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REVIEW ARTICLE

New Approaches in Computer Aided Printing Technologies

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A B S T R A C T

CAD/CAM technology which entered dentistry in the 1980s has provided new developments in various areas. The demands of patients which moved away from standardized to customized products have initiated a new era in computer-aided manufacturing. For the fabrication of a physical prototype in dentistry, three approaches have been identified: Additive Technique, Subtractive Technique and Hybrid Technique. Within these techniques, additive manufacturing has arisen due to its advantages such as arbitrarily manufacturing of complex customized geometries with low volume. In addition to this, additive techniques have minimized the amount of waste material by increasing efficiency. In this way, additive manufacturing that refers to the manufacturing of parts in an additive or layer by layer manner, plays a crucial role in today's dentistry. This review aims the investigation of different computer-assisted manufacturing techniques which are routinely used in dentistry and to evaluate their systematic advantages and disadvantages.

Keywords: CAD/CAM; Additive Manufacturing; Customized Manufacturing.

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INTRODUCTION

The foundation for the automated manufacturing of prosthetic restorations was laid by the *Computer Aided Design (CAD)/Computer Aided Manufacturing (CAM)* systems introduced in the dentistry in 1980s. Increased demands of patients in terms of the life of the restorations, their biological fit and aesthetic specifications enabled the development of the CAD/CAM systems.[1-3]

Three different approaches are used for the manufacturing of a physical prototype in terms of both industry and medicine: Subtractive method, additive method and hybrid method.[4] Within these techniques, additive manufacturing has arisen due to its advantages such as arbitrarily manufacturing of complex customized geometries with low volume. In addition to this, additive techniques have minimized the amount of waste material by increasing efficiency.

SUBTRACTIVE METHOD

Subtractive method is also called milling technique.[5,6] The restoration manufacturing to be formed in this method is based on the principle of obtaining by block milling. However, wasting a large number of materials is in question. This is because an average of 90% of a prefabricated block is used in order to form a typical restoration and every time approximately 10% of the block is wasted. Moreover, the 10% residue cannot be recycled.[4-6] More than 20 milling systems have been developed from past to present and these systems have been categorized into 2 basic groups as hard machining and soft machining.[7]

In the hard machining method, which is defined as obtaining the restoration milled from sintered block, densely sintered non-porous ingots are used. Carrying out milling process in this method is extremely difficult. However, they do not need to be subjected to sintering process again. Soft machining is defined as the process of obtaining restoration milled from the subsequently sintered block. Ingots are porous in pre-sinterized form, which allows a fast milling process. They must be subject to repeating sintering process in order to eliminate the porous structure.[7,8]

As both systems are subtractive methods, the greatest disadvantage of both systems is wasting a considerable amount of materials. This is because the wasted parts are not used any more after the milling process and it is not possible to recycle such material any longer. While the restorations manufactured by hard machining method have advantages such as accurate shape and dimensions, they also have certain disadvantages such as the high cost of processing sintered ceramics and the time consumption during process. Furthermore, the tools used in this method are exposed to heavy abrasion, because the milling procedure is not performed prior to sintering. In addition, it is risky that microscopic fractures may appear on the surface of the ceramic material during hard machining. This problem does not occur during soft machining, as milling is performed before the sintering process. Moreover, milling the white post-sinterized monoblocks (softer than pre-sinterized monoblocks) reduces the processing time and enables the tool to have a longer use cycle. The accuracy of the structure and shape of restorations manufactured by soft machining method is a more problematic issue compared to hard machining. The reason for this is shrinkage which will occur during the sintering which will be carried out later.[7,9,10]

Although the subtractive methods are clinically widely used, the additive manufacturing methods which have significant advantages and advanced features are rapidly developing.

ADDITIVE METHOD

Additive manufacturing systems are defined as systems which allow the manufacturing of a 3-dimensionally designed (CAD) object with the computer-aided systems by adding layer over another layer.[5,11-13] Additive manufacturing is defined by *American Society for Testing and Materials (ASTM)* as follows:

"*It is the process merging the materials by stratification (adding layer upon layer), in contrast with subtractive manufacturing methods, in order to manufacture objects by the computer data of the three-dimensional model."*

The additive manufacturing system which is widely used in dentistry nowadays can also be defined as 3D printing, additive fabrication, rapid prototyping, layered manufacturing or solid freeform fabrication.[5,11-14] The additive method, taking its name from rapid prototyping/manufacturing, first used in 1980s' in order to manufacture the prototypes, models and printing elements.

Although the additive systems have different operating cycles, they generally have 5 common stages. These stages are:

- forming the CAD model
- transforming CAD model data to stereolithography (STL) file
- slicing STL model mathematically into layers
- carrying out manufacturing layer by layer
- carrying out additional processes following the completion of manufacturing[5]

The idea that the additive manufacturing is a great opportunity for dentistry was emerged over the time and its use was spread quickly in the dental field. The techniques which are widely used in engineering and which have entered into routine use in dentistry are: *(i)*Stereolithography, *(ii)*Laminated Object Manufacturing Technique, *(iii)*Selective Laser Sintering, *(iv)*Selective Laser Melting, *(v)*Fused Deposition Modelling, *(vi)*Selective Electron Beam Melting and *(vii)*Multi-jet Solidification.[5,11-13,15-18]

1. Stereolithography Apparatus - SLA

SLA technique in which 3 dimensional models are manufactured by photosensitive polymer is the most widely used among the additive techniques.[19] The technique defined by Hull in 1984, systematically consists of 3 basic equipments: *(i)*Pool with a photosensitive liquid, *(ii)*Platform where the model is manufactured, *(iii)*Ultraviolet (UV) laser.[5,6,11,18]

When photopolymer resin is exposed to UV light, the first layer at a certain thickness hardens. Following the hardening of the first layer, the platform where the model is produced is lowered at a certain distance in the pool and a new layer of photopolymer resin is applied on the previous layer. The basic processes continue until the construction of the three-dimensional solid material (Figure 1) is completed. The self-adhesive feature of the material helps layers stick together. After the completion of the process, newly produced hard material is removed from the pool and kept in the UV cabinet for a while until the hardening process is completed.[5,6,11-13,16,18]

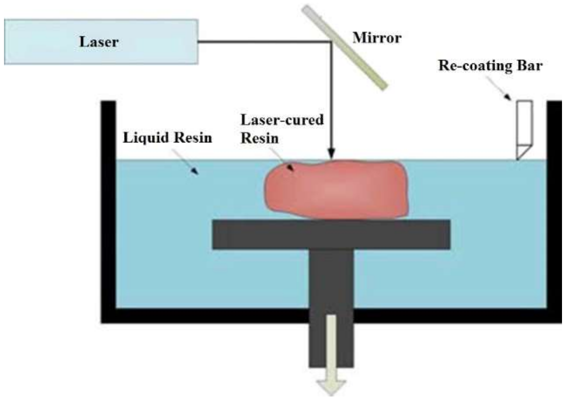

Figure 1: Stereolithography[13]

SLA, which has the basic advantages such as high accuracy, good surface finish, ability to carry out transparent model manufacturing, high mechanical resistance and well reflection of details, is routinely used in the fabrication of surgery guides which are important in the correct placement of the implants.[6,20-24] Surgery guides can be transparently manufactured by the SLA technique. This case allows the monitoring of all anatomic structures. However, SLA is an expensive technique in terms of both equipment and materials[22] and it has a limited material range (natural and synthetic polymers reinforced with ceramic and metallic powders, hydrogels). It is also regarded as a disadvantage that the technique requires an additional stage such as placing the material in the UV cabinet for a longer while after the completion of the process.[5,11-13,16]

2. Laminated Object Manufacturing - LOM

The LOM technique, in which the sheet-form material coated with a heat-sensitive adhesive, first used in 1986 by Helisys.[15,25] Studies are in progress for the availability of materials in different structures. In this technique, metals, papers, plastics, composites and synthetic materials can be used.[6,15,22]

It systematically includes both additive and subtractive techniques.[26] Layers are bonded together using thermal adhesive under application of heat and pressure. The material formed by using 3D CAD data and STL files is milled by 25-50 Watt carbon dioxide laser beam until the demanded form is obtained. The heat-sensitive adhesive becomes activated with the aid of hot rollers and it allows the new layer to stick together with the previous layer. The manufactured part must be sealed by urethane lacquer, liquid silicone or epoxy resin after the completion of the process depending on the water absorption in order to avoid any distortion. No additional support unit is needed as the waste part of the material serves the support function during the manufacturing stage. [6,15,19,22,26-28]

As the milling technique is used, a great amount of material is wasted. Manufacturing of structures with a complex internal geometry is quite difficult in this technique. However, it should be noted that the system has advantages such as low cost, avoiding deformation or phase changing during the process. In addition to these advantages, there is no need for the additional processing after the completion of the object and also no need for a support unit during manufacturing.[6,19,22,26]

3. Selective Laser Sintering – SLS

The selective laser sintering technique in which powder materials can be used and which allows the fusion of powder particles by carbon dioxide laser was defined for the first time in 1989 by Deckard. When the powder material distributed by rollers is exposed by laser beam, it melts selectively.[29] In other terms, it is sintered. A new layer is distributed on the platform downward in the form of a thick layer and the selectively melt (sintered) material is bonded to the previous layer by laser beam. Stages (Figure 2) are repeated until the final product is obtained.[5,18,19,22,26,30]

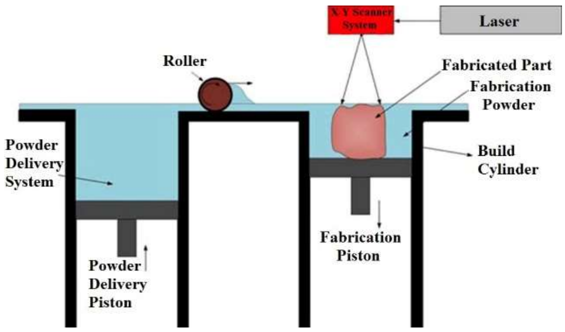

Figure 2: Selective Laser Sintering[13]

The heat applied by the laser during operation, should be kept below the material's melting point and heat should be sufficient to ensure that the particles of the material are sintered.[12,19,26] If the material is not completely melt but only sintered, it saves a huge amount of time. The technique with a wide range of materials does not need a support unit during the manufacturing.[19,22] Casting waxes, metals, ceramics, thermoplastic materials such as thermoplastic composites can be used in selective laser sintering. One of the most important features is that the material is recyclable and can be used again. This decreases the cost significantly.[12,19,26] As the objects are porous, extra material infiltration may be necessary in this technique.[19]

Although SLS is not as a successful technique as stereolithography in terms of surface finish and product accuracy; it allows a fast manufacturing of object.[19,31,32]

In order to minimize the complications in the system, a series of precautions have been taken. In such technique, all the manufacturing stages are carried out in a vacuum chamber. The aim here is to eliminate the difficulties such as humidity and oxidation.[33] Moreover, it should be noted that deterioration may occur in polymer properties depending on the size, speed of the laser beam or fluctuation in its power. Controlled use of the laser is important at this point.[34]

It must be emphasized that laser sintering eliminates many stages in laboratory such as waxing up and investing.[35] Therefore the technical complications which may occur during these stages are also eliminated.

4. Selective Laser Melting – SLM

The powder material is completely sintered and melted in selective laser melting technique and the molten pool is created. The system uses commercially available powder materials. Size of the particles may vary between 20-50 micrometres.[21,29,36]

The first bench-type SLM machine was manufactured in 2009. SLM technique is a technique carrying out productions by using laser. Therefore, problems such as shrinkage, cracks, distortion and surface hardening are expected in SLM technique as in all laser welding processes. In order to overcome all these, fine-grained powder materials are used and the process is carried out in a protective gas. Setting the diameter of the laser beam small (0.2-0.4 micrometers) and keeping the layer thickness thin (30 micrometers) minimize both stair type effect and the aforementioned risks such as shrinkage, distortion.[36]

The stair type effect is a result of slicing process and it is the most important parameter affecting the dimensional accuracy in manufacturing. The angle (β) formed by the tangent line to the surface with a vertical line can be calculated by the layer thickness (Figure 3).[28]

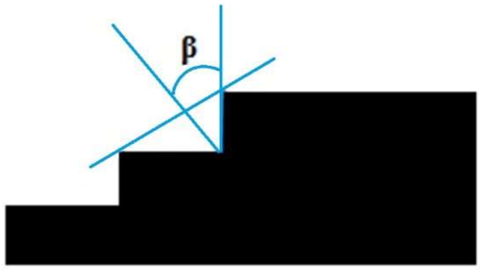

Figure 3: Stair Type Effect[28]

The STL model is sliced as vertical planes. Each slice reflects the cross-sectional data of the object to be produced. The layer thickness is defined as the distance between these planes. As the layer thickness increases, the duration of manufacturing decreases. It should be borne in mind that the stair type effect will increase in a directly proportional manner to the layer thickness. As the layer thickness decreases, smooth object manufacturing is performed. This is because the stair type effect will decrease in such case. However, the manufacturing duration of the object will prolong.[28]

5. Fused Deposition Modelling – FDM

Fused deposition modelling technique is the second widely used fast prototyping technique after stereolithography enabling the layer by layer extrusion of the thermoplastic material with the help of a nozzle controlled by heat.[5,11,12,19,28]

In this technique, the filament of the thermoplastic polymer material feeds the extrusion nozzle controlled by heat. The wire-like plastic material in strips leads to extrusion nozzle and here the material is melted by heating. The extrusion nozzle forms the first layer of the product by spraying the distilled molten material on the platform. At this stage, the heat of the platform is kept at lower degrees and thus, the sprayed thermoplastic material is immediately (in 0.1 second) hardened. The manufacturing platform is brought one step down in each layer and thus the product is constructed in layers.[5,11-13,28,32,37]

These procedures are repeated until the entire part is constructed. During construction, the parts have to be supported by support structures which are either manually or automatically designed. After the completion of the manufacturing, these support structures are removed from the part. Water-soluble materials can be used as support units. [5,11-13,19,37]

FDM equipment has low maintenance costs. However, it should be noted that it has disadvantages such as formation of a connection line among the layers, requirement of a support unit, a long manufacturing duration and separation of layers depending on fluctuations in heat.[32]

6. Selective Electron Beam Melting – SEBM

Selective electron beam melting technique is the additive manufacturing method used in the manufacturing of metal parts. This technology is manufacturing by melting the metal powder layer by layer by using electron beam in high vacuum.[5,16,26,38] In this technique, three dimensional parts are transferred into two-dimensional plane by using special software (such as obtaining the CAD data and transferring into STL format).[5]

The system is basically formed of two equipments. These equipments are:

- Electron Beam Gun
- Manufacturing Platform in high vacuum[5,16,26]

Although the systematic of SEBM and SLM seems to be similar, there are severe differences between them. While SLM uses laser beam as thermal resource, SEBM uses electron beam. While SEBM carries out manufacturing in a vacuum atmosphere, SLM carries out manufacturing in an atmosphere containing inert gas. SLM causes high energy costs while SEBM causes an average energy cost. While resolution is limited in SEBM, it is perfect in SLM. While SLM has a wide range of materials (metals, ceramics, polymers), SEBM can only use metals in terms of materials.[16]

The electron beam gun in the device is located at the highest point of the vacuum chamber. System operation begins with the submission of an electron beam from the filament. A number of bobbins are used in order to control and scan the beams. The energy necessary to melt the powder is produced by the electrons between the cathode and anode. The manufacturing platform is located in the vacuum system, and thus it provides an extremely clean environment free from contamination.[16]

The SEBM process begins with the formation of the first layer by sending the global metal powders 45-100 µm in size on a steel platform serving as a starting plate. New powders are sent to form the second layer after scanning and melting a layer respectively by an accelerated electron beam. Pre-heating is performed between layers in order to enable the addition and sintering of powders to the previous layers by low thermal voltage. After melting a layer, new metal powders are added in order to form the other layer and in this way, the cycle continues until the final piece is constructed depending on the CAD design.[5,16,38]

7. Multi-Jet Solidification

Multi-jet solidification consists of 2 additive techniques. One of these techniques which is currently used in dentistry is 3-dimensional printing technology (3D-P).[15]

First of all, a certain amount of powder material is distributed by a moving piston in this technique. The powder material is then compressed on the top of the fabrication chamber by a cylinder. Subsequently, the liquid adhesive is sprayed on the powder material through multichannel jetting head, so the first layer of the object is formed. After all the layer of the object is formed by jetting process, the milling nozzle is passed over the layer in order to maintain a homogeneous thickness. The particles emerging during this process is absorbed and removed by a filter. When this layer is completed, piston helps the distribution and bonding of other powder layer. The process continues until the product is completed (Figure 4).[5,11-13,19,28,32,39,40] After the object is completed, the wax support material used is melted or dissolved and removed.

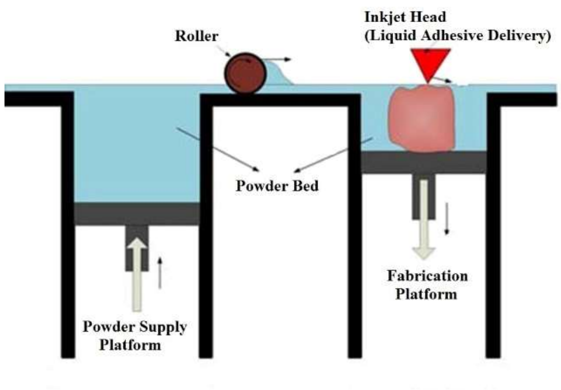

Figure 4: 3-D Printing[13]

High degree firing process may be performed in order to further strengthen the bonding of the manufactured part. The aforementioned process can be performed on metal, ceramic and metal/ceramic composition parts. 3D-P, which is the fastest technique among additive manufacturing techniques, has a very low material cost. The system has disadvantages such as rough surface finish and size limitation.[32]

HYBRID METHOD

The idea of combining additive and subtractive CAM techniques was used for the first time in 1990s in the University of Missouri (*Laser Aided Manufacturing Process-5 axis vertical)*.[41] This technique called hybrid manufacturing brought together the most important features of additive and subtractive techniques such as fast manufacturing and sensibility whilst minimising their disadvantages.[41,42]

The certain CAD/CAM systems may contain both additive and subtractive manufacturing techniques; although they are in limited number. The commercial examples of such manufacturing approach may be *Procera (Nobel Bio-Care, Göteburg, Sweeden)* and *Wol-Ceram (Wol-Dent, Ludwigshafen, Germany)*.[4,43]

In *Procera*, an enlarged metal die for prepared tooth is initially milled with the support of a subtractive approach. Formation of an enlarged unit aims to take cognizance of shrinkage associated with sintering the final restoration. Thereafter additive approach which includes compression of powder-based material onto the metal die in layer-by-layer manner to form an oversized block, is used. Consequently, the oversized block is milled to form the outer contours of restoration and then sintered to obtain its final degree of density. The manufacture of restorations via *Procera* is very technique-sensitive because the amount of enlargement must exactly match the amount of shrinkage produced by sintering the alumina or zirconia.[43]

The second hybrid approach which includes the application of semi-liquid mixture (with the use of an additive approach-*electrophoretic dispersion*) to create a coping is *Wol-Ceram*.[4] Thereafter the coping is milled to form the outer contours of restoration with the use of a subtractive approach. Consequently the operator infiltrates glass.[43]

Moreover, although LOM is categorized under additive techniques, it is a technique working with a hybrid approach. It must be emphasized that additive manufacturing in LOM is dominant and that the subtractive manufacturing is important but relatively neglible.

RESULTS

CAD/CAM technologies have initiated in a new era in dentistry. Various manufacturing techniques have been developed for over 25 years. It is known that almost all the technological methods have a field of application in dentistry but they are preferred or not preferred due to their advantages and disadvantages.

Although subtractive systems have an active use for a long time, additive systems have drawn significant attention due to their aforementioned advantages. Recently the popularity of hybrid manufacturing techniques have remarkably increased. Increased dimensional accuracy, appliance life, ability of complex manufacturing have been achieved by using hybrid technique.

UV curable resin (SLA), thermoplastics (FDM, SLS), waxes (FDM, SLS), polymers (3D-P), composites (FDM, 3D-P, SLS, SLM, LOM), metals (SLS, SLM, SEBM, 3D-P, LOM) in different states (liquid / paste / powder / solid sheet) are used for computer-assisted manufacturing of prosthetic restorations.

The ever-increasing patient demand for rapidly produced prosthetic restorations with acceptable aesthetics and function is the greatest proof of the continuation of the rapid development of CAD/CAM technologies.

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