Journal of Computational Applied Mechanics 2023, 54 (2): 323-335

DOI: 10.22059/jcamech.2022.351445.774

REVIEW PAPER

Impact of additive manufacturing on advances in the design and production of the dental implants

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Abstract

Dental implants are one of the restoration methods used to revitalize the function of a lost tooth. The natural tooth has a unique structure and composition that enable it to withstand mastication loads at different rates and angles of applying load in the wet and warm environment of the mouth. To simulate such behavior, the structure, material, and design parameters (implant diameter and length, abutment connection, etc.) in dental implants are under unremitting study. A favorable dental implant should have sufficient strength and ultimate fatigue life on behalf of minimum displacement. It should be wear-resistant to keep the crown profile on the occlusal surface and remain in touch with other teeth. In this review, the effect of the usage of additive manufacturing on the quality of the 3D printed dental implant parts and important design guidelines have been studied and analyzed. Collected results are, based on finite element studies and experimental, empirical, and statistical investigations.

Keywords: Dental implants, Crown, Abutment, Additive manufacturing, 3D printing.

1. Introduction

Dental implants are a set of dental restorations that mimic the function and structure of a lost tooth. The principle of this method was first introduced in 1907[1]. The structure of dental implants mainly consists of a crown, an abutment, and an implant. There are cement and retaining screws to connect the crown to the abutment and the abutment to the implant, respectively. Fig. 1, shows the schematics of dental implant parts [2]. The manufacturing procedure of these parts has undergone several changes so far. The introduction of the CAD/CAM process to dentistry products increased the accuracy and cost of parts. Now, after the emergence of additive manufacturing, the new form of production has come to decrease costs while increasing product customization [3]. In addition to manufacturing issues, the biocompatibility and osseointegration of dental implants have been improved since the utilization of additive manufacturing [4]. In this paper, the studies conducted in the field of dental implants focusing on the usage of additive manufacturing in the production of the parts on behalf of the important guidelines in the design of dental implants have been reviewed and analyzed.

2. Terminology and Definitions

Study on the subject of dental implants includes idioms, vocabularies, and frequently used words described below:

- Gingiva: soft tissue of the mouth which covers jaws or gum.
- Incisor: cutting tooth.
- Molar: grinding tooth.
- Mastication: the act of chewing.
- Mandible: the lower jaw of the mouth.
- Maxilla: the upper jaw of the mouth.

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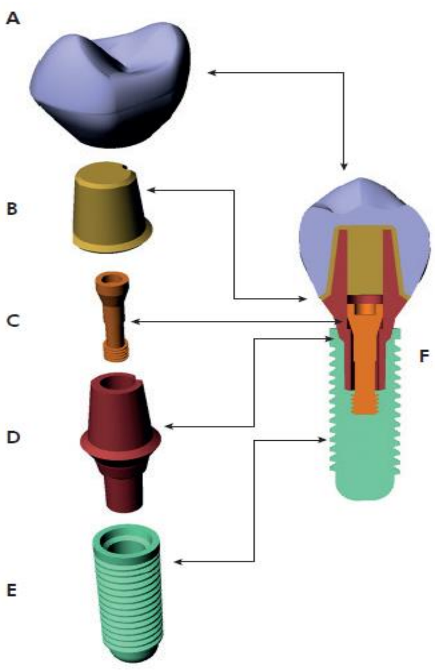

Fig 1. A. Monolithic crown B. Cement C. Retaining screw D. Abutment E. Implant and F. Dental implant [2]

- Osteoblast: cells that form the bone.
- Gingival fibroblasts: cells that form the gingiva.
- Osseointegration: growth of bone into the host part.
- Dentin: the inner part of the tooth.
- Enamel: the hard outer layer of the tooth.
- Cortical bone: high-density outer part of the jaw’s bone.
- Cancellous bone: the low-density inner part of the jaw’s bone.
- Alveolar bone: thick area on the tip of bone that holds the tooth.
- Lingual side: part of the tooth which is in contact with the tongue.
- Buccal side: part of the tooth which is in the proximity of the cheek.
- Mesial (direction): toward the midline of the mandible and maxilla.
- Distal (direction): opposite to the midline of the mandible and maxilla.
- Marginal segment: the lower part of the crown in contact with the gum.
- Occlusal surface: the upper surface of the tooth which has the main role in chewing.
- Intaglio surface: the inner surface of the prosthesis which comes into contact with gum or body.
- Bridge: Partial prosthesis for some teeth.
- Denture: complete prosthesis which covers the gingiva and touches the tongue.
- Implantoplasty: mechanically smoothing the implant surface to remove the plaques.
- Pre-implantitis: inflammation of the soft tissue and bone loss around the dental implant.
- Cytotoxicity: toxicity created by the chemical reaction of the foreign agent inside the cell environment.

3. Crown

The Crown is the visual part of the dental implant. It should be aesthetically and functionally acceptable, so the size and strength of the crown both are important parameters defining its quality. Hence, a group of studies is concerned with dimensional accuracy and fit of the crown and another group of researchers focuses on fracture strength and fatigue life of the crown. It should be noted that the dimensional accuracy of the crown is essential not only aesthetically but also for biomedical purposes. A faulty crown will not sit properly on the abutment and forms crevices that will become the nest for plaque growth or pushes the neighboring teeth. An ideal crown that fits the space between adjacent teeth and has sealed margins is depicted in Fig.2 [5].

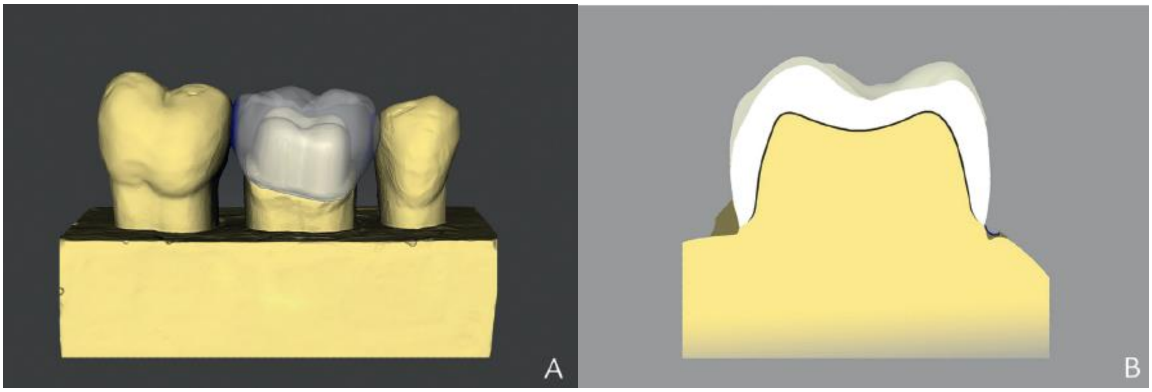

Fig 2. Interim crown design. A. placement between teeth. B. cross section in buccal direction. [5]

On the other side, the crown should have similar mechanical properties in comparison with the natural tool. A natural tooth consists of Hydroxyapatite, protein, and water [6] and the fraction of them varies in different locations of the tooth forming a hard outer layer (enamel) and a stiff inner core (dentine). This change in the fraction of constituting materials causes the modulus of elasticity and hardness of the tooth to not be constant and have a gradient profile from buccal to the lingual direction and from top to bottom of the tooth [7]–[9]. Thanks to this unique structure, the natural tooth has a high energy absorption capacity and minimum sensitivity to the rate of applying load [6]. Based on the current review, artificial crowns have focused to have a comparable or higher fracture and fatigue strength compared to natural crowns.

The main ways for manufacturing the crowns include 1- PFM[†] 2- Milling and 3-3D Printing. The produced crowns by these methods are categorized as permanent and temporary crowns. Co-Cr alloys or compositions of Zirconium are used to make crowns with permanent life, While composites, glass ceramics, and temporary resins are utilized to manufacture the temporary crowns (3 to 6-month lifetime).

PFM: in this method, a metallic core is precisely cast and porcelain is used to cover the surface of the crown. The production process is followed by polishing with Glaze and painting to give the crown a natural look. Co-Cr alloys are commercially used for metal core production. In comparison with milling, produced crowns have higher strength and low price in this method but the durability and wear resistance of the painting layer are lower than a monolithic milled crown.

Milling: this method uses pre-fabricated cylindrical or cubic work pieces to produce the crown. The workpiece is made of Zirconia ceramics or resins in this method and the ability to prepare colored workpieces has eliminated the painting process. Shrinkage of the material after the cure is noticeable but can be compensated by further calculation and considering the proper offset. In comparison with PFM, the milling method has higher accuracy in terms of the crown sitting on the abutment.

3D printing has newly joined the set of production methods. 3D-printed crowns from various types of resins, especially resins mixed with Zirconium have been manufactured but not commercialized yet. These crowns have lower mechanical strength but do not need painting or coating.

3.1. Dimensional accuracy

As mentioned before, the crown is cemented to the abutment of the dental implant’s structure. So a fine space between the crown and abutment is required for cement. Before 3D printing, painting the abutment during the impression was the common method of producing the gap, but with the abilities of CAD/CAM systems and additive manufacturing, this gap can be designed, manufactured, and numerically controlled. The ability to produce this gap with 3D printing and milling has been measured. The result of cross-section measurement showed the inability of the 3D printer in producing a uniform gap [10] but in the measurement of the intaglio surface, 3D printing has high

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[†] - Porcelain Fused to Metal

accuracy in production even more than the milling method [11]. The accuracy of production of the intaglio surface in the SLA method is more than in the DLP method [12]. Also in manufacturing occlusal surfaces, 3D printing has higher accuracy than milling and pressurized molding [5]. The accuracy of the final product is dependent on layer thickness in additive manufacturing, as well. The measurement carried out on different layer thicknesses indicating the accuracy of 3D printing is not competitive in all layer thicknesses [13].

Based on the current database, 3D printing especially production methods with point-wise scanning have the privilege of manufacturing part with the highest possible resolution but in the case of offset surfaces or different layer thicknesses, the accuracy of production depends on the interpretation of mesh and STL file. Since the CAD software of 3D printers is being designed to deal with all kinds of mesh and print them, there is a low accuracy in offsetting or slicing a mesh to make the surfaces printable. This explanation can justify the reason why a 3D printer can print a part with high accuracy but cannot produce accurate offset surfaces.

There are several ways to measure the dimensions of a crown. These methods are cross-section measurement, silicon replica technique, triple scan method, tomography, and optical tomography. Having used all methods on one sample, it has been stated that the results of measurements with each method cannot be simply used and compared with the results of other methods [14]. It is important to mention the crowns should have a clinically acceptable range of accuracy in the marginal fit section. Although, different ranges have been issued for it, unanimously, 120 μm have been reported for the maximum acceptable error of marginal fit [15]. The commercial CAD/CAM process for crown manufacturing has 3 main stages scanning, modifying, and a manufacturing method (mainly milling). Copious intra- or extra-oral scanners have been introduced by providers to probe the tooth surface, inside or outside the mouth, respectfully, and the quality of each device is different [16], [17]. The same issue existed in manufacturing methods [18], [19]. Generally, a combination of intra-oral scanners with 5-axis dental milling machines is capable of producing the crowns with an acceptable inaccuracy limit.

3.2. Fracture and fatigue strength

The fracture and fatigue strength of the crown are other important aspects. In terms of structure, crowns are usually divided into two groups: monolithic and 2-layer crowns. Monolithic crowns are made of Alumina, Zirconia, Ceramics, Lithium Disilicate, resin, Dental Composites, and mixed resins with ceramic particles [20]. 2-layer crowns are made of a metallic/ceramic inner core and an outer ceramic coating. The fracture and fatigue strength of each group of material and structure is different.

A fracture test is often conducted with a uniaxial tensile test machine and a rigid ball imposes the force on the fixed crown. The rate of applying force is between quasi-static to 1 mm/min. According to reviewed articles, metallic crowns have the highest amount of fracture strength followed by ceramics, resins, and dental composites, respectively. Despite their lower fracture strength, dental composites have the advantage of similar fracture strength in comparison with dentin. Table 1, shows the range of fracture strength for different material types. It is important to mention although various set of resins and their mixed forms was introduced by additive manufacturing, 3D-printed crowns still have less fracture strength than milled samples [21], [22].

Table 1. Fracture strength of different crowns

Crown material	**Fracture load (N)**	
Metals	~1600-1800	[23]
Ceramic	~1200-1400	[24]
Resin	~300-600	[21]
Composite*	~500-1600	[25]

*-strength varies based on combined materials and thickness

The fatigue test of crowns based on the degree of the simulation consists of cyclic loading of force and temperature to simulate mastication in the mouth environment [26]. These tests are often conducted in distilled water. Crowns with core and coating structures have the tendency to crack propagation in the contacting area of layers [24].

In crown manufacturing, competitive accuracy of the production is not the only positive point of utilizing

Additive Manufacturing and it has brought other advantages with itself. Before the introduction of 3D printing, dental resins were used in pressurized molding for manufacturing dental crowns and shrinkage was a common setback. Shrinkage is not the subject of discussion after the utilization of 3D printing. Because of the physics of the process, the resin in 3D printing has a higher degree of curing in comparison with pressurized molding. 3D printed parts produced by commercial resins have mechanical properties (i.e. modulus of elasticity) in the range of dental resins [27] so there is no hindrance to using commercial resins for medical purposes in terms of mechanical behavior.

4. Abutment

Abutments are the connecting part of the dental implant which create the bases for crown sitting. The bottom of the abutment sits on the implant surface and is connected to it by a retaining screw. The Crown sits on the surface of the abutment and a layer of cement with the defined thickness [28] is applied to stick the parts together and form the integrity of the dental implant. A wide range of materials from Titanium, Zirconium, Alumina, Lithium Disilicate, and ceramics, to a combination of them have been studied as abutment constituent materials [3], [29]. However, Zirconium abutments failed in fatigue tests [30]. Similar to a crown, additive manufacturing has been used in the production of the abutment [31]–[33]. Inkjet and selective laser sintering 3D printers have been used to produce Co-Cr and Ceramic abutments, respectively [31], [33]. The Co-Cr samples have fracture strength in a scale of the Titanium abutment [31]. As abutment location is defined in contact with the crown and implant, the related studies about abutment are often in combination with its effect on them.

Crown and abutment materials are important in terms of transferred stress to the implant. This stress has an impact on implant loosening over long periods. The best combination of materials is a hard material with a high modulus of elasticity for the crown and stiff material with a lower modulus of elasticity for the abutment [29]. This combination increases the stress on the crown but reduces the deflection of the crown and consequent effects on adjacent teeth [34]. The connection type between the crown and abutment is also important. The proper type of connection can reduce stress and increase fatigue life. [35], [36]. Fig. 3, shows two types of crown and abutment connections [36].

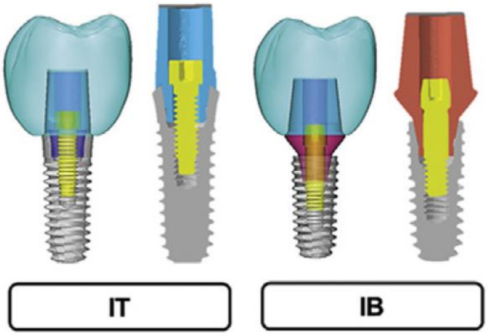


Fig 3. Internal Tissue level (IT) and Internal Bone level (IB) abutment [36]

The abutment and implant are mainly connected by retaining screws. One of the major problems, in this case, is screw loosening. Some studies have shown that in lateral loading conditions, the external load increases the torque on the retaining screw and tightens it [35], [37]. Having a sloped contact surface between the implant and the retaining screw has a positive effect on loosening resistance but maximum preload and fatigue resistance will achieve on a plain surface [38]. Fig. 4, represents the concept of design for the slope and plain sitting surface of the retaining screw.

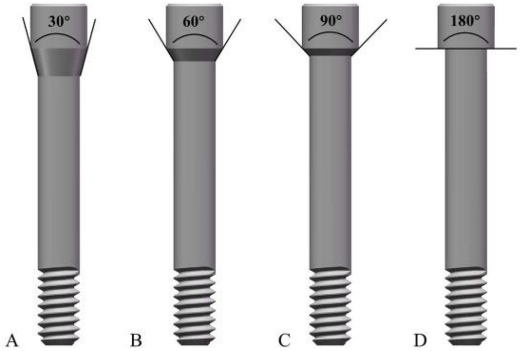
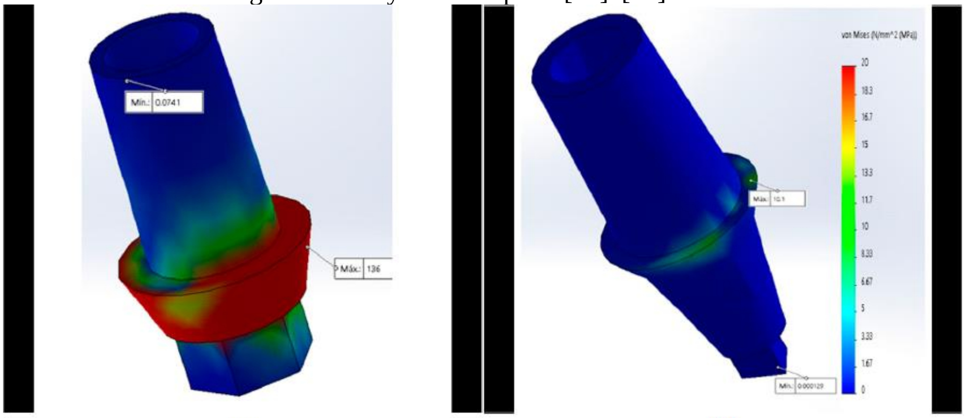


Fig 4. Retaining screw with different angles of sitting surface [38]

Also, the presence of fluids like saliva or a mouth washer is beneficial in terms of increasing the preload on the screw and reducing the screw loosening [39]. Using the abutment from a different manufacturer has no negative effect on retaining screw loosening, as well [40].

Abutment and implant connections have different shapes: inner hexagon, outer hexagon, and morse type. Different types of connections induce different stress profiles on dental implants but do not affect the stress generated on adjacent tissue [41]. Some modifications on these connections have been stated to have positive effects on stress distribution on the connection [42] (Fig.5). Some studies stated that the type of connection has no negative or significant effect on screw loosening and stability of the implant [43]–[45].



(a) (b)

Fig 5. Distribution of stress on Inner Hexagon (a) and Modified (b) abutment and implant connection [42]

5. Implant

An implant is the artificial root of a dental implant that is fastened in the jaw. Because of its length, it passes through cortical bone and touches the cancellous bone tissues. It is the main part that bears occlusal and lateral loading during mastication. The material of the implant should be corrosion/erosion resistant and stiff enough. Having all these properties and the tendency of merging with bone tissues, Titanium remained unrivaled for manufacturing not only the implant but also orthopedic screws [46]. However, recent researches have raised issues about the particle and Ion release of the Titanium implants in the surrounding environment during fixation [47], [48]. These particles are produced not only in the fixation process but also during the mastication. Even periodical maintenance may worsen the condition [49]. These particles trigger the macrophages and cause inflammation and implant loosening [50]–[52]. So surface treatment of titanium implants is an important parameter in the manufacturing process. The main parameters in implant design are the diameter, length, and thread type of the implant. There are 3 different types of implant threads: square, triangle, and buttress threads. Type of the thread has a significant effect on cortical bone distributed stress [53]. The design of the implant can be optimized by using a single [54] or multiple [55], [56] threads pitch to optimize the von Misses stress distribution on cortical bone. Increasing the diameter and length of the implant decreases the stress and displacement on the implant [36], [57]–[59]. The diameter has a higher effect on reducing the stress and displacement and the length of the implant affects the stress in cancellous bone [57]. Increasing the diameter also increases the fatigue life of the implant [35]. Tooth and dental implants normally experience occlusal loading but in the case of lateral loading, it is the root or implant's duty to bear force. Although lateral loading has a beneficial effect on retaining screw and its fatigue life [35], [37] on the other hand, it will loosen the implant in bone [37]. A controversial parameter is the ratio of the crown to implant height. Based on statistical and empirical studies, the natural ratio of the tooth to root height cannot be adopted for the crown-to-implant ratio [60]. Moreover, high ratios of the crown to implant height have no negative effect on the implant [61]. According to the investigated database, a high ratio of the crown to implant height can only increase the probability of loosening the implant [62]. This issue has been shown numerically, as well [37]. Fig. 6 depicts the crown and implant height in a radiography picture, respectively. To sum up, using an implant of titanium with a 4 mm diameter and a crown-to-implant ratio of 2 or more is generally safe for both low and high-density bones. Using lower diameters can have the risk of loosening or fatigue failure [35].

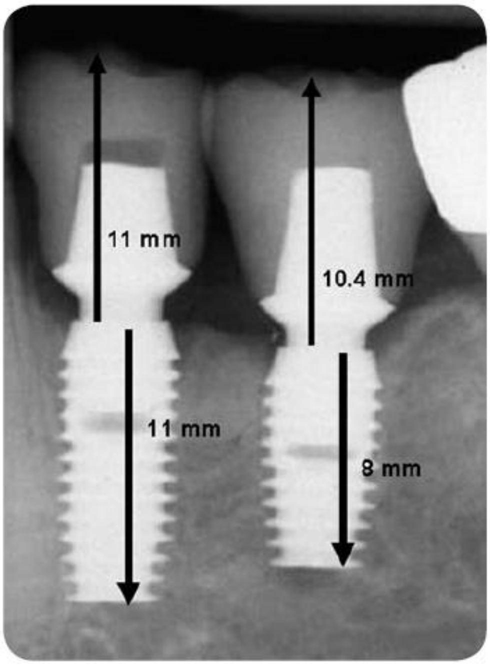


Fig 6. Example of the crown and implant height [60]

There are some innovative solutions to increase the stability and reduce the displacement of the implant in the jaw. For instance, imbuing a 3D printed scaffold with a biocompatible material and sufficient mechanical properties to support the implant in poor alveolar bone [63], use of 2 implants for one dental implant which significantly reduces the displacement in lateral loading condition [58] and using the FGM implants. In the case of using FGM implants, the displacement is not reduced in all slopes of the gradient and further optimization is required to reach the optimum results close to the titanium implant [64]. Fig. 7, represents the implant structure and finite element model used for the study [64].

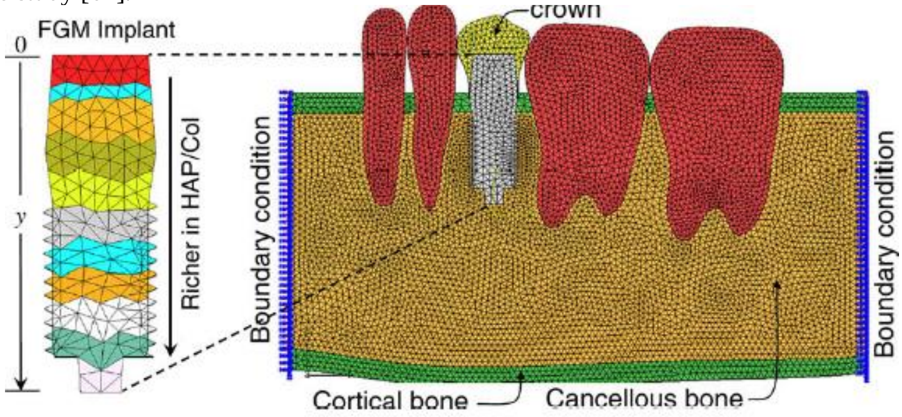


Fig 7. FGM implant in contact with cancellous and cortical bone and other teeth [64]

In addition, to gradually change the composition of the Titanium, additive manufacturing allows us to gradually change the density/porosity of the Titanium in the implant. In examined cases, a Titanium implant with a dense core and porous surface was investigated [65]–[68]. Functionally graded porosity from the inside to outside the implant, improve the Osseointegration condition and gives the implant similar mechanical properties (modulus of elasticity and yield strength) to bone tissue [65], [67], [68]. Furthermore, functionally graded porous structures have less weight and better energy absorption [69]. The proper density to reach the desired results depends on the Meta structure used for creating the porosity [65], [68]. Even a functionally graded porous zirconia implant with a dense core and porous surface has been additively manufactured and stated to have proper fatigue strength and osteoblast proliferation conditions. The emergence of additive manufacturing facilitates the use of different biocompatible metals in the production of dental restorations [70]. Engineering polymers (PEEK) have been used in implant production by additive manufacturing and successfully passed mechanical tests but the biocompatibility and non-cytotoxicity of these materials should be carefully checked [71].

6. Wear

Whole parts of dental implants are under cyclic loading during mastication and subjected to wear. In crown production, Studies have reported that The use of additive manufacturing has increased the wear resistance of the resin crowns [22] but harmed the wear characteristics of the metallic abutments [31]. The deficiency of 3D printing in fully sintering metallic particles may be the reason for this result. In the abutment and implant connection, decomposed particles have been observed on top and inside the implant [72]. A wear-resistant modified Titanium surface has been investigated that can be used in the interfaces of the implant/abutment and abutment/crown. This modification includes texturing the Ti6Al4V substrate by laser, dispersing ZrO2 particles on the substrate, and finally pressing them at a hot temperature [73]. It should be noted that erosion is not the sole form of wear at the interface of the implant and abutment. Corrosion of the interface is important, as well. Contact of the abutment made of Zirconium with Titanium implant has been reported to have the minimum rate of corrosion and erosion [74], although the search for the best pair of materials has not finished. In the implant section, coatings and various surface modifications have been investigated to reduce wear. There are different thermal-based techniques like laser cladding, thermal spraying, thermal oxidation, and electro-discharge machining that have positive effects on enhancing the corrosion and erosion resistance of Titanium implants [75]. Successive implementation of arc plasma nitriding and physical vapor deposition of a coating layer on the titanium implant, have improved implant anti-loosening performance and reduced surface wear [76].

7. Antimicrobial Feature

Dental implants do not have an active defense against the proliferation of bacteria like living organs, and it causes problems in their long-term performance. Implantoplasty is a periodical solution for removing the plaques from the implant. In situ studies have proven the effectiveness of implantoplasty in reducing bacterial film formation on the implant [77]. However, implantoplasty reduces the fracture strength of the implant and had the potential to damage the neighboring teeth [78]. Although implantoplasty successfully decreases the biofilm proliferation rate and pre-implantitis, the main issues are inflammation and bone loss leading to implant loosening. Pre-implantitis is a contributor to inflammation but not the only reason. It has been shown that implants shed nano-sized particles in the surrounding gingiva during implantoplasty [79]. As mentioned in the Implant section, these particles can become a source of inflammation again [80]. Furthermore, based on the Titanium grade used in the implant, these particles may contain vanadium and this element has been reported to be cytotoxic in certain doses [81]–[83]. Eventually, Implantoplasty has shown no significant effect on implant loosening [84]. Proper washing of the surgery location during the implantoplasty has been suggested to reduce the number of particles left in the environment, but the danger of spreading them is a concern in this method [85].

Coating the Titanium implants are other ways to preclude the proliferation of bacteria on the implant, but there is a challenge in prolonging the coating layer lifetime [86]. The emergence of surface modification methods has raised hopes to create smart surfaces which can release antibacterial material whenever needed, instead of being coated with antibacterial material [87]. Either way, the problem of refilling antibacterial agents still exists. Silver is suggested as an antibacterial material in dental restorations to reduce the density of bacteria [88]. Some researchers have examined the use of graphene Nanoparticles to improve the hardness and modulus of elasticity and have the chronic presence of an antibacterial material [89]. Also, graphene platelets have a positive effect in enhancing the stiffness of porous structures in dental implants [90]. Using antimicrobial resins in the 3D printing of dental restorations is pursued by other researchers [91]. The search for multifunctional materials that have antibacterial and other positive aspects is still in progress [87].

8. Conclusion

In the current review, the main parts of dental implants and studies on the design and manufacturing of each part were analyzed:

- Additive manufacturing has brought a wide range of options in material selection for crowns. Low cost, competitive accuracy, high wear resistance, and sufficient mechanical properties are the positive aspects of 3D-printed crowns.
- Additive manufacturing enabled us to manufacture functionally graded implants in terms of composition or density and allows us to merge the implant with the bone tissue.
- Despite the good features, AM has deficiencies in the accuracy of the offset surface production and wear resistance characteristics of the metallic parts. Further development in additive manufacturing software and printers is expected to alleviate the drawbacks.
- Crown to abutment and abutment to implant connection types are effective on distributed stress and fatigue life of the dental implant.
- Abutment to implant connection types does not affect retaining screw loosening.
- Lateral loading fastens the retaining screw and loosens the implant and axial (occlusal) loading has more effect on retaining screw loosening.
- Crown to implant ratio is an important parameter in design. The natural ratio cannot be used for dental implants and high ratios (>2) has no negative repercussions.
- Implant thread types affect the stress distribution on cortical bone. Different thread shapes and optimizations were used to improve the stress distribution.
- Titanium is the original material for implant production but tends towards particle release during fixation. Developing surface treating methods or proper process parameters in production can be useful in reducing the tendency.
- Dental implants are subject to the wear and proliferation of bacteria. Choosing proper materials with antibacterial and wear resistance features are beneficial in this manner.

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