross-sectional layer representations [9]. This is performed in the process planner of a RP system. A post processor then generates trajectories for guiding the RP process to physically build up these layers on a rapid prototyping machine. A RP machine is basically a CNC system capable of interpreting the motion commands generated by the post processor. The RP process also joints layers together to form the object. Supporting layers (support structure) are also simultaneously built up as fixture to the object [1].

RP technologies have four important attributes; first, they can build complex 3D geometrical shapes. Second, the process planning is automated, based on a CAD model. Third, they use a generic fabrication machine, i.e. do not require part-specific tooling. Fourth, they require minimal or no human intervention to operate. They have two main advantages; the first one is the ability to manufacture a prototype that has a complex geometry. The second one is to generate the prototype accurately in a short time at minimum cost. Rapid prototyping research seeks enhancing these advantages by focusing on improving the fabrication speed, part dimensional and geometrical accuracy, and material selection [10].

In the following section, rapid prototyping techniques are classified according to the raw material used for the RP process and according to the way in which model is built. In section 3, the common RP processes are reviewed. In section 4, recent trends in RP are highlighted. In section 5 a comparison of RP techniques is provided. In section 6, the components of a RP system are analyzed. Discussions and conclusions are given in section 7.

2. Classification of RP techniques

There are two possible classifications of rapid prototyping (RP) techniques. The first classification relates to the state of raw material when applied for building the model. The second classification relates to the way in which the model is built. These classifications are highlighted in the following different subsections [10].

2.1. Classification according to the raw material

Raw material can be applied in three different states; liquid, powder, or solid. Techniques that employ liquid raw material can be further classified into two groups. In the first group, liquid polymers are employed as raw material. These polymers solidify by impact of light, lasers (Stereo-lithography, and Interference Solidification) or by heating (Thermal Polymerization). In the second group raw material, such as plastics or resins, is melted, applied in a liquid state and then left to solidifiy to form the model. (Shape Melting, Fused Deposition Modeling, and Ballistic Particle Manufacturing).

Powder raw materials are usually applied in the form of tiny grains. The grains are bounded by melting the grain contact area by laser (Selective Laser sintering), or by gluing the grains together by selectively adding a binder (3D Printing). More than one type of powder can be mixed and applied.

Solid material are usually applied in the form of thin foils which are welded or glued on top of each other to produce the required shape (Laminated Object Manufacturing). Semi-polymerized plastic foils can also be used. The foils are bounded together by photo-polymerization (Foil Polymerization).

2.2. Classification according to shape building

Building up the shape can be done directly in 3D space. However, most techniques build up parts in successive 2D layers created on top of each other. The 2D layers technique of shape building depends on tracking a CAD model of the part and slicing it into a number of layers. Lower layers have to be created first before the top ones. A single layer can be created at once (layer-by-layer – one layer at a time) such as (Laminated Object Manufacturing, and Stereo-lithography). Most processes, however, create a solid layer by scanning and solidifying it in a point-by-point technique. This scanning can be done in a continuous mode (Fused Deposition Modeling and 3D Printing) or discrete (Stereo-lithography, Thermal Polymerization, Foil Polymerization, and Selective Laser Sintering) [10].

Direct 3D techniques do not require the lower part of a product to be created before a higher part. This gives more flexibility in shape creation. For 3D techniques, distinction can be made between processes creating a whole 3D surface at once (surface-by-surface manufacturing) such as (Holographic Interference Solidification) and those producing the object point-by-point in a continuous (Fused Deposition Modeling, and Shape Melting) or discrete mode (Beam Interference Solidification, and Ballistic Particle Manufacturing) [10, 11].

3. Overview of RP techniques

In this section the most widely used RP technologies are presented, following the classification of RP techniques based on the raw material.

3.1. Liquid-based techniques

There are at least eight technologies that involve the solidification of liquid-based materials. Five technologies depend on solidifying a liquid polymer by the effect of light or laser or by thermal effect in order to create the model. The other three technologies are based on melting, deposition and re-solidification of plastic or resin material.

3.1.1. Stereo-lithography

Stereo-lithography (SL) is the most widely used rapid prototyping techniques. Using this technique, it is possible to build 3D physical models of parts with complex geometry in a very short time. The accuracy and resolution of the models are high. Stereo-lithography was developed commercially by 3D Systems, Inc. (Valencia, California, USA) and first patented in 1987 [12].

The stereo-lithography technique is based on the principle of curing a photo-polymer into a specific shape. The system consists of four main components; they are: slicing software, the 3D control system, the process chamber, and the laser unit. The slicing software reads a triangulated CAD model of the prototype and cuts it into thin slices. The thickness of a slice can be selected from the software and it depends mainly on the resolution of the mechanical movements of the RP system and the geometry of the part. Slices can have different thickness. The output of the slicing software is then directed to the control computer, which generates corresponding translations and rotations of the mechanical components of the RP system. The process chamber is the heart of the RP system. It contains a mechanism by which an elevator like platform can be lowered and raised vertically and filled with a photosensitive liquid polymer. The laser unit generates an ultraviolet laser beam that scans the cross-sectional area of the surface following the contours of the slices obtained from the slicing software [10, 13-16].

A schematic diagram of a SL system is shown in fig.1. When the platform is at its highest position, the layer of liquid above it is shallow. A laser beam, reflected on a mirror, scans the selected surface area of the photo-polymer. The beam moves in x-y directions when the angle of the reflecting mirror changes. The beam cures the scanned portion of the polymer producing a solid section. The platform is then lowered so that a shallow layer of the liquid polymer covers the cured polymer. Then, the sequence is repeated to produce another section (layer) of the part. Upon part completion, the part is moved from the platform, cleaned using ultrasonic vibration with alcohol bath.

By controlling the movement of the laser beam and the platform through a servo-control system, a variety of parts can be formed by this process. Stereo-lithography models have wide range of application in the industry, which includes [13]:

- Visualization of products.
- Design and flow analysis tests.
- Prepare parts used for functional tests.
- Manufacturing of medical parts.

Today, there are about ten different developers of stereo-lithography systems. They all have the same basic principle but different system layouts.

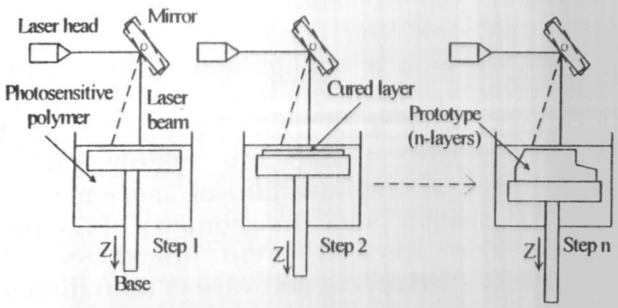

Fig. 1. Principle of operation of stereo-lithography systems [10].

3.1.2. *Holographic Interference Solidification (HIS)*

This technique is also based on photo-polymerization. The main idea of this technique is to project a holographic image of a model in a photosensitive liquid polymer chamber. The holographic image solidifies a whole 3D surface of the model at once. This saves prototyping time. This process was developed by Quadtec Pty Co. (Melbourne, Australia). The range of application of this process today is still limited for the production of copper electrodes of EDM, but progress in this field growing very fast [10].

3.1.3. *Beam Interference Solidification (BIS)*

This technique applies to a photosensitive liquid polymer in a chamber. Part creation is made by a point-by-point solidification of the liquid at the intersection of two laser beams, mounted at right angles, emitting light at different wave lengths (different frequencies). The first laser beam excites the liquid to a state that polymerizes upon impact of the second laser beam, fig. 2. [10].

This process was developed by Batelle and Formigraphic [10]. But, there are no industrial applications found for this method, because of some technical difficulties:

- Light absorption (drop of intensity with depth).
- Shadow effect from previously solidified parts.
- Diffraction effects caused by temperature gradient or solid sections.

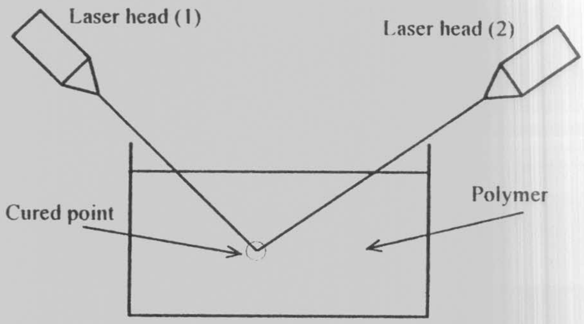

Fig. 2. Beam interference solidification technique [10].

3.1.4. *Solid Ground Curing (SGC)*

This rapid prototyping system was developed and commercialized by Cubital Ltd. (Israel). It uses a photo-polymer sensitive to UV-light. In this technique, a computer analyzes a CAD file and renders the object as a stack of slices. The image of the working slice is printed on a glass photo-mask using an electrostatic process similar to laser printing. That part of the slice representing solid material remains transparent[17]. A thin layer of photo-reactive polymer is laid down on the work surface and spread evenly. A UV light is projected through the photo-mask onto the newly spread layer of liquid polymer causing it to harden. The unaffected polymer, still liquid, is vacuumed off. Liquid wax is spread across the work area, filling the cavities previously occupied by the unexposed liquid polymer. A chilling plate hardens the wax. The entire layer, wax and polymer are now solid. Then the milling head mills the layer to the correct thickness. The process is repeated for the next slice, each layer adhering to the previous one, until the object is completely finished. Then the wax is removed by melting, revealing the finished prototype [13]. This technique is similar to the stereo-lithography. However, three differences can be seen they are:

- The polymer chamber moves horizontally as well as vertically. The horizontal movements take the workspace to different stations in the machine.
- The light source is an UV-lamp (mercury) that is used to flood the

chamber and expose and solidify the entire layer at once.

- The third difference is that the parts are surrounded by wax, eliminating the need for a support structure [17].

3.1.5. *Liquid Thermal Polymerization (LSP)*

This process is very similar to stereolithography. However, the type of polymer used (thermo-setter instead of photo-polymer) is different. Also, solidification is based on heat rather than impact of light or laser. Heat dissipation might cause problems to control the accuracy. Also, thermal shrinkage and distortion may be another problem [10].

3.1.6. *Fused Deposition Modeling (FDM)*

This technique depends on building up the model layer by layer by deposition of molten material onto a base plate or onto previously solidified material [18]. The FDM technique was commercialized by Stratasys, Inc. and first patented in 1992. In this technique, the model is built up layer-by-layer from a solid filament, 0.003 mm in diameter, of thermoplastic material. This filament if fed into the FDM machine through a controlled heat extrusion head, which liquefies the material, fig. 3. The system's operating software, 3D modeler, imports CAD file (.STL file). The software then orients the part for optimum build, slices the model and creates the paths for building the model. The extrusion head moves in the *x-y* axis, following the path created by the operating software, laying down a very thin layer of molten material. One layer upon another, the model is built from the bottom up, each layer bonding to the pervious after cooling [14]. The designed object is produced as a 3D-solid part in a single stage process without need for tooling. This process may, theoretically, be applied to any thermoplastic material. Parts built up of different materials or colors may even be produced easily.

Today, this system is able to work on four different materials:

- A wax-filled plastic adhesive material.
- ABS plastics.
- An investment casting wax.
- A tough nylon filament.

All materials used in connection with the FDM process are nontoxic materials. Stratasys, Inc. also developed an FDM system with two extrusion heads, one for the modeling material and the other for the support structure material, called "Quantum" designed for high throughput and superior quality modeling. High-speed electro-magnetic drives are used to rapidly and precisely move and control the FDM extrusion heads.

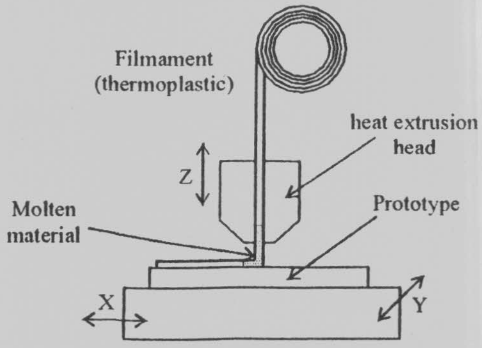

Fig. 3. Schematic diagram of the FDM technique [3].

3.1.7. *Multi-Jet Modeling (MJM)*

MJM builds models using a technique similar to inkjet or phase-change printing, applied in three dimensions. A printing head comprising 96 jets oriented in a linear array builds models in successive layers [13], each individual jet applying a specially developed thermo-polymer material only where necessary. The MJM head shuttles back and forth like a line printer (*X*-axis), building a single layer of what will soon be a 3-dimensional model. If the part is wider than the MJM head, the platform repositions (*Y*-axis) to continue building the layer. When the layer is complete, the platform is distanced from the head (*Z*-axis), and the head begins building the next layer. This process is continued until the concept model is complete. Fig. 4. depicts the principle of the MJM technique. This technique was developed by 3D Systems, Inc [1, 13].

MJM technology is an extremely efficient and economical way to create concept models. The large number of jets allows fast and continuous material deposition for maximum efficiency. And the inexpensive thermo-polymer material ensures cost-effective modeling.

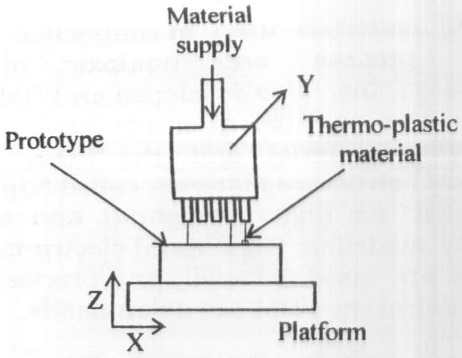

Fig. 4. Principle of MJM technology [13].

3.1.8. Ballistic Particle Manufacturing (BPP)

In Ballistic Particle prototyping, a stream of molten material is ejected from a nozzle. The material separates into droplets, which hit the substrate and immediately cold weld to form a part, fig.5. The stream may be a drop-on-demand system or a continuous jet. With a continuous jet, a piezoelectric transducer excites the nozzle at a frequency of about 60 Hz. Although a capillary stream will naturally decompose into droplets, the excitation forces the production of a stream of small, regular droplets with uniform spacing and distance. Using a low frequency carrier wave modulated by a higher-frequency disturbance, tailor-made streams can be produced where the user can specify larger droplet separations. BPM Technology, Inc. (USA) has developed this system of prototyping recently [10].

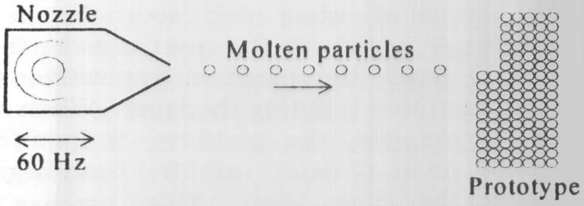

Fig. 5. Ballistic particle prototyping [10].

Parameters that will affect the eventual part characteristics are the temperature and velocity of the droplets and the electronic charge they acquire when the stream is ejected, which is used to guide the droplets to the surface. The maximum deflection of a drop is limited and the substrate or the jet must therefore be movable to allow a large enough build area. The temperature will control the speed at which the molten material solidifies; if the droplets are too cold they will solidify in flight and will not weld to the part. On the other hand if the droplets are too hot, the part will lose shape. The deformation and placement accuracy of the droplet depends on its velocity. This technique has already been applied for creating wax models for investment casting without the need for dies. A major advantage of ballistic particle manufacturing is that it allows applying different materials or colors within a single part [10].

3.2. Powder-based processes

There are two main classes of rapid prototyping techniques that build the part by joining powder grains together. In the first class, powder grains are welded together by the application of laser. In the second class, a binding material is used to connect powder grains.

3.2.1. Selective Laser Sintering (SLS)

SLS technique is a free-form fabrication process based on sintering of metallic or non-metallic powders selectively into an individual object. Fig. 6. Shows the SLS system developed by DTM INC., Texas, USA in 1992 [19- 21]. The bottom of the processing chamber is equipped with two cylinders; the powder cylinder and the prototype cylinder. The powder cylinder is raised incrementally to supply powder to the processing chamber. The roller mechanism moves the powder to the prototype cylinder, which is lowered step by step. A thin layer of powder is first deposited in the prototype cylinder. A CO_2 -laser beam, guided by process control computer and based on a 3-D CAD system of the part to be produced, is then focused on that layer, tracing and sintering a particular cross-section into a solid mass. The powder in other areas remains loose, and they support the sintered portion [21]. Another layer of powder is then deposited and the cycle is repeated. Successive cycles are repeated until the entire three-dimensional part is produced.

A variety of materials can be used in this process, including polymers (ABC, PVC, nylon, polyester, polystyrene, epoxy, wax, metals and ceramics with the appropriate binders). Its applications are similar to those for stereolithography.

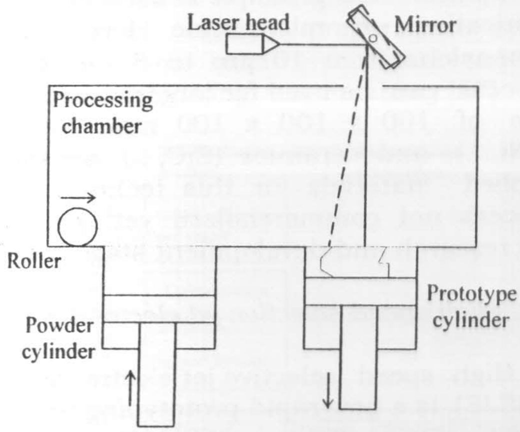

Fig. 6. Schematic diagram of the SLS technique [10].

3.2.2. Three-Dimensional Printing (3D Printing)

3D Printing is a rapid prototyping technique developed at the Massachusetts Institute of Technology (MIT) and patented in 1993. It is used for rapid and flexible production of prototype parts and tooling directly from a CAD model. 3D Printing works by building parts in layers [1]. First, a thin distribution of powder is spread over the surface of a piston in a cylinder. From a computer model of the desired part, CAD file, a slicing algorithm computes information for the layer. A nozzle jets a binder at the powder, similar to ink-jet printing, to connect its particles where the object is to be formed. The piston then lowers so that the next powder layer can be spread and selectively joined. This layer-by-layer process repeats until the part is completed. Following a heat treatment, unbound powder is removed, leaving the fabricated part. A schematic diagram of the 3D printing technique is shown in fig.7 [10,11].

In principle any material that can be obtained in powder form can be used in the construction of components and different binders are used depending on the powder being bonded. After printing a component is either fired or sintered to increase its structural strength. Ceramic molding for metal casting and tooling is one of the application areas for this technology. 3D Printing can be used as a means of tool-less production of any part that might ordinarily be made by forming processes. These include parts made of ceramics, and common metallic alloys [22].

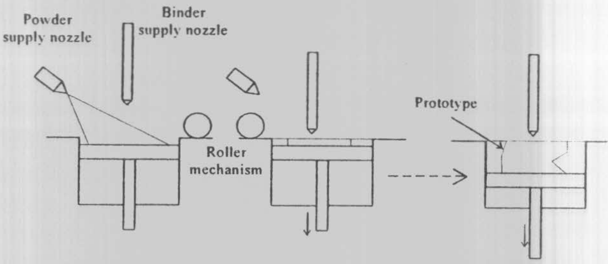

Fig. 7. Schematic diagram of the 3D printing technique [22].

3.3. Solid-based techniques

3.3.1. Solid Foil Polymerization (SFP)

This technique applies solid-to-solid polymerization, rather than liquid-to-solid. The part is built up using semi-polymerized plastic foils progressively stacked on top of each other. On exposure to Ultra Violet light, the semi-polymerized foil solidifies and bonds to the previous layer. The area of foil that do not constitute the eventual part are used to support it during the build process, but remains soluble and so are easy to remove once the part is complete. No commercial systems are available for this technique yet [13].

3.3.2. Laminated Object Manufacturing (LOM)

Laminated models are constructed from adhesive foils. They bond under the application of heat. With this method the build material is cut rather than cured or fused. A CO_2 -laser is used to cut the foils. fig. 8. shows a schematic diagram of LOM technique. The adhesive foil is fed into the working area via two rollers, 1 and 2. A laser beam then follows a contour corresponding to a layer of the prototype to separate it from the foil. Then a heated roller is passed over the foil. Heat and pressure are used to bond the separated foil to the previous layer of the prototype. Then the tray is lowered and adhesive foil is fed to the working area. The process continues until the prototype is complete [10]. Virtually, any foil material can be applied: paper, metals, plastics, fabrics, synthetic materials, and composites. Helisys, Inc. first commercialized the Laminated Object Manufacturing (LOM) method in 1992 [23].

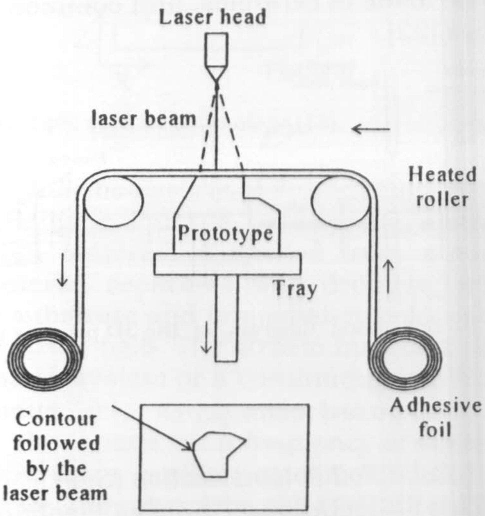

Fig. 8. Principle of LOM process [10].

4. New trends in rapid prototyping

Because of the growing trends towards concurrent engineering, the development of rapid prototyping techniques for metallic parts is looked forward. This is because metallic prototypes would allow check not only for geometry but also for the design of the product. This means that the product designer can check product for mechanical properties, ability to withstand complex stresses and strains during an early stage in the development of the product. As a result, a considerable research work has been and still being conducted to develop RP techniques for producing metallic models.

4.1. Selective Laser Chemical Vapor Deposition (SLCVD)

The Max Planck Institute in Gottingen (Germany) and the Texas University in Austin (USA) both developed a new rapid prototyping process derived from the Laser Chemical Vapor Deposition process (LCVD). The process is called Selective Area Laser Deposition (SALD). The process starts from a gas mixture that contains a complex combination of the material to be deposited. A scanning laser beam activates local thermal of photodecomposition of the gas into the elements of interest that are fixed onto the workpiece. This principle is used for free-form fabrication on micro-scale level with part dimensions from 10 μm to 5 mm. Also, this process can be used for larger structures of a size of 100 x 100 x 100 mm. Metals (Al, FeNi,...), and ceramics (SiC,...) are the most applied materials for this technique. This process not commercialized yet, and still in the research and development stage [24, 25].

4.2. High speed selective jet electro-deposition

High speed selective jet electro-deposition (HSSJE) is a new rapid prototyping technique, which can produce metal parts by electro-deposition of metal using high velocity jet of a suitable plating electrolyte (Copper nitrate aqueous solution) from a small diameter nozzle. By moving the nozzle under computer control, patterns may be directly written from CAD file, Bocking et al. (1995) applied the jet system to the rapid prototyping of electrodes in the EDM process and injection molding tools using electro-deposition of copper. The electrolyte jet discharged from a nozzle scans the cathode surface to electro-deposit metal ions, which are dissolved in the electrolyte. The metal ions are consequently electro-deposited on the cathode surface. Since the formed part is free from residual stress or pores, no sintering or post curing process is required [26].

5. Comparison of RP techniques

Table 1 compares various processes used by RP systems. The comparison is mainly in terms of advantages, limitations, applications.

6. Components of a RP system

A RP system comprises three main sections: They are; geometric model preparation, SFF fabrication and physical model preparation. The geometric model preparation is software based. It comprises three subsections; geometric data creation, model validity and repair and data exchange. The SFF fabrication section has two software-based sections and one hardware section. The software based sections are; compensation and support structure. The hardware section is the physical RP process. The physical model preparation section comprises two hardware based sections; physical model curing and finishing [27].

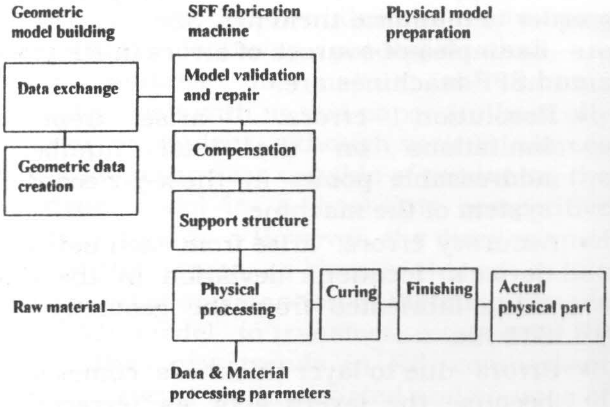

Fig. 9. Components of a RP system.

6.1. Geometric data creation

The first step in rapid prototyping a product is the creation of a geometric model that represents the product. The model can be created using a generic CAD system or a solid modeler. The model can be built as a 3D solid. However, it can be also built as 2D slices using a scanning device. In either case, the data must represent a valid geometric model. The model is valid only if for each point in 3D space it is possible to determine whether that point lies inside, on, or outside the boundary surface of the model. The simplest scheme for a data format is to represent the solid as a sequence of surfaces. A surface is represented as a sequence of triangular elements, facets, with no regard to order or topology. A triangular element is represented as a sequence of its three vertices and its outward (from the surface) pointing normal vector, defined according to the right hand rule by the order of the vertex sequence. This representation, along with its data types, delimiters, and other file information is called the STL format [28-30].

6.2. Data exchange

CAD systems utilize a variety of geometric mathematical representations and data formats. Mathematical representations include Bezier, non-uniform rational B-spline (NURBS), coons patch, Gordon patch, planer patch, and cycloid. Data formats include HPGL, DXF, SLC and STL. CAD vendors are responsible for providing CAD post-processors that translate their internal CAD mathematical representations into different data formats. The STL (Stereo lithography Interface) data format is usually accepted by RP systems and is the standard for RP processes. STL data format has two representations; ASCII representation and the binary representation. Both describe the coordinates of three points that form a triangle in space and its associated normal. The binary format results in much smaller file size, whereas the ASCII format can be read and visually checked. The binary format which is almost exclusively used due to the file size and speed of transfer, was described in ref. [29] and is as follows: The header record consists of 84 bytes, the first eighty are used for information about the file, author's name and other miscellaneous comments, the last 4 bytes represents the number of triangular facet, then the x, y, and z coordinates of each vertex of the triangle. 4 bytes are used for each coordinate, resulting is 48 bytes per facet. The last two bytes are not used.

6.3. Model validity and repair

CAD post-processors usually approximate the internal CAD geometric entities by triangular facets, which in turn are expressed in a specified data formats, STL. This approximation can introduce geometrical anomalies. For example, if spatial sampling is done too grossly, then small local features and local surface curvatures are lost. As a result, a boundary of a 2D layer may become incomplete, open. This condition, in turn, generates an erroneous control signal to a laser beam or other solidifying agent, causing the agent to continue solidifying material until it reaches the wall of the material container, thus fabricating a thin ray of material emanating from the part and producing waste. RP systems have software to check the input model to ensure it is a valid solid. If this is not the case, then capabilities are needed to repair the model.

6.4. Compensation

Given a valid model, a series of geometric operations must be performed on the model (model preparation) to ensure that the physical part will meet the input specifications. For example, the model needs to be oriented and scaled for the SFF machine workspace. The orientation depends on factors relating to surface quality, build time, support structures, downstream processing characteristics (shrinkage, curling, distortion, resin flow), and parts tolerance [33].

6.5. Support structure

Support structures are needed in liquid-based processes to support overhanging portions of the 3D part, to attach the part to the workplace platform, and to internally buttress hollow parts. Parts and supports may need drain holes. Support locations for overhangs can be determined by checking the direction of surface normal and by z-axis projections of the model. Software exists to automatically generate support structures that attempt to use the least possible amount of material. Powder and solid-based processes use the surrounding unprocessed material for support.

Using a manufacturing interpretation. SFF software can be categorized as the following types: (1) Design (original part); (2) Computer-aided process planning (part orientation, scaling, nesting, support design, compensation); and (3) Computer-aided manufacturing programming (slicing, commands, and control) [1].

7. Sources of errors in RP parts

Manufacturing processes are approximate. They can produce parts only within tolerances. No part geometry can ever be produced exactly according to absolute exact specifications. Additive processes are worse than typical subtractive processes. This is because RP processes are usually followed by curing operation or suffer from shrinkage and curling even during processing. Therefore, it is a good idea to be familiar with the sources of the approximation errors in RP processes in order to minimize them [31, 33].

Examples of sources of errors in RP process and SFF machines are:

- Resolution errors: arise from the limitations on the total number of addressable points in the x-y-z coordinate system of the machine.
- Accuracy errors: arise from each individual device's location deviation in the object being fabricated from the geometry in the STL file.
- Errors due to layer thickness: comes about because the layers acts as "terraces" and stair-steps give the surface a roughness it was not supposed to have. This is very similar to the familiar computer graphics aliasing problems. However, whereas artifacts can be fixed by blending in surrounding pixels, no analogous process exists for fabrication. This means that shallow surfaces (in the fabrication coordinate system) will have rougher-feeling surfaces than will steeper surfaces. Indeed, this is one of the things we look for in a part before fabricating it. We oftentimes will rotate a part before fabrication to gain a more a favorable orientation.
- Post-Processing errors: arise from each RP technology's post-fabrication characteristics. For example, Stereolithography parts might warp during the curing process or might sag if exposed to too much heat. LOM parts might change shape by absorbing moisture if not properly sealed.
- Some errors occur due to the preparation of the STL file.
- Insufficient triangulation: happens when not enough triangles are used to

approximate the curved surfaces. The control of the number of triangles is usually a parameter that is left to the discretion of the user. Too few triangles results in a model, whose curved surfaces feel crude, not smooth [10].

8. Concluding remarks

Rapid prototyping (RP) techniques represent a group of modern manufacturing methods that can be used to generate a three dimensional prototype solid model from a CAD model. It was shown that RP techniques involve manufacturing processes that are mainly additive in nature, the various methods dealt with in this paper are basically material dependent, although various sources of energy/setup are capable of producing the prototype model in a short time, competitive cost and quality. However, the discussion of various techniques, as given in this paper has also included explaination of the main phases of a CAD model to transform into a solid RP model, the new trends in RP, comparison between several methods listed and sources of errors in the final model.

It is rather interesting to seek the effective measures of assessing how to adopt and implent RP technology to suit needs of scarce finance and/or expertise to use a certain machinery or set up. This of course needs a lot of data and analysis that seems to be necessary to elaborate further in a future work.

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