REVIEW
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Metal Manufacturing Techniques Used in Prosthetic Dentistry

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Abstract

Although the traditional casting method has been used frequently from the past to the present, it has been replaced by computer-aided manufacturing with the development of technology, and many computer-aided manufacturing techniques are available. Although restorations without metal substructures have been developed, metal–ceramic restorations are still the gold standard in long bridges where force is intense and durability is required. It seems that they will continue to be used for many years. In this review, metal manufacturing techniques and application methods are described.

Keywords: Metal manufacturing techniques, SLM, SLS

INTRODUCTON

Metalceramic restorations, which provide appropriate mechanical properties, adequate aesthetics, and low cost, have been widely used for many years in partial missing teeth. Considering the current all-ceramic systems and their contraindications, metalceramic restorations are expected to be used for many years. Although the porcelain surface is the part that functions directly in the mouth, the mechanical and physical properties of the metal substructure affect the success of the restoration.

The traditional casting method, which is one of the manufacturing techniques, is a multistage method that requires high precision. Errors made in any of the casting stages adversely affect the metal–porcelain connection. Computer-aided design–computer-aided manufacturing (CAD–CAM) technology, which was introduced to dentistry by Francois Duret in the early 1970s, has enabled the rapid production of designed frameworks. In the milling system, dental restorations designed in the computer environment are obtained by milling from blocks. The biggest disadvantages of milling of metal blocks consisting of base metal alloys are rapid wear of milling equipment, loss of time, and excessive material loss.[1]

Laser sintering technology, which is accepted as one of the "rapid prototyping" systems as an alternative to CAD-CAM systems, has started to be used in framework manufacturing. Objects with much more complicated forms can be produced with this technology. It is obtained by assembling powdered alloys layer by layer and most errors in the casting system are prevented. Laser sintering systems are divided into categories according to the melting and bonding mechanisms of the powder particles.[2] Laser sintering devices used in dentistry mainly work with selective laser sintering (SLS) or selective laser melting (SLM) principles. These techniques, which have rapidly taken their place in the production stage, have been developed and direct part manufacturing has been started from metal powders.

GENERAL INFORMATION

Alloys Used in Metal-Supported Ceramic Restorations

Considering the clinical and economic expectations, many alloy systems have been introduced in the literature for the construction of metal-supported ceramic restorations. Each alloy system may have advantages and disadvantages.

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Material selection is made by considering clinical and economic factors. Alloys used in metal–ceramic restorations have been classified according to their cost, type of use, and content. O'Brien[3] classified the metal alloys used in metal–ceramic restorations according to their content as follows:

A. Noble metal alloys
   a. Palladium (Pd) alloys
   - Palladium–silver (Pd–Ag) alloys
   - Palladium–copper (Pd–Cu) alloys
   - Palladium–cobalt (Pd–Co) alloys
   b. Gold (Au) alloys
   - Gold–platinum–palladium (Au––Pt–Pd) alloys
   - Gold–palladium (Au–Pd) alloys
   - Gold–palladium–silver (Au–Pd–Ag) alloys
B. Base metal alloys
   a. Nickel–chromium–beryllium (Ni–Cr–Be) alloys
   b. Nickel–chromium (Ni–Cr) alloys
   c. Cobalt-chromium (Co–Cr) alloys
   d. Titanium (Ti) and titanium alloys

Noble Metal Alloys

Noble metal alloys contain at least 25% noble elements. They are highly resistant to corrosion and oxidation due to their high chemical stability. There are 2 basic systems in this group: palladium alloys (3 formulae) and gold alloys.

Palladium–Silver Alloys

Palladium–silver alloys contain 50%-60% palladium. This ratio makes the alloy resistant to corrosion. The most important advantages of this alloy are high modulus of elasticity, excellent porcelain bonding, and good castability. The disadvantage is the greenish discoloration of the porcelain due to the high silver content.[3]

Palladium–Copper Alloys

This group usually contains 70%-80% palladium, more than 15% copper and 9% gallium. Gold is either not contained at all or can be found in very small amounts. For a porcelain connection with a metal, an oxide layer of ideal thickness is required and noble metals do not have the ability to oxidize. There are trace amounts of oxidizable elements such as tin, indium, gallium in order to form an oxide layer of the desired thickness. Its use is limited due to its disadvantages such as difficult polishing, high hardness, thermal deformation, and distortion of marginal adaptation.[4]

Palladium–Cobalt Alloys

Palladium–cobalt alloys contain 78%-88% palladium, 4%-10% cobalt, and trace amounts of easily oxidizable base metals. The dark-colored oxide layer formed is very difficult to mask. Despite this, it has advantages such as the compatibility of the thermal expansion coefficient with the porcelain used, low density, and low cost.[4]

Gold–Platinum–Palladium Alloys

They contain 11% palladium, 75%-88% gold, and 8% platinum. Trace amounts of iron, indium, and tin are present to form porcelain connection. Although it has low hardness, its high cost limits its use.[4]

Gold–Palladium–Silver Alloys

It contains 39%-53% gold, 12%-22% silver, and 25%-35% palladium. Palladium content is high, and therefore it shows less bending. The biggest disadvantage is that the silver content causes the porcelain to stain.[4]

Gold–Palladium Alloys

In order to solve the color problem caused by the alloy containing silver, silver-free gold–palladium alloys were developed. It contains 35%-45% palladium and 44%-55% gold. Elements such as tin, indium, and gallium are added to provide a connection with porcelain. However, the biggest disadvantages are the high cost and the incompatibility of the thermal expansion coefficient with porcelain with a high expansion coefficient.[4]

Base Metal Alloys

Besides titanium and titanium alloys, the 2 most well-known groups of base metal alloys are based on nickel and cobalt. Both systems contain chromium as the second largest component. Alloys in this group are described as white in color due to their high levels of nickel, chromium, and cobalt.[5,6]

Nickel-Chromium-Beryllium Alloys

The addition of beryllium to nickel-chromium alloys prevents the formation of a thick oxide layer at high temperature. It also increases the flowability of the alloy and improves its castability. Since beryllium has a carcinogenic effect on the body and is difficult to excrete from the body, beryllium-free nickel-chromium alloys are used.[4]

Nickel-Chromium Alloys

Nickel–chromium alloys contain at least 60% nickel and at least 20% chromium. The addition of chromium to Ni–Cr alloy increases corrosion resistance. They have high tensile strength compared to precious alloys. It can be made thinner than precious alloys and Metal ceramic (MS) connection is strong.

It can also be used in long bridges. It is examined in 2 categories as beryllium and beryllium-free, but due to its carcinogenic effect, the use of beryllium-free Ni–Cr alloys is recommended. Due to its disadvantages such as uncontrolled oxide layer formation, nickel causing allergic reaction, and deformation in the margins after casting, its use is less common.[3]

Cobalt-Chromium Alloys

Cobalt chromium alloys are mainly composed of Co, Cr, W, Mo, and Si elements. In addition, trace amounts of Fe, Ni, Mn, N, and C elements may also be present. Cobalt is the main component of the alloy and increases the resistance of the alloy. Due to the chromium content, a thin oxide layer (Cr_2O_3) forms on the surface of the substrate. This determines its corrosion resistance.[7]

Cobalt chromium alloys have better corrosion resistance than nickel-based alloys. Their advantages include not causing allergic reactions, low cost, low heat conduction, biocompatibility, and high resistance. The biggest disadvantages are that laboratory processing is difficult and more oxidized than nickel-containing alloys.[8]

Today, Co–Cr metal substrates can be obtained by CAD-CAM and traditional lost wax (casting) methods. Alloys produced for casting are available in the form of cores (ingots), in the form of solid prefabricated blocks in the subtractive method, and in the form of metal powders in the additive method.[9-11]

Titanium and Titanium Alloys

Titanium and its alloys are widely used in the medical sector. Low cost, excellent biocompatibility, good corrosion resistance, and low thermal conductivity are the reasons why titanium is preferred in metal-supported ceramic restorations. The biggest disadvantage of titanium is the need for a special equipment for casting. It has a high melting point and casting is carried out under argon atmosphere. Another important disadvantage is the formation of a thick oxide layer at temperatures above 800°C during firing. This thick oxide layer weakens the connection with porcelain. For this reason, low temperature porcelain is used in titanium applications. With the development of techniques such as spark erosion and milling systems, these problems have been overcome.[3]

Metal Manufacturing Techniques

Conventional Lost Wax Technique

The conventional lost wax technique, also known as the casting technique, was first applied by Martin in 1891. However, the first casting device was developed by Dr Taggart in 1907.[12]

The wax structure formed on the model is surrounded by the revetment. The wax is eliminated by heat, and the molten metal is transferred to the revetment cavity through the casting channel called tij. In this way, the casting process is completed. The most desirable feature of the alloys used in the casting process is that they are castable. Castability is the ability of the alloy to fill all the details and the finest edges of the wax modeling completely. Factors affecting castability include the density and composition of the alloy, the number and shape of casting channels, the surface tension of the molten alloy, and the casting method.[13] The casting process, which consists of long laboratory stages, is a process that requires technical precision.

Problems Encountered in Casting of Frameworks

The casting technique is still frequently used in the manufacturing of metal–ceramic restorations, but it does not give the desired ideal result in the production of complicated restorations.[14]

Base metal alloys are more economical than noble metal alloys but have higher oxidation properties than noble metal alloys. Casting of base metal alloys is difficult due to the high melting temperature and oxidation. In addition, contraction of the substructures due to thermal contraction during the cooling of the melted metal cast into the cuff is one of the problems encountered. Since the hardness of base metal alloys is high, leveling and polishing processes take time.[15]

The casting process consists of successive stages and if the necessary precision is not shown, defects such as porosity, distortion, and defective margin formation may occur on the substrate. These defects weaken both the bonding of the metal substrate to the porcelain and its resistance to corrosion.[16]

There have been changes in metal production techniques used in dentistry with the development of technology. Thanks to CAD-CAM technology, alternative metal-forming techniques other than the traditional casting method have started to be used in dentistry.[17]

Computer-Aided Design and Computer-Aided Manufacturing Methods

All CAD-CAM systems technically consist of 3 stages: data collection, design of restorations, and production of restorations.[18] In this method, data are collected by scanning the gypsum models obtained directly from the patient's mouth or from the measurements taken. On the resulting 3-dimensional (3D) jaw models, the substructure design or restoration is created and recorded by CAD software. The design is transferred to the device that will perform the production, and production is provided with CAM software.[19-21] Due to its high production speed and sensitivity, the production of frameworks with CAD-CAM has become quite widely used. Computer-aided design–computer-aided manufacturing systems are analyzed in 2 sections as subtractive and additive methods.[19]

Subtractive Manufacturing Method

The subtractive manufacturing method uses milling machines to produce substructures or restorations that have been designed in a CAD program. The working strategy of the milling device is determined by processing the design file created with the CAM program and the production is carried out by milling prefabricated solid blocks. Many materials can be processed with this method, including ceramics, polym ethylmethacrylate, polyetheretherketone (PEEK), titanium, and Co–Cr alloys. Depending on the etched material, liquid cooling can be used during production.[10,22]

The advantages of this system are faster production compared to the casting method and a reduction of the mistakes that may occur due to the technician to a minimum level.[23] Since restoration is obtained by milling the blocks, a lot of residual material is formed, which is a waste of material. At the same time, the life of the burs used is limited, and there is a need for continuous bur renewal, especially in the engraving of metal blocks. All these increase production costs. The ability to produce complex shapes is limited compared to additive manufacturing. Due to these disadvantages, additive manufacturing methods are more preferred in framework manufacturing.[11,20-23]

Additive (Layered) Manufacturing Methods

According to the definition of the American Society for Testing and Materials, the production of a 3D virtual model by layering CAD data is called "additive manufacturing." A variety of materials are processed with this method, including polycarbonate, nylon, wax, plastic, ceramic, metal, powders, or composite powders made from mixtures thereof.[24] There are many additive manufacturing methods based on different principles. These are

- Scanning light curing technique (Stereolithography)
- Fused deposition modeling
- Selective electron beam melting
- Three-dimensional printing (3D ink jet printing)
- Laminated objected manufacturing (LOM)
- Solid ground curing (SGC)
- Laser production directly from metal powders

Laser Production Directly from Metal Powders

Laser beam forming of metal powders is also known as direct metal laser manufacturing. According to the classification of Greulich[25] and Levyin,[26] the main methods based on the melting or non-melting of metal powders are divided into 2 as fusion and non-fusion methods. The fusion method includes SLM and 3D laser coating systems, while the fusionless method includes SLS and laser micro sintering systems.

Among the laser manufacturing methods directly from metal powders, SLS and SLM are the most frequently used systems in metal substructure production today.

Selective Laser Sintering-Direct Metal Laser Sintering

Selective laser sintering is the manufacturing of 3D objects by melting and joining powdered material with a laser under computer control. This system was first developed by Carl Deckard in his doctoral study and commercialized by Direct Tooling Manufacture Corp (DTM). After DTM company, it was included in 3D Systems company. In the following periods, many companies, especially Electro Optical Systems (EOS), launched their own SLS devices.[2]

The SLS system is based on the principle of combining partially melted powders. These powder materials have the ability to fuse with each other when heated. The powdered material is first spread in a uniform, thin layer, and then a laser beam is sent to selected areas in direction of CAD data. When the laser beam hits the surface, heat is generated, which partially melts the powder particles and fuses them together. When the process is complete, the platform is lowered down the thickness of the layer and a new layer of powder is created. This process is repeated as many times as necessary to produce each layer. Afterwards, the free powders that have served as support are removed with a vacuum suction system or manually with a brush and the produced parts are removed from the table. The production surface is kept hot with external heaters so that the laser beams can be fused with less energy and faster.[2]

The materials that can be processed in the SLS system are metal alloys such as nickel-chromium, cobalt-chromium, titanium, stainless steel, carbon fiber, and plastic materials such as polystyrene, polyamide, and aluminium silicate ceramics. During the process, the moisture content increases as a result of the laser beam hitting the surface and may cause oxidation of the sintered metal. In order to prevent oxidation, the sintering process is carried out under nitrogen or argon gas.[27]

In the SLS system, melting takes place locally, not throughout the particles. The powder materials used can consist of 1 or 2 or more components. In 1-component materials, melting takes place on the outer wall of the particles or only in areas in contact with each other. In mixtures with 2 or more components, the component with a low degree of melting acts as a binder. The component with a high degree of melting is called the structural material. In these mixtures, the structural and connective material may be independent of each other or the structural material may be covered with the connective material.[28,29]

The direct production of parts from metal powders with SLS technology is called direct metal laser sintering (DMLS). The first patented DMLS system appeared in 1994. The first known commercial DMLS machine is the EOSINT M 250 laser sintering unit introduced by EOS. With the introduction of the EOSINT M 250, the groundwork was laid for the development of rapid production systems, and a great commercial success was achieved.[27]

Since a mixture of metal powders with different melting points is used in DMLS systems, there is no need to coat the structural material with a connective material. Among the alloys used, the alloy with a low melting point acts as a binder. In this way, metal parts with high density and superior mechanical properties are produced.[2,27]

The DMLS technology has become very popular in the production of dental restorations. Within 24 hours, it is now possible to produce hundreds of metal substructures. The larger the area of the platform on which the metal powder is spread, the more production is realized. Thanks to its high productivity, quality standardization of the products is ensured. The marginal compatibility of the restorations produced with this system, which has high working precision, is quite high.[30]

Selective Laser Melting

Selective laser melting is an additive manufacturing system based on SLS. The working principle is very similar to the SLS system. However, it differs in terms of the power of the laser beam used and the way the powder particles are bonded to each other. In the SLM system, a high-energy laser system is used to completely melt the particles, and since the particles are completely melted, high-density parts are produced.[2]

While many materials in metal, polymer, ceramic, and composite structures can be processed with SLS systems, SLM technology is generally used in the production of metal materials. In SLM machines, the heat generated in the area where the laser beams hit the surface is directly proportional to the power of the laser beam, and the heat increase is higher than the SLS system. For this reason, argon or nitrogen atmosphere is needed more to prevent oxidation in SLM systems.[27]

The first desktop SLM machine was launched by Realizer in 2009. The SLM machine, the Realizer SLM-50, was developed for businesses that produce small and customized parts. Since these machines can produce a large number of parts in a short time, they quickly became the target of dental laboratories. Today, SLM technology is also used in the production of customized implants and abutments as well as metal-supported restorations.[31]

With the developing technology, many SLM systems with the same working principle have been introduced. LaserCusing® technology developed by Concept Laser is one of them. System materials include high quality steels, aluminium and titanium alloys, nickel-based alloys, and Co–Cr alloys. The most important feature of this system is the fiber laser technology that works with the "Islands" scanning strategy, which provides equal cooling in each region by applying the laser beam randomly to different points rather than in a specific direction, and is successfully used in the production of metal-assisted restorations.[32]

In metal parts produced by both SLS and SLM systems, thermal stresses and porosities that occur after the sintering process can cause contraction of the part, weakening of its mechanical resistance, surface irregularities, and dimensional changes. In order to reduce these effects, metal parts are subjected to a secondary process called "post-processing." The post-processing process, which is usually applied as a thermal treatment (thermal annealing) in the form of a secondary firing, reduces thermal stresses on the metal part and improves structural stability and mechanical properties.[2]

RESULTS

The easy and rapid production of dental prostheses directly from a computer model using various manufacturing techniques is a revolutionary innovation. However, there is still a need to develop better quality and accuracy. Studies on metal-based materials and production techniques are continuing. Although the number of studies using new manufacturing methods has increased in recent years, there is a need for randomized and controlled long-term clinical studies with high evidence value.

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