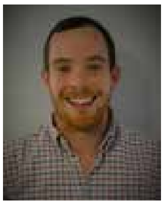

Dominic P Laverty

Matthew BM Thomas, Paul Clark and Liam D Addy

The Use of 3D Metal Printing (Direct Metal Laser Sintering) in Removable Prosthodontics

Abstract: The use of 3D printing is expanding and it is envisaged that it will have an increasing presence within dentistry. Having an appreciation and understanding of such technology is therefore paramount. It is currently used to produce a variety of dental objects/ prostheses. This paper briefly looks at 3D printing in dentistry and specifically describes the use of the direct metal laser sintering 3D printing technique in the production of cobalt chromium removable prosthesis frameworks.

CPD/Clinical Relevance: Understanding the different technologies that can and are being used within the dental field is important, particularly as it is a rapidly changing field. Having an understanding of such technologies will allow practitioners to utilize such technologies appropriately in the management of their patients.

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Three-Dimensional (3D) printing is a process of making a 3D object from a digital file. The 3D object is created using an additive process whereby successive layers of material are placed until the object is created. These layers are thin horizontal 2D cross-sections of the eventual 3D object.[1]

It was Charles Hull in the early 1980s who invented 3D printing. He described the process of stereolithography or the 'printing' of successive layers of material on top of each other to create a 3D object.[2]

Dominic P Laverty, BDS(Hons), MFDS RCSEd, ACF/StR in Restorative Dentistry, Birmingham Dental Hospital, (dominiclaverty560@hotmail.co.uk), **Matthew BM Thomas**, BDS(Hons), MPhil, MFDS RCS, MRD RCS, FDS(Rest Dent) RCS, Consultant in Restorative Dentistry, Cardiff University Dental Hospital and **Paul Clark**, Chief Dental Prosthetic Technologist, Cardiff University Dental Hospital and **Liam D Addy**, BDS, MFDS, MPhil, FDS(Rest Dent), Consultant in Restorative Dentistry, Cardiff University School of Dentistry, Heath Park, Cardiff, UK.

The use of 3D printing is expanding, with the entire 3D printing industry currently worth around $700 million, and is expected to grow to an estimated $8.9 billion industry in the next 10 years.[3] Even NASA have used 3D printing to produce a fuel injector and plan to have a 3D printer on board their next space flight.[4]

This expansion in 3D printing is also being experienced within the medical field.[5] The current 3D printing industry is worth $11 million for medical applications but is projected to have exponential growth over the next 10 years to $1.9 billion.[6]

One of the advantages that 3D printing offers in its medical application is the ability to allow customization and personalization of medical products and equipment, at relatively low costs (as the cost of the first item is the same as the last)[5] and produced relatively quickly.[7] Hence, 3D printing is ideal for making one of a kind items at cost-effective prices.[5]

3D printing has been applied in medicine and dentistry since the early 2000s with dentistry quick to embrace the use of this technology, particularly with regards to dental implant reconstructions.[8]

A number of published articles have described the use of 3D printing in medicine to produce cell cultures, blood vessels and vascular networks,[9] bandages,[10] bones,[11] ears,[12] exoskeletons,[13] windpipes[14] and corneas.[15] The use of 3D printing is also being investigated in repairing or replacing defective organs, such as kidneys, the heart and skin.[5]

In dentistry, 3D printing can produce metallic, polymer[16] and ceramic-based objects.[1] It has been used to produce a variety of dental objects including stereolithographic models, implant fixtures and components, removable prosthesis frameworks, fixed prosthesis and maxillofacial structures (hard and soft tissue).[17-26]

Denture frameworks have traditionally been produced using the lost wax technique and metal casting; however, 3D printing methods are now available. These offer quicker and more cost-efficient production with reduced recasting. Removable partial dentures are still a well-recognized treatment, and around 19% of adults in the UK are wearing some form of removable prosthesis, as shown in the UK Adult Dental Health survey in 2009.[27]

This article aims to demonstrate the use of 3D printing in the production of removable prosthesis metal cobalt chromium (CoCr) frameworks.

Overview of 3D printing

3D printing is an additive process whereby successive layers of material are placed until the 3D object is created.[1]

This is markedly different from subtractive manufacturing, such as CAM (computer aided manufacture) Milling, where a block of material is cut away until the final object is created.

3D printing is a digital manufacturing process based on digital data with the 3D object being produced using computer-aided design (CAD) and manufacture (CAM).

This digital data/CAD file of the 3D object is divided into thin 2D sections using software programs. This sectioned data is sent to the printer layer-by-layer using CAM so that each layer is accurately formed and successively built on to produce the 3D object.

This CAD file data can be created in one of two ways; the first by optically scanning a 3D object via a process called reverse engineering[24] or by designing the 3D object using CAD software.[18]

The benefits and challenges of 3D printing in dentistry is shown in Table 1.

A range of 3D printing technologies (additive process) are being used in dental industry, which include; stereolithography, fused deposition modelling, selective electron beam melting, laser powder forming methods and inkjet printing.[1]

This article will discuss the use of laser powder forming methods.

Benefits	Challenges
Cost-saving materials (in comparison to traditional subtractive milling process of metal or ceramic or the conventional lost wax casting technique)[31,34]	Initially outlay of equipment expensive[33]
Multiple jobs can be produced at once [18,35]	Need appropriate training in the use of machinery and the software programs
Unlimited design and manufacturing capability[34] (unlike milling machines which are limited by their milling axis) allowing customization, flexibility and geometric freedom[24]	If using conventional techniques in impression taking and casting of impressions this could be a source of error
If the CAD data is saved, the prosthesis can be re-made exactly or the design modified where required	If using digital scanners and software to transform the scanning data into a 3D model this to could be a source of error
High reproducibility of design (CAD) into the actual prosthesis, with reduced inclusions, defects or distortions (commonly occurring in manual casting processes)[35]	Faults include – defects: rough surface, pores, cracks, and distortion – but often can be rectified with finishing and polishing procedures[24] and can be reduced by using small layer thickness and a small laser beam diameter[36]
Able to produce highly detailed complex surfaces[34]	
Simplified post-processing procedures[18]	
Minimal wastage[1]	

Table 1. Benefits and challenges of utilizing 3D printing in dentistry.

Laser powder forming methods

Laser powder forming methods are carried out by directing a laser via mirrors at a layer of fine powder substrate. The laser causes the powder either to melt, via a process called selective laser melting (SLM), or sinter via a process called selective laser sintering (SLS).[28,29] The powder particles fuse together,[28,29] and layer-by-layer build up by distributing an even layer of powder to produce the 3D object.[1]

SLM is very similar to SLS in terms of equipment but uses a much higher energy density. This enables full melting of the powders, whereas SLS sinters the powders.[28]

When using metal powders the process can either be known as SLM, if melting the powder, or DMLS (direct metal laser sintering) when sintering.[1]

To control this complex set of parameters, the process runs under shielding gas; fine grained powders are applied and sophisticated scan programs are used to govern the exposure by the laser beam. To achieve fine detail and reduce faults, a small layer thickness and a small laser beam diameter are necessary.[30]

A range of metal powders can be used including steel, titanium, titanium alloys, and Co/Cr alloy.[1] Optimization has to be carried out for each material and the geometry of the part being produced and its supporting structure need to be considered. The resulting data is termed the material dataset,[30] which is often produced by the manufacturers.

DMLS and dental use

The laser sintering process was first described by Deckard and Beaman, who created the DTM (desk top manufacturing) machine at the University of Texas.[28,31] The process is referred to as 3D printing as it builds up an object in a series of successively thin layers.[17]

The physical process involved with the laser sintering can be full melting, partial melting, or liquid-phase sintering.[32]

This DMLS process is carried out by forming a thin layer of metal powder (ranging from 20 μm to 100 μm) and sintered by a laser (high powered ytterbium fibre laser) to form a 2D cross-section. This is then built up layer-by-layer by distributing an even layer of metallic powder to produce the 3D object.[17] This process is carried out within a controlled inert atmosphere[35] (Figure 1).

The 3D object being created has to be adequately supported during the DMLS process and thus have supporting structures designed into the 3D object. These are produced during 3D printing. The supporting structure ensures that the object is fixed in position to the underlying baseplate and ensures geometric accuracy, which is a vital part of the DMLS process. These supporting structures will then need removing after the production process.

The DMLS process is performed by one of two methods, powder deposition or the powder bed method:[33]

- In the powder deposition method, the metal powder is sintered in a hopper then deposited in a thin layer onto the build platform;
- In the powder bed method, a re-coater arm distributes a thin layer of powder onto the powder bed and is then sintered.

In both methods, layers are built on top of one another with the build platform being lowered each time to allow the application of the next layer of powder (Figure 2).

Once complete, the excess powder is removed and the metal framework is carefully separated from the underlying baseplate. They then undergo a heat treatment process called annealing which advances the material to its equilibrium state.[37,38] This involves heating the framework above the critical temperate and then cooling.[38-40] This annealing process produces a more homogeneous metallic structure,[38,41] and affects the microstructure and hardness of the alloy.[39,40]

The framework is then finished which includes removal of the supporting structures, sand blasting, polishing and ultrasonic cleaning.[34,35]

The printing time varies and is dependent on the 3D printer used, the number of jobs and the height of the jobs.

DMLS can be used to create crowns and bridges,[18,20,22] crown copings for metal ceramic crowns,[18, 25,26] bridge frameworks, denture frameworks,[21,23] implant abutments and implant fixtures.[17,19,24] (Figures 3 and 4).

There are a number of papers that have demonstrated the use of laser sintering in the production of denture frameworks.[6,21,23]

In comparing the use of DMLS to conventional lost wax technique and CAD/CAM milling in their use in producing metal dental prosthesis, it has been demonstrated that the marginal fit of prosthesis produced by DMLS is equal to, if not better than, these other methods.[36,42-44] It has also been shown that restorations fabricated using this method produced good surface properties, such as proper hardness, homogeneous microstructure, and also showed sufficient corrosion resistance, and is appropriate for dental use.[45]

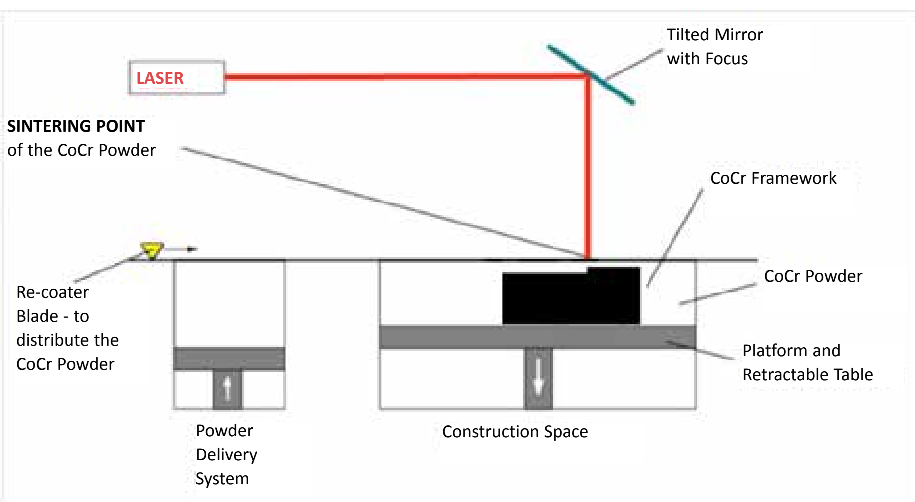

Figure 1. Schematic diagram of the DMLS process.

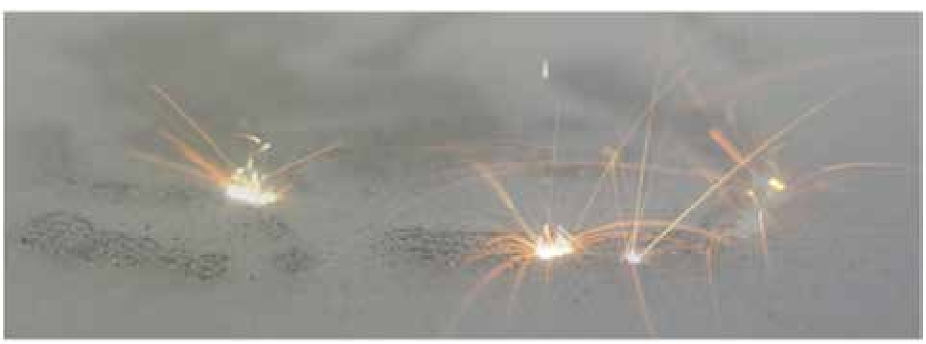

Figure 2. The DMLS process. (By kind permission of 3D Systems Leuven.)

Production of the prosthesis using 3D printing/DMLS

There are a number of companies that offer 3D printing in dentistry for removable partial dentures (RPDs) metal frameworks. Renishaw plc, based in Gloucestershire, UK, offer a variety of 3D printed products for the dental market, and are close to commercially offering 3D printed CoCr Framework. 3D Systems Leuven, On Demand Parts Manufacturing site for healthcare, formerly known as DentWise, also offer a variety of 3D printed products for the dental market. They offer either CoCr or Titanium (Ti) RPD metal frameworks. They require an stl file (stereolithography file) with a designed RPD metal framework to be sent electronically, which is used to print the framework. The RPD frameworks are then trimmed and either delivered as a sandblasted or mirrored finished framework.

Individual 3D printed frameworks have the same cost range as conventional cast frameworks. However, it is envisaged that the cost of 3D production will reduce as this technology becomes more readily available and there is increased uptake and usage by practitioners.

The framework parameters and design software need to be discussed with the manufacturer to ensure compatibility.

There is a variety of DMLS 3D

Figure 3. Variety of DMLS dental products produced by 3D Systems Leuven. (By kind permission from 3D Systems Leuven).

Figure 4. Completed CoCr Framework using DMLS produced by Dentwise. (By kind permission from 3D Systems Leuven.)

printers available on the market that are capable of producing an RPD metal framework which include; the AM250 laser melting additive manufacturing machine (Renishaw plc) and the EOS INT M 270 (Electro-optical systems GmBH), 3D Systems Leuven use their own 3D printer.

Cobalt chromium composition

Table 2 shows different dental CoCr alloys used for a variety of manufacturing techniques which include; conventional casting, CAD/CAM milling (S&S Schefner, Starbond CoS) and DMLS techniques (EOS, Cobalt Chrome RPD and Renishaw, Co-Cr-DG1). The alloys all have similar composition, despite having different manufacturing processes and all alloys are compliant with the standards of the International Organization for Standardization (ISO), as stated by the manufacturer.[49]

The CoCr dental alloys used for DMLS, however, have little scientific evidence reporting on their characteristics.[50] The evidence currently available would suggest that the manufacturing technique, whether that be conventional casting, laser sintering or milling using CoCr dental alloys, has adequate mechanical properties satisfying the ISO standards of dental alloys.[47]

Digital impressions

Intra-oral digital impression scanners can be used to digitalize the process fully. The main intra-oral digital impression systems currently available on the market include CEREC, Lava COS system, iTero, E4D and TRIOS. All these systems vary in their key features, such as their working principle, light source, the need for powder coating, the clinical operative process, and the output file format.[51]

The digital scanner uses a 'triangulation' process to collect the 3D structures being scanned. To create this, a source of light and the receptor unit are in a specific angle to one another; this angulation allows the computer to produce a three-dimensional data set from the image on the receptor unit.[52]

In general, there are two types of intra-oral scanners on the market. The first uses blue LED (light-emitting diode); these systems depend upon a reflective surface and require a contrasting medium or powder to be placed on the structures being scanned. The other systems use laser technology to scan and measure distances from the tooth surface to acquire the image; they do not require powder.

It is advised to check the compatibility of the intra-oral scanner and RPD design software to ensure compatibly.

CAD software

There is a variety of RPD design software packages which include, 3Shape, Dental Wings, Exocad and Freeform plus™. These software packages vary in complexity. The simpler software packages can be used on a standard computer without the need for any additional equipment. However, more complex software packages may require the use of specialist equipment such as the use of a haptic arm which often requires further training and experience. These software packages create an stl file which is then used to produce the framework. The majority of 3D printers are capable of producing a framework from an stl file, but it's best to check with the manufacturer to ensure compatibility of the software and the printer.

Clinical and manufacturing technique

The following is an example of a design and manufacturing technique that has been utilized at University Dental Hospital in Cardiff.

Impression taking and conventional casting of impressions

Conventional master impressions are taken in an appropriately prescribed special tray with addition cure silicone-based material. This is then conventionally cast up (using Crystacal® R Plaster) creating the master model.

Digital scanning of models

The master model is then scanned using the DS30 Optical Scanner (Renishaw plc). The light optical scanner

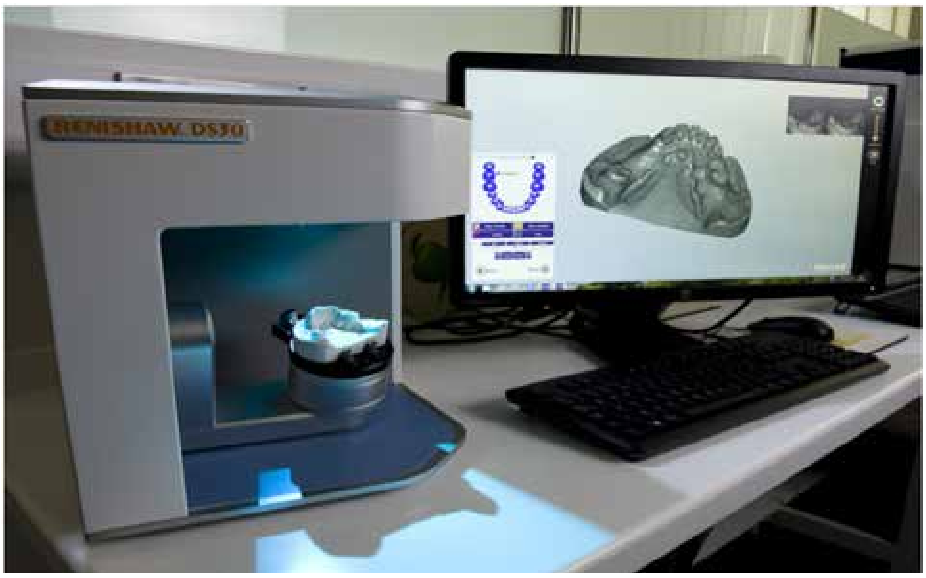

Figure 5. DS30 Optical Scanner and Freeform plus™ software.

Figure 6. Use of The Touch™ X (Geomagic®) Haptic arm and Freeform plus™ software.

scans the model, registration and triangulation algorithms are then used to reconstruct the scanned data into an stl file which is a virtual model consisting of a mesh of triangles.[53]

An stl file format is used to interpret the data in a CAD file, allowing these instructions to be communicated electronically to the 3D printer.[15] The data is then imported directly into the Freeform plus™ software (Geomagic®) (Figure 5).

Denture design

The Touch™ X (Geomagic®) Haptic arm and Freeform plus™ software (Geomagic®) are used by the operator to design the prosthesis.[54]

The software can be used to survey the models, block out undercuts, identify insertion paths and guide planes and to design the prosthesis, offering the same capabilities as for a traditional prosthesis.[54]

The haptic arm is used to design the prosthesis and can accurately measure the 3D spatial position and the orientation of the handheld stylus. The device uses motors to create forces that push back on the user's hand to simulate touch and interaction with virtual objects[54] (Figure 6).

Once the design is complete, the stl file data is then 'sliced' into sections by MagicsAutoFab (Materialise NV) software. The stl file is then sent directly to the manufacturing machine to construct the CoCr framework.[35]

With a digital design it can be electronically sent to the practitioner and/or patient for approval prior to production; the data can also be saved and re-used/modified at a later date if required as well (Figure 7).

Element	Bego – Wironium Plus	Jelenco – Supra chrome	Dentsply prosthetics – Vitallium	Bredent – Brealloy F400	EOS – Cobalt Chrome RPD	S&S Schefner – Starbond CoS	Renishaw – Co-Cr-DG1
Co	62.5	63.6	63.4	64.7	63.8	59	63.9
Cr	29.5	28.5	29.0	29.0	24.7	25	24.7
Mo	5.0	6.0	5.2	5.0	5.1	3.5	5
Si	<1.0	<1.0	<1.0	0.5	1.0	1	<1.0
Fe	<1.0				0.5	<0.5	
Mn	<1.0	<1.0	<1.0	0.4	0.1	<0.1	
W					5.4	9.5	5.4

Table 2. Cobalt chromium alloy composition for a variety of processing techniques for dental prosthesis.[46–8]

Manufacture

The CoCr framework is produced using the AM250 laser melting additive manufacturing machine (Renishaw plc). It uses a high-powered ytterbium fibre laser to fuse the fine metallic powders together, in a vacuum environment.[35]

The process is carried out by forming a thin layer of CoCr metal powder, 40 microns thick and sintered using the ytterbium fibre laser with the denture framework being built up layer-by-layer. This process is carried out within a controlled inert atmosphere[35] (Figure 8).

Figure 7. Denture design using Freeform plus™ software.

Figure 8. CoCr Framework once 3D printing complete.

Figure 9. CoCr Framework after polishing and trimming.

The metal supporting structures are removed from the metal framework. These supporting structures ensure that the framework is fixed in position to the underlying baseplate and ensure geometric accuracy, which is a vital part of the DMLS process. This is then removed after production, which is similar to the removal of the sprues used in conventional casting techniques of metal frameworks.

Once the framework is complete it can be trimmed, smoothed and polished in the conventional way.

The rest of the laboratory process in the production of the prosthesis is via conventional methods (Figure 9).

Conclusion

The use of 3D printing is expanding and it is envisaged that it will have an increasing presence within dentistry. Dental practitioners therefore need to be aware of what this technology can offer them and their patients and how this technology is developing.

The DMLS method has been shown to be successful in the production of removable prosthesis metal frameworks and has a number of advantages over conventional methods of production. It is a relatively new technique for producing metal RPD frameworks and is being introduced in clinical practice; however, research on its clinical utility compared to traditional methods is limited, and the process involves expensive equipment and processes to which dental practitioners may not be accustomed. It is recommended that long-term clinical trials be carried out to provide evidence to support this technique further.

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