Powder bed fusion in dentistry

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Complex dental component which are individually tailored to the patient can be obtain due to new 3D printing technology. Understanding the manufacturing and post-production processes is essential in order to obtain a product which can be used in clinical applications.

Powder Bed Fusion Selective Laser Sintering Selective Laser Melting Electron Beam Melting Dentistry

1. Introduction

CoCr-based alloys are commonly used in dentistry because of their excellent corrosion resistance and outstanding mechanical properties, such as high stiffness. Since its development in 1907, lost wax casting is still the dominant method of dental metal processing [1]. Unfortunately, this technique has some limitations, one of which is the fact that metal shrinks during its transition from the liquid to the solid phase, and this shrinkage should be taken into account when preparing the part for casting. Additionally, pores and other defects are usually present in the structure of the cast element [2][3], the process is time-consuming and requires certain skills for the operators [4], and CoCr alloys are difficult to treat and process because of their high hardness [5].

Nowadays, metallic materials are processed by computer-aided design and computer-aided manufacturing (CAD–CAM) (Table 1) that allows 3D structures to be produced based on data (appropriate conversed–segmented) regarding individual organs, bones or blood vessels obtained from medical imaging devices such as magnetic resonance imaging (MRI), computed tomography (CT), cone beam tomography (CBCT) or ultrasound (USG). Segmentation and analysis software is available as open source versions (e.g., InVesalius or 3D Slicer) and as a paid version with extended functionality (Materialize Mimics, Amira or Dolphin 3d). Three-dimensional models can also be obtained using 3D scanning; this is the most common type of solution used in Dentistry (i.e., in prosthetics and orthodontics), using optical scanners employing photogrammetry or scanning with structured light. The 3D data obtained in this way are used for the design of prosthetic restorations, orthodontic appliances, surgical templates or individualized implants using dedicated CAD software [6][7][8][9].

Table 1. Computer-aided design/computer-aided manufacturing (CAD/CAM) processes currently upgraded into dentistry.

Process	Technology	Ref.
Digital impression	It is a non-invasive method to obtain a virtual model of the hard and soft tissue of the patient's oral cavity. This involves the use of an intraoral scanner which records a series of snapshots of the oral cavity of the patient.	[10]
Prosthetic designing	Scanner data are evaluated and processed by the dental laboratory using special software. The digital prosthetic model is individually tailored to the patient.	[10]
Manufacturing process	Milling (subtractive manufacturing): a prepared prosthetic design is mechanically cut from a metal block. This process is controlled by software. Milling units in the last decade were optimized—large angulations of the fourth and fifth axes (>30 degrees), dry or wet grinding.	[5]
	Sintering (subtractive manufacturing): technology developed by Amann Girrbach. The prepared prosthetic is mechanically cut from metal blanks with a wax-like texture. The process is controlled by software. The blocks are made from unsintered metal powder held together by a binder. After the milling process, the structure is subjected to sintering in a special furnace.	
	Powder bed fusion (PBF, additive manufacturing): the prepared prosthetic is formed by the thermal consolidation of a metal powder (layer by layer). The process is controlled by software. Selective laser sintering (SLS), selective laser melting (SLM) and electron beam melting (EBM) are three methods classified as PBF.	

2. Powder Bed Fusion (PBF)

Powder bed fusion can be subdivided into three methods: selective laser sintering (SLS), selective laser melting (SLM) and electron beam melting (EBM). In SLS, metal powder compacts are transformed into coherent solids at temperatures below their melting point. In SLM and EBM, the metal powder is fully melted, however, the two methods use different ways to achieve their melting point [11].

2.1. Selective Laser Sintering (SLS)

Carl Deckard and Joe Beaman developed and patented in 1989 selective laser sintering (SLS) technology [12]. In this method, a high-power laser is focused onto a thin layer of metal powder. The layer is heated, and next bonding processes between metal particles is started. This step requires the transport of material from inside the powder to points and areas where particles are in contact with each other. There are five different transport mechanisms possible: volume diffusion, grain-boundary diffusion, surface diffusion, viscous or plastic flow. Elements made by SLS technique are characterized by high porosity. It is crucial to correctly select the parameters of the SLS process (temperature, time, geometrical structure of the powder particles, composition of the powder mix, density of the powder compact, composition of the protective atmosphere in the sintering furnace) [13]. Unfortunately, the complete elimination of porosities is not possible due to the partial melting and sintering caused by the melting point not being reached [14].

2.2. Selective Laser Melting (SLM)

It is possible to melt metal powder using powerful, high-quality lasers. In 1995, commercial machines using SLM technology were launched on the market. Selective laser melting printers use CO_2 lasers or fiber lasers (Nd:YAG or Yb:YAG) [15]. The laser beam is focused onto the powder, and the energy supplied by the laser is able to melt it. The melting process can be adjusted by varying the wavelength, laser source and power. The resulting products are characterized by a lower occurrence of blisters and a better superficial finish than those made by SLS. Unfortunately, high internal stresses are found in materials, caused by the thermal gradients induced during manufacturing. To reduce these stresses, additional heat treatment is required [16][17][18]. Selective laser melting technology is the most popular approach to metal processing in Dentistry (Table 1).

2.3. Electron Beam Melting (EBM)

This technology is very similar to SLM. However, EBM technology uses a focused electron beam in a vacuum environment to melt the layers of powder. During EBM processing, a tungsten filament is heated, and this gives off electrons which are accelerated into a beam by two magnetic coils. The beam strikes the metal powder, which is melted by the transmission of kinetic energy [19][20].

3. Summary

Additive manufacturing processes have opened new possibilities, allowing the production of complex components, individually tailored to the patient. In dentistry, SLM is the most popular of all powder bed fusion technologies. Seemingly, this method seems to be less complicated than casting. However, the CAD–CAM specialist should have the knowledge to choose the right process parameters as well as post-processing methods. Without this ability, the resulting product may not be suitable for reliable use in practical applications.

The following conclusions can be drawn from the literature review:

- PBF-manufactured parts are characterized by an anisotropic γ-phase (face-centered cubic (fcc)) and ε-phase (hexagonal close-packed (hcp)). The microstructure, roughness and properties of the samples depend on build orientation. Parts built at 0° were characterized by the worst mechanical properties.

- Basic parameters, such as the laser power, scanning speed, laser beam size and layer thickness, are connected and they influence the density of the melted material. These parameters determine the material properties. In the SLM processes, energy input values above 0.36 J/s result in reduced sample density. The optimized range of laser energy density (LED) for $Co_{28}Cr_6Mo$ SLM parts is 150–200 J mm^{-3}.

- Post-processing heat treatment is considered necessary to ensure the reliable use of PFB-built parts in practical applications. Heat-treatment up to 1050 °C (even for six hours) is insufficient to eliminate anisotropy and residual stress. As heat-treatment temperatures increase from 750 °C to 1050 °C, homogenization also increases, compared with the as-built samples. Heating samples at 1150 °C for one hour causes the total homogenization of the sample’s microstructure.

- Optimization of the heat-treatment conditions for improving the mechanical properties (especially fatigue properties) remains a major challenge in SLM.
- Surface finishing of PFB-built parts is necessary.

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