An Overview Material Process and Characterization of Dental Additive Manufacturing: A Review

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Review Article

Received: 19-Dec-2022, Manuscript No. JOMS-22-84169; **Editor assigned:** 21-Dec-2022, PreQC No. JOMS-22-84169 (PQ); **Reviewed:** 04-Jan-2023, QC No. JOMS-22-84169; **Revised:** 11-Jan-2023, Manuscript No. JOMS-22-84169 (R); **Published:** 19-Jan-2023, DOI: 10.4172/2321-6212.11.1.005.

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Citation: Gobena ST, et al. An Overview Material Process and Characterization of Dental Additive Manufacturing: A Review. RRJ Mater Sci. 2023;11:005.

ABSTRACT

Additive Manufacturing technology is currently promising technology, which is highly applicable in modern medical equipment, for restorative and dental implants and etc. Nowadays fixed dental prostheses are designed and fabricated different techniques of Additive Manufacturing to replace missing tooth/teeth and other dental parts. Dental material and some of basic 3D printing are overviewed from recent literature.

Methodology: this literature was carried out using science direct, google scholar, pubmed, cochrane library, and medline search engines. In addition, the use of google search engine also included hot literature. Included were publications between 2017 and August 2022.

Aim of the paper: This paper review is discusses the types of 3D printing technologies used for dental fabrication, dental materials, different characterization techniques and their various applications in dentistry.

Keywords: Additive manufacturing technology; Dental material; Material properties; Material characterization

INTRODUCTION

Additive Manufacturing technologies are currently having a promising future due to their potential for applications in several industries. The medical industry is one of the industries where design freedom and more accuracy are needed. Consequently, Additive Manufacturing can be preferable in application of dentistry and dental prosthetics area [1]. Since the late 1950s, the metal ceramic crown system has remained a standard modality for rehabilitation of anterior dentition, because of their good mechanical properties and to somewhat satisfactory esthetic results, along with a clinically acceptable quality of their marginal and internal adaptation [2].

The introduction of computer-aided design/computer-aided manufacturing led to a more accurate manufacturing of prosthetic frameworks, greater accuracy of dental restorations, and in particular, implant-supported prosthesis [3].

Traditional and Computer-Aided Design (CAD) and Computer-Aided Manufacturing (CAM) technologies have led to major improvements in dentistry [4]. They make it possible to produce reliable restorations with accurate dimensions [2] and to reduce manufacturing parameters [1]. However, these processes are limited by the waste of raw material (loss of idle portions of blocks and difficulty in recycling excess material) and heavy wear of milling tools. Additive Manufacturing processes avoid these limitations by building objects layer-by-layer while such processes are already being used to manufacture metal and polymer prototypes [5], the shaping of ceramics for dental applications is still in its infancy [6]. Currently, the most widely used areas 3D printing are esthetic aligners, crowns, and bridges. As recent research shows by 2027, Three-Dimensional (3D) printing technologies will become the leading production source for dental restorations worldwide, beating milling and analog fabrication [7].

Applications of Additive Manufacturing help dental professional to fabricate any implant and different dental devices. Technology can precisely help to improve the future work of a dentist and medical Industries. It provides development in the medical instrumental manufacturing Industries, and now it explores its applications in dentistry. Before performing actual surgery, reoperations can also be performed on the 3D model and analysed it [8].

In dentistry, Additive Manufacturing applications are used to improve many things like, preoperative planning, education, custom manufacturing and make reliable operation [9]. Ceramics, polymers and Metal can be additively manufactured by many mechanisms like Stereolithography (SLA) [10] Fused Deposited Modeling (FDM) [11].

A literature search for processing polymers in dentistry using Additive Manufacturing was carried out using science direct, google scholar, pubmed, cochrane library, and medline search engines. In addition, the use of google search engine also included important literature. Included were publications between 2017 and August 2022.The keywords used were: Additive Manufacturing or 3D printing and dental prosthodontics, complete denture, denture, dental ceramics, and dental metal/dental polymer. In addition, a manual search was carried out in referenced papers. The aim of this paper is to evaluate the mechanical characteristics of metal, ceramic and polymers material and a novel Three-Dimensional (3D) printing technology able to create dental parts.

LITERATURE REVIEW

Additive manufacturing vs. casting

Additive Manufacturing opens new possibilities for complex part production and can change the way the parts are designed and produced in the future [12]. Casting technology is one of the oldest production technologies in the world. Due to its simplicity, the basic principles of technology have not changed for many years [13]. Casting technology and Additive Manufacturing are completely different technologies by the principles how they performs, but it may possible to find similarities in the parts that can be manufactured with technologies: complex internal channels, surface roughness, and dimensional accuracy for both technologies are in very close tolerances [14].

The main disadvantage of the casting technology is start-up costs for a new project because it is time consuming and expensive to produce a new pattern [15]. It takes too hours for redesign a 3D model with all necessary draft angles and with complex features for pattern design which lead that in reality the produced part will not be the same as designed in the beginning [16].

The major conceptual difference between the 3D-printed AM models and the Conventional Dental Stone (CDS) is the design of the implant analogs [17]. On the CDS models, the implant analog is designed as a spongy element so that it does not move when pouring the dental implant impression.

Additionally, when manufacturing a 3D-printed AM model, the digital implant analog is placed after the model is manufactured, and consequently is retrievable from the cast [10]. Different studies have analyzed the accuracy of AM casts [18], however, only one study analyzed the accuracy of the implant analog position on the AM cast Revilla-León, et al. [10,12] compared the duplication capabilities of a completely edentulous cast with six implant analogs using AM technologies and conventional procedures [19].

Material used for dental application

Currently, materials used in dentistry are several groups; metals, polymers, ceramics, and composites. They are used, for partial and complete dentures, permanent and temporary implants, denture linings, resin cements and etc. [20].

The materials use in dentistry should meet several requirements that can be categorized; chemically, they should not dissolve in fluids present in the mouth or ingested by the patient, nor should they absorb such fluids, as this causes dimensional changes. Biological aspects require that the material used be non-toxic, non-irritating, non-carcinogenic, and biocompatible [20].

A wide variety of these materials ranging from dental cements, resins, metals, and alloys to ceramic materials are used in fabrication of dentals. Metals and alloys commonly used in dentistry include Titanium (Ti) and their alloys such as nickel-titanium (NiTi), stainless steel, cobalt-chrome alloys, nickel-chrome, gold-based alloys, or dental amalgam [21]

Despite the wide availability of biomaterials, no material has ultimate physical, mechanical, biological, and surface characteristics. Therefore, optimizing material properties for dental use depends on numerous factors such as their corrosion behavior, mechanical properties, cost, availability, and esthetics are very important [21]

Ceramic material for dental

The most commonly used ceramic biomaterials in dentistry are made from calcium phosphates, halloysite, alumina, and zirconia [22]. Compared to other biomaterials, ceramic biomaterials are characterized by high compressive strength and abrasion resistance, high corrosion resistance in the tissue environment, the possibility of sterilization without changing the material properties, and brittleness [23]. Ceramic biomaterials, apart from their many advantages, have significant disadvantages. They are brittle materials with low flexural strength, are non-deformable, not are resistant to dynamic loads [24]. According to Baumgartner, et al. [2] studied the flexural strength of alumina bioceramics and hydroxyapatites are almost similar and compatible.

Metal AM for dental application

The AM technologies for the fabrication of metallic structures rely on the local binding of metal powders (using a binder, or *via* sintering approaches) in a layer-by-layer fashion [25]. Many of researchers are agrees for 3D metal printing in dental applications, currently Cobalt Chrome (Co-Cr) and titanium (Ti-6Al-4V, Ti-6Al-7NB), stainless steel, zirconium oxides are the most commonly used alloys [26].

The metal powder of Co-Cr also contains molybdenum, tungsten, silicon, cerium, iron, manganese and carbon, while nickel and beryllium are not present in the composition anymore. The metal powders used in conjunction with AM technologies are a mixture of particles with sizes ranging between 3 μm and 14 μm [26]. According to Kroczek, et al. evaluations, their advantages include high strength, resistance to fracture and cracking, high workability, ductility, and electrical conductivity, as well as a good balance between stiffness and elasticity [27].

The metals used as biomaterials must be resistant to corrosion, as corrosion results in the dissolution of metal ions, so that they may exhibit toxic effects [28]. Kroczek, et al. had examine the uses of metal to manufacture dental implants, plates for maxillary prostheses, bridge wires, dental restorations, denture bases and bone screws [21]. They are characterized by high specific strength (strength to weight ratio), and their Young's modulus is half that of stainless steel and cobalt chrome [20,27].

Thompson, stated that, Titanium is preferable due to its characteristics such as, non-ferromagnetic, good corrosion resistance, good tissue compatibility, chemical stability and it can save human body. Furthermore, low torsional strength is considered as the drawback [20].

The metal AM techniques have been capable to form fine features at certain levels for biomedical purposes. Those features, as defined during the Computer-Aided Design (CAD) modeling, are the basis for the selection of a suitable technique for implant fabrication [29].

Polymers for dental

Polymeric Materials (PMs) are widely used in biomedical fields [28], and their use has increased due to their improved properties and wide applicability.

Polymers play a major role in different aspects of dentistry, such as preventive, restorative, and regenerative therapies [30]. The use of PMs and Polymeric Films (PMFs) rather than traditional materials (such as dental amalgam and cements) used in dentistry is becoming more common due to their physical, mechanical properties and biological properties [21]. Likewise, ease of processing, low cost of production, and the possibility of obtaining excellent surfaces for both polymeric materials and films [31].

The most commonly used for dental applications are Poly-L-Lactic Acid (PLLA), Polyetheretherketone (PEEK), Polylactide (PLA), and Polymethyl Methacrylate (PMMA). Polymer materials and polymer composites meet dental requirements such as mechanical and biological properties, corrosion behavior, ability, cost, aesthetics, and relative ease of processing. In addition, the use of polymeric coatings enables increased biocompatibility of bulk materials (Tables 1-3) [32].

Table 1. Polymer material and bio polymers used for dental application.

Polymers	Their purpose reference	Reference
Polylactide (PLA)	Guided tissue in dental application	[32]
Poly Ether Ether Ketone (PEEK)	dentistry as an element of abutments, fixed prosthetic skeletons and skeletons of partial skeletal dentures, including precise fixing	[22]
Poly-Glycolic Acid (PGA)	guided tissue regeneration (in dental applications)	[21]
Polymethyl Methacrylate (PMMA)	dental prostheses, use in the production of intraocular	[21,33]
Poly-Lactic-co-Glycolic Acid (PLGA)	guided tissue regeneration (in dental applications)	[34,35]

Material properties for dental application

Many researches show that in mechanical terms, the modulus of elasticity and resilience should be high. So that, the relevant components such as, the denture base will be rigid in relation to the acting osculation forces [32]. High proportionality and elasticity limits prevent permanent deformation under occurring loads. For materials of dental applications, the specific gravity should be low and they are required to be dimensionally stable, while possessing sufficiently high abrasion resistance and sufficient mechanical strength to prevent cracking of the components under repeated biting forces [36].

The thermal expectations placed on the materials include their being good thermal conductors, their coefficient of thermal expansion being compatible with that of the teeth, and their softening point being higher than the boiling point of water [25,37].

Table 2. Main properties of dental material are discussed as follows.

Types of properties	Material properties	Reference
Mechanical properties	Modulus of elasticity, resilience, fractural strength, Flexural strength	[38]
	Thermal conductivity	
	Thermal absorption	
Thermal properties	High coefficient of thermal expansion	[37]
Chemical properties	Not dissolved in fluid	[39]
Biological properties	Nontoxic, non-irritating, carcinogenic and biocompatibility	[40]

Additive manufacturing process for dental

AM for dental practices is not a new talk of the town. It has been there for almost 20 years. For metallic dental crowns, Researchers have used FDM, SLS, SLA, and LOM techniques for dental applications specifically for dental pieces, crowns, bridges etc [41]. SLA and FDM are generally used for non-metallic oral implants, models for dental study, orthodontics, crowns and bridges, and surgical equipment, specifically surgical guides for dental surgery [5]. FDM, the fused deposition modeling technique has the potential for creating polymer dentures with hollow, semi-hallow, or solid structures [42]

The researchers are using Additive Manufacturing for maxillofacial implants where the metallic powder using Selective Laser Melting method (SLM) [8] replaces the entire jaw of the patient. Additive Manufacturing technologies have been used for creating complete or partial dentures. DLMS, a direct laser metal sintering process has been used for creating metallic dentures (Figures 1-4) [23].

Figure 1. SLM additive manufactured complete maxillary CoCr implant framework [43].

Figure 2. Crown placed on a plaster model [2].

Now the research is being conducted for developing the dentures using AM, which have the anti-microbial property [44]. Researchers have used processes such as FDM and SLA for the generation of bioresorbable polymer dental implants, which even exhibit odontogenic properties.

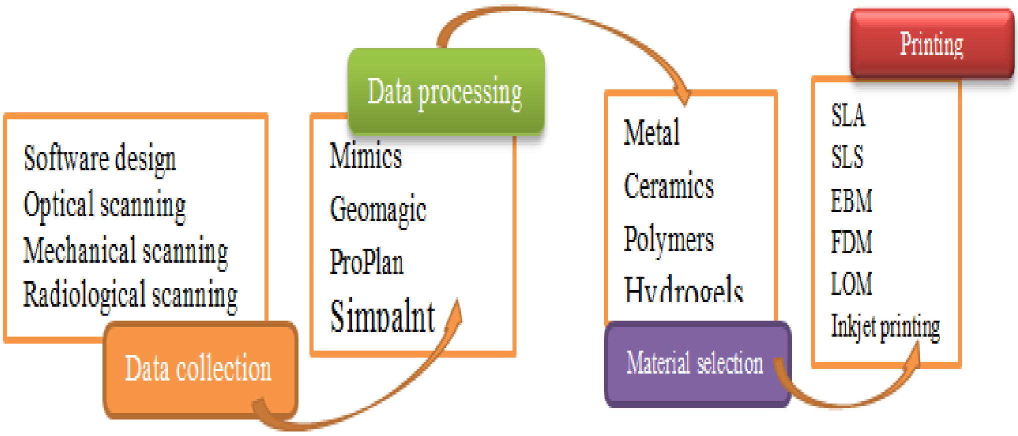
Figure 3. The image of the single step to realize a glass infiltrated dental crown prosthesis [32].

Some Recent advances in the field given in Table 2 clearly show that basic technologies taking lead in dental applications.

Table 3. Different additive process are used for the application of dental 3D printing are present Stereolithography [45].

Dental technology	Application	Literature
Digital Light Processing (DLP)	Temporary restorations, Frameworks for removable dentures, custom trays production of artificial teeth for complete dentures silicone index for provisional try-in	[46]
Polymer jetting/material jetting	Dental implants, Abutments dental prosthesis, base for digitally manufactured, complete dentures biodegradable implants with medical active, ingredients (e.g. antibiotics) bioresorbable, bio-composites and bio-ceramics, production of artificial teeth for complete dentures.	[33]
Fused Deposition Modeling (FDM)	prototype of complete, dentures made of ABS or polycarbonate casts, for the fabrication of orthodontic, splints medical carrier, substances/medicines, medical implants, biomedical applications, tissues	[47]
Stereolithography (SLA)	Orthodontic appliances, cast fabrication, complete dentures, biological frameworks (polycaprolactone), implant drilling guides, p rovisional crowns, esthetic diagnostic template custom tray	[33]

Figure 4. Workflow of additive manufacturing in dentistry.



DISCUSSION

Characterizations of dental additive manufacturing material

Many researchers believe that, Characterization in dental material sciences is essential to understand the material structure and properties [48]. It is used to understand the structure and properties of material properties by probing and measuring.

In dental Additive Manufacturing and conventional milling characterization used for analysing varies from macro to microscopic level [49]. Many techniques are available, and different methods of characterization are followed. It is used to evaluate the particle size, morphology, structural, and mechanical characterization of for Additive Manufacturing application. The techniques and the instrumentation are different in features and are in constant evolution [27].

According to investigation of Nguyen, et al. both macro and micro characterization are involved in dental material [46,50] The material is observed for the strength, structure, color, composition, and shape. In mechanical, the dental materials are evaluated for compressive strength, tensile strength, flexural, torsion, and fatigue strength [51]. Stögerer, et al. the micro investigates are taken in the surface or subsurface of materials process through electrons, photons and physical penetration. It measures the scale of atoms and grain sizes [47].

The micro characterization techniques have been used over many years. It can be depended on the source like light–optical microscopes, electron-electron microscopes, and probes Scanning Probe Microscopes (SPMs). The microscopes that are commonly used for material characterization and processing are optical microscope, SEM, TEM, field ion microscope, scanning tunneling microscope, Atomic Force Microscope (ATM), and X-Ray diffraction Topography (XRT). The microscopes aid in Evaluating the composition and internal structure of the materials of prosthodontics and restorative dentistry, the SEM and TEM have been commonly used.

Arabian J Chem, clearly stated in his paper of dental material characterization "SEM or TEM images of the samples can provide in depth information and understanding of morphological characterization, particle size, and surface characterization". For detail grain structure and atomic structure characterization, atomic force microscopes and XRT are used.

CONCLUSION

This paper intended to provide a scientific overview of process, material and characterization of the different additive procedures in dentistry. Various additive processes are on a par with or superior to established manufacturing processes and already offer considerable advantages. It is possible to produce dental work on economically and with increased complexity on-site. Recently, Many of Industries are experiencing the beginnings of the Additive Manufacturing age. The current rapid development in the field of AM dental fabrication is certainly also based on the material types and 3D printing techniques. The additive processes of FDM, 3DP, SLA and SLS can be regarded as promising processes for the future. Different characterization techniques were overviewed for understand mechanical, thermal, chemical and biological properties of material as well as their structure, size and morphological analysis. Some of characterization mechanisms like SEM, X-RT and TEM are discussed.

Some research gaps were found during working this review

- Further studies are needed to understand the influence of the printing parameters and solid load on mechanical properties after infiltration, in order to improve strength and accuracy.
- Many studies on new materials lack complete macroscopic evaluation of mechanical, thermal, and physical properties such as torsion, creep, toughness, hardness, thermal expansion, contraction, coefficient of expansion, differential thermal analysis, and electrical properties are required for more complete evaluation in dental material and essential to understand the material in detail.
- Future developments in dentistry must aim at optimizing surface quality and increasing process reliability and property gradients within the materials at lower costs and with shorter production times.

Overall, it can be assumed that from the time when the advantages of additive methods exceed their limitations, the demand for the use of the methods will increase. For this, however, higher requirements must be achieved, especially in the area of dental devices.

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