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Review

Removable Partial Denture Frameworks in the Age of Digital Dentistry: A Review of the Literature

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Abstract: Alloys of cobalt chromium have been used for decades to create frameworks for removable partial dentures. While cobalt chromium has multiple advantages, such as strength and light weight, the casting process is laborious and requires special care to ensure that human error is minimized. Furthermore, the display of metal clasps in these frameworks may be considered a limitation at times, especially with esthetically demanding patients. The introduction of digital technology to manufacturing in dentistry has brought forward new methods of fabricating cobalt chromium frameworks, some of which eliminate the casting process. Moreover, the development of high-performance polymers for use as removable partial denture frameworks brings multiple advantages, but raises concerns over design guidelines and principles. This review examines alternatives to conventionally cast frameworks so that clinicians may make evidence-based decisions when choosing framework materials and fabrication methods in the rapidly advancing world of digital dentistry.

Keywords: removable partial dentures; RPD frameworks; dental materials; CAD/CAM; milling; 3D printing; digital dentistry

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1. Introduction

The United Nations predicts that by mid-century, individuals over the age of 60 will represent approximately 32% of the global population [1]. With the geriatric population on the rise, the prevalence of partial edentulism has increased proportionally [1,2]. According to the American College of Prosthodontists, more than 120 million people in the United States are missing at least one tooth [3]. In Japan, the Survey of Dental Diseases revealed that 81% of the elderly population are missing some or all of their natural dentition [4]. Today, partially edentulous patients, like most others, are esthetically aware and present to the dental clinic seeking not only restoration of function, but also improved esthetics [5,6]. Cast metal removable partial dentures, fabricated from different alloys, have been used to treat the partially edentulous patient for decades. Although initially made from alloys of type IV gold, cobalt and nickel chromium alloys have been used for the fabrication of cast frameworks since the 1930s [7,8]. Cobalt chromium alloys are composed of cobalt (60–65%), chromium (27–30%), and molybdenum (5–6%) along with traces of other metals that may include nickel [7]. These alloys have become increasingly popular as they not only have a lower cost and excellent mechanical properties, but are also one-half the density of gold-based alloys [8]. As a result, frameworks fabricated from cobalt chromium are significantly lighter and stronger.

One of the limitations of cast metal frameworks is the inevitable display of metal clasps, which may be deemed unesthetic by some patients (Figure 1). While avoiding or minimizing metal display may be possible by utilizing design features, such as rotational paths of insertion, precision attachments, and implants, this is not always feasible as it usually incurs extra cost and meticulous lab work. Recently, new materials have been introduced by manufacturers to address esthetic concerns and laboratory-based errors.

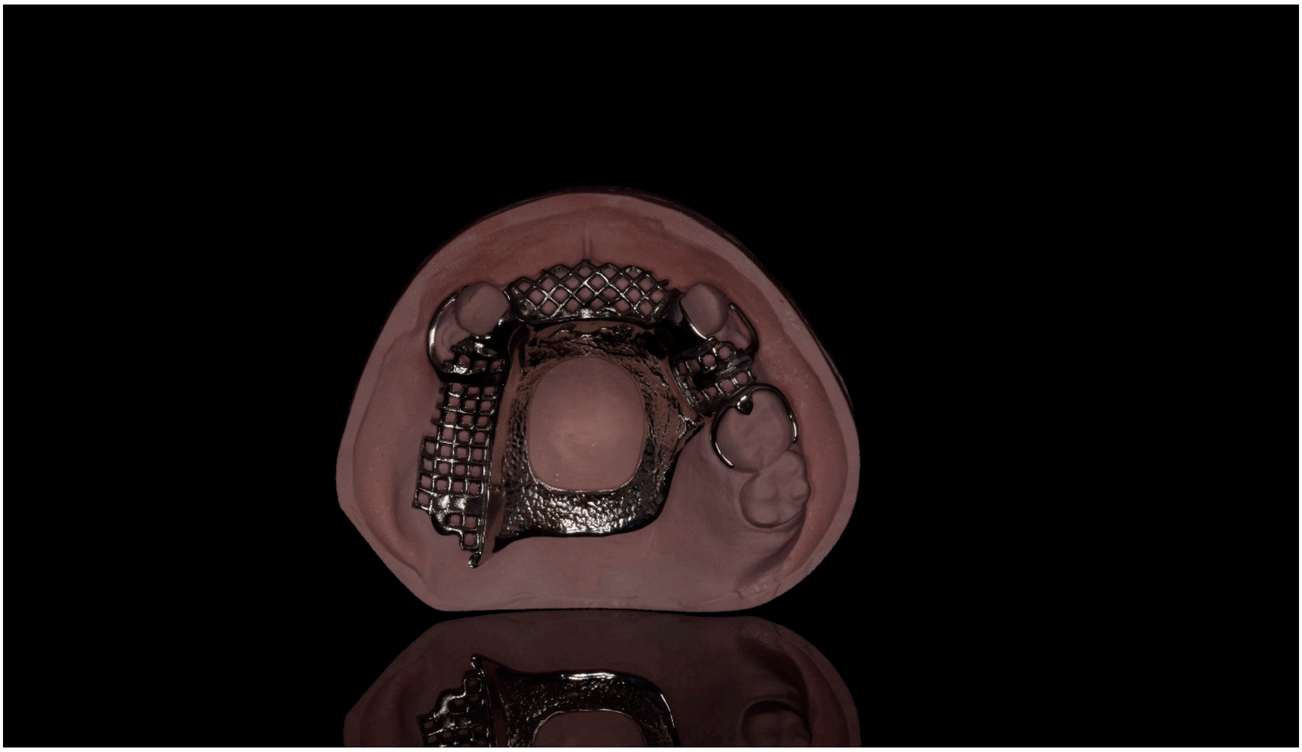

Figure 1. Traditional cast cobalt chromium framework with conventional infrabulge and cast circumferential clasps. Display of such clasps may be deemed unesthetic by patients.

Traditional methods of casting removable partial denture frameworks have been well documented. However, the fit of finished castings may not be exact [9]. Shrinkage of the metal during casting is a potential source of inaccuracy, with variable shrinkage among different alloys. Cobalt chromium, for example, has an average casting shrinkage of 2.3% [10]. Manipulation of the same alloys at different casting temperatures and dimensions also affects shrinkage and subsequent fit [11]. Investment materials used in casting cobalt chromium frameworks must have a direct compensatory effect to address casting shrinkage. Each investment material has a unique set of expansion parameters that impact the fit of clasp assemblies, minor connectors, and major connectors [10].

The rough, as cast, surface of the framework necessitates finishing and polishing prior to finalization. Finishing procedures that are not done meticulously may alter the framework to affect fit as well as the physical properties of the cast alloy [10]. In a three-part article, Rudd and Rudd describe 243 different errors that could occur during the fabrication of a removable partial denture [12–14]. Although many of the described errors were clinical, the vast majority were laboratory based.

Digital technology and the rapid development of computer aided manufacturing methods and novel materials have created alternatives to cast removable partial denture frameworks [15]. Additive and subtractive computer aided design and manufacturing (CAD/CAM) protocols are being developed to overcome casting limitations and inaccuracies. Concurrently, various resin-based polymers have been introduced to the market to address the increasing demand for more esthetic clasp assemblies. This review seeks to clarify common terminology and examine alternatives to cast metal frameworks, to allow clinicians to make evidence-based decisions when choosing framework materials and fabrication methods.

2. Methods

The key terms of RPDs, RPD framework, partial denture framework, partial dentures, 3D printing, printed, milling, milled, acetal, PEEK, Valplast, Duraflex, Ultaire

AKP, aryl ketone polymer, polyaryletherketone, polyamide, and polyoxymethylene were used separately or jointly in a comprehensive search of electronic databases that included PubMed/MEDLINE, SCOPUS, and Google Scholar. Relevant original or review articles published between 1 January 2012 and 1 January 2022 were identified. This was followed by citation mining for relevant articles. Articles published in non-peer reviewed journals and those written in languages other than English were excluded. Additionally, articles that did not focus on the removable partial denture frameworks in particular were excluded. Identified articles were carefully screened for eligibility. A total of 67 articles were considered and are discussed within the different sections and subsections of this review.

3. The Digital Manufacturing Process

3.1. Milled Frameworks

The term milled removable partial denture frameworks in the reviewed studies has a wide array of applications and meanings. Milling is a subtractive manufacturing process that utilizes burs operating on multiple axes to machine materials within certain parameters, based on a digitally designed file [16]. Five-axis milling machines are needed to create complex three-dimensional objects, such as denture bases and partial denture frameworks [17]. The milling process has become increasingly popular with the introduction of resin-based polymers in lieu of cobalt chromium for removable partial denture frameworks (Figure 2). Most novel polymers are manufactured as pucks or discs that undergo milling to produce the final denture frameworks. Generally, they require minimal adjusting, finishing, and polishing after completion of the milling process. Frameworks milled from various polymers are described in this review.

Figure 2. Milled polymer-based frameworks with supports in place. After removal of the supports, frameworks require finishing and polishing prior to beginning tooth setting.

Despite the mention of “milled cobalt chromium frameworks” and “milled titanium frameworks” by some studies and manufacturers, the milling of removable partial denture frameworks from blocks of metal is technically difficult. This has been attributed to the extensive wear of burs that occurs during the milling process, particularly with base metals [18]. The term “milled cobalt chromium/titanium framework” generally describes a framework pattern that was milled from wax or resin, invested, and cast in a conventional manner. Milled patterns eliminate the laborious task of creating a refractory cast from the master cast and forming the wax pattern by hand. Further, milling renders a pattern that is consistent in size and thickness based on the software design [17]. Therefore, these frameworks represent a hybrid method of fabrication as they are cast from a CAD/CAM milled pattern.

3.2. 3D Printed Frameworks

In contrast to milling, 3D printing is an additive manufacturing process that utilizes printing processes, materials, and technologies and to synthesize the final product. 3D printing technologies may be employed directly or indirectly to fabricate removable partial denture frameworks.

Stereolithography (SLA) and digital light processing (DLP) are two of the most commonly used processes for resin printing [19]. Both SLA and DLP printers work in a similar fashion in which light is directed at a transparent resin tank at specific coordinates based on the digital file. The framework is built layer by layer as curing progresses. The main difference between the two is the light source. SLA printers employ an ultraviolet laser beam to cure the photopolymers, whereas DLP printers use short wavelength light that is carefully guided through a liquid crystal display panel or digital micromirror device to cure the resin layers [19,20]. DLP printers are generally faster and result in less waste and lower operating costs when compared to SLA printers [20]. 3D printing technology may be used to fabricate resin patterns that are ultimately invested and cast using conventional methods. The term “3D printed metal framework” is often used to describe this hybrid technique. The term “3D printed” may be used to describe frameworks made by other methods of additive manufacturing such as laser sintering [21]. While these frameworks are technically 3D printed, in that a 3-dimensional model is fabricated from an alloy powder, the interchangeable use of nomenclature may be confusing. In this review, 3D printing with a SLA or DLP printer shall describe the printing of a non-metal (i.e., resin) framework, or a castable resin pattern.

Selective laser sintering (SLS) and selective layer melting (SLM) are additive manufacturing techniques wherein high energy laser beams, guided by a 3D model, sinter or melt metal powders together, layer by layer, to create a solid object [20,22]. Contrary to 3D printed castable resin patterns, laser sintering and melting techniques represent methods of direct “printing” of frameworks. Both SLS and SLM techniques employ similar concepts with the difference being the complete melting of the metal alloy powder in SLM. Consequently, SLM manufacturing produces accurate and extremely dense frameworks with minimal porosities [22]. SLS is more commonly used in dental applications and utilizes different materials, such as wax, thermoplastic polymers, ceramics, and metal alloys [22,23]. Both techniques are used for the additive manufacturing of metal frameworks and are gaining popularity as they reduce laboratory steps and eliminate errors associated with the casting process [20].

4. Digital Frameworks: Common Materials and Properties

4.1. Cobalt Chromium

Cobalt chromium alloys are biocompatible and have many desirable mechanical properties for the fabrication of removable partial denture frameworks. Therefore, it comes as no surprise that digital technology is being employed in an attempt to overcome the limitations of the casting process. As mentioned, there are multiple methods of fabricating a cobalt chromium framework using CAD/CAM. The hybrid method begins with digital design of a framework, followed by either milling or 3D printing of a resin or wax pattern that is invested and cast using conventional methods. SLS and SLM are alternative techniques that rely on a fully digital workflow.

Multiple studies have compared the fit of frameworks made from milled/3D printed resin patterns to each other, as well as to conventional cast frameworks [17,24–27]. Although results varied among studies, the authors agreed that the three methods resulted in frameworks that are within clinically acceptable limits. When comparing milled and printed patterns, Snosi et al. found that milled patterns improved the fit of occlusal rests, as well as overall framework fit [17]. This agreed with a second study that found that milled patterns that were cast demonstrated significantly better fit as compared to conventional cast frameworks, cast frameworks from 3D printed patterns, SLM frameworks and direct laser sintered frameworks prior to finishing and polishing [25]. Interestingly, however, these findings changed after polishing. Milled then cast frameworks still showed significantly better fit than conventionally cast and SLM frameworks but were comparable to frameworks from direct laser sintering and 3D printed patterns. This highlights the impact that careless manual finishing and polishing may have on fit [10]. Further, it is noteworthy to mention that conventionally cast frameworks took the longest time to finish and polish, with an average of 2 h. In contrast, milled then cast frameworks required an average of 1 h to finish and polish [25].

Two studies that compared SLS frameworks to 3D printed then cast patterns showed superior fit of the SLS frameworks [28,29]. This was not the case when SLS was compared to conventional casting. Although both methods were within the clinically acceptable range (50–311 μm), conventionally cast frameworks showed superior fit and accuracy [26]. Another study that compared the fit of retentive clasps and different techniques for framework fabrication found distinct differences in terms of accuracy, with the milled/printed cast patterns exhibiting the highest discrepancies [18].

Manufacturing techniques affected the fit and accuracy of the major and minor connectors [25,26]. When comparing conventional, SLS, and 3D printed cast patterns, Soltanzadeh et al. found that the poorest fit was within the anterior strap of the major connector of 3D printed resin patterns [26]. Another noteworthy finding was that only conventionally made frameworks showed no visible rocking on the cast. This was attributed to the support provided by the refractory cast for the wax pattern. Without this support, milled or 3D printed patterns may be subjected to distortion during investment and casting procedures [25].

Although studies did not show consistent results with regard to superiority, the accuracy and fit of digitally designed and manufactured frameworks appear to be within the clinically acceptable range (Figure 3).

4.2. Titanium

Titanium is considered a core material in dentistry as it boasts several desirable characteristics, many of which are similar to cobalt chromium [30]. It is biocompatible, resistant to corrosion, ductile, and has a low density, which makes it significantly lighter than other metals [30,31]. Despite its light weight, titanium exhibits excellent mechanical strength. Commercially pure titanium is classified into grades I–IV, with grade IV titanium being recommended for the fabrication of removable partial denture frameworks [32]. Early interest in titanium subsided as a result of the challenges associated with its casting [30,31]. While some of these limitations remain, advances in material science and technology have made it possible to fabricate removable partial denture frameworks from commercially pure titanium [30,31]. Some studies show that cast cobalt chromium and cast titanium frameworks exhibit similar clinical fit, porosity, and surface roughness [30]. In the world of computer aided manufacturing, both milling and SLS/SLM of titanium frameworks have been reported.

Milled titanium removable partial denture frameworks undergo a process that is similar to that of cobalt chromium, wherein a wax or resin pattern is milled, invested, and then conventionally cast [33]. Milling of frameworks from titanium discs has also been attempted. However, the poor machinability of titanium when compared to other dental alloys necessities longer milling times and results in significant wear of cutting tools [34,35]. Worn burs result in an inevitable decline in milling accuracy, as well as increased material waste. As with milling cobalt chromium, these limitations render the process highly inefficient.

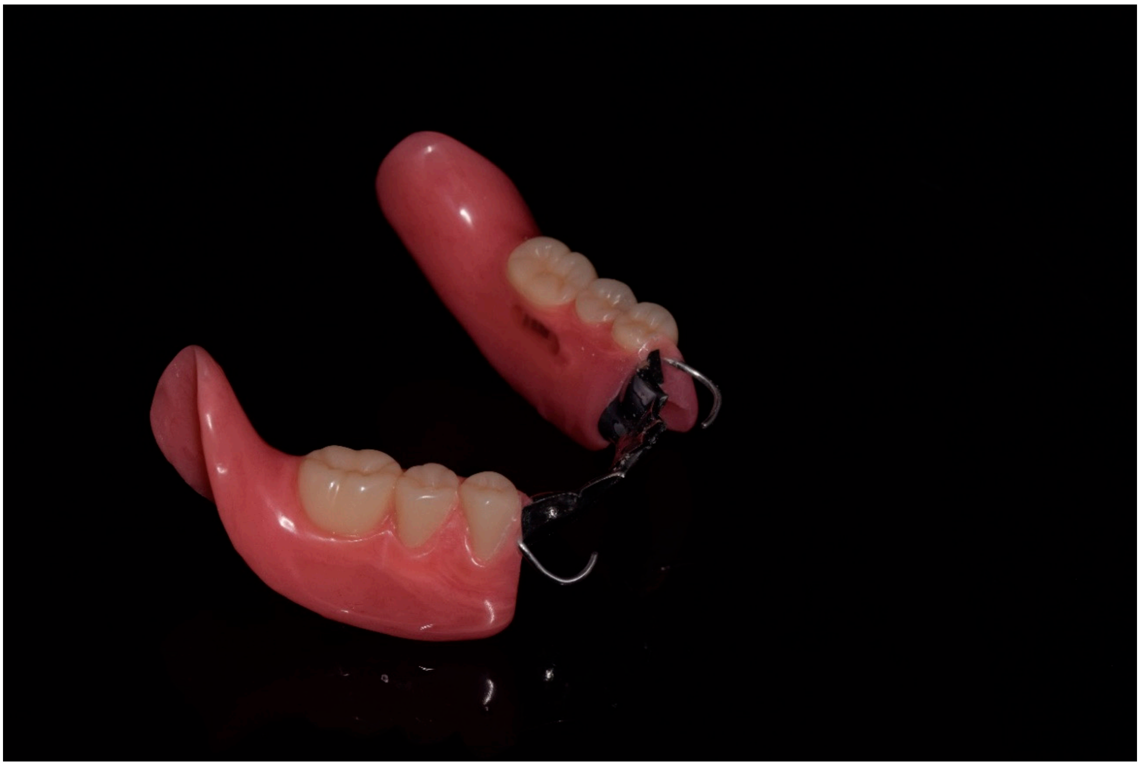

Figure 3. Finished cobalt chromium removable partial denture with wrought wire clasps. While framework fabrication methods vary, the steps of tooth setting, acrylic resin processing, and final finishing and polishing remain the same.

Multiple studies assessed the properties of titanium alloys, particularly Ti6-Al4-V, fabricated using SLS [36]. However, these studies investigated titanium from a material science perspective, and no studies were found that evaluated additively manufactured titanium removable partial denture frameworks [37]. Two studies evaluated the fit and retentive qualities of laser sintered titanium clasps. Tan et al. compared SLM, milled, and conventionally cast titanium clasps [38]. They found that although SLM clasps had significantly higher initial retentive forces, laboratory cycling significantly diminished retention, and all SLM clasps fractured at 4000 cycles. The authors concluded that laser sintering of titanium should be improved prior to clinical applications [38]. In contrast, Takahashi et al. found that laser sintered titanium clasps provided similar retention to cast titanium clasps [39]. Further, they noted that cast titanium clasps tended to have a larger decrease in retentive capabilities with repeated insertion and removal. The different outcomes may have been influenced by handling and polishing protocols, as the additive manufacturing of titanium produces rough surfaces as a result of the large particle size used [33].

4.3. Polyoxymethylene (POM)

While cobalt chromium alloys fulfil the requirements for partial denture frameworks, compromised esthetics due to the display of metal clasps is a common complaint amongst patients. Improving clasp esthetics is a challenge for restorative dentists [40]. As a result of increased esthetic demand and awareness, research has been on focused on finding alternatives to metal clasp assemblies. One such material, polyoxymethylene (POM), is a thermoplastic technopolymer made of chains of alternating methyl groups linked together by oxygen molecules [41]. It is more commonly known as acetal resin. Acetal is biocompatible and has been successfully used for total hip replacements [42], temporomandibular joint reconstructions [43], and other medical applications. Smith first suggested the possibility of using acetal resin as a denture base material in 1962 [44]. Marketed since 1986, it has been promoted as an esthetic clasp material that may be attached to a cast framework and as a denture base material [45]. Currently, acetal resin is available in 20 different shades, 17 of which are compatible with the VITA shade guide (VITA Zahnfabrik; Bad Säckingen, Germany), as well as three different pink or gingival shades [45]. It is manufactured in small pellets that can be used for injecting or pucks for wet or dry milling (Figures 4 and 5).

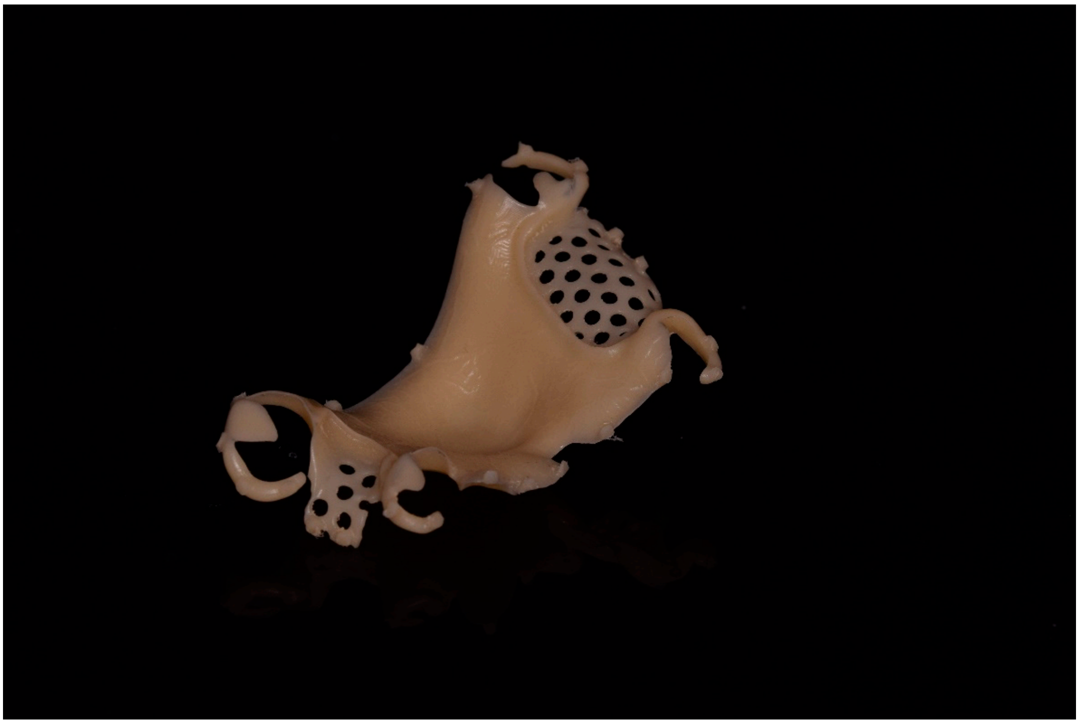

Figure 4. Acetal frameworks prior to finishing and polishing. Although rest seats were incorporated into the design, they are thin and do not provide adequate support.

Figure 5. Intaglio surface of acetal frameworks with processed acrylic resin after finishing and polishing. The frameworks were designed with meshes and finish lines to provide mechanical retention between the acetal and acrylic resin.

Acetal clasp arms may be color matched to the patient's tooth shade. Material testing of these clasps has demonstrated high wear resistance and impact strength, flexibility, elastic rebound, and resistance to most solvents and oils [45,46]. As a clasp arm, the flexibility of acetal resin allows placement in retentive undercuts that may not be suitable for cobalt chromium alloys [45]. A study by Meenakshi assessing clasp deformation showed that the initial retentive capabilities of cobalt chromium clasps were superior to acetal resin clasps. However, cobalt chromium clasps lost retention after approximately 730 cycles, while the retentive capabilities of acetal resin clasps did not diminish over the testing period [47]. In contrast, other studies have shown significantly greater deformation in acetal clasp assemblies over a three-year period when compared to those made from metal alloys [48]. To address this issue, Turner et al. suggested new specifications for acetal clasp arms. Their study showed that an acetal clasp that is 5 mm in length and 1.4 mm in cross sectional diameter would exhibit the same modulus of elasticity as a cobalt chromium clasp that is 15 mm in length and 1 mm in diameter [49]. Another study by Fitton et al. confirmed that acetal clasps require a greater cross-sectional area than metal clasps to provide adequate retention [41]. One acetal manufacturer specifies a length of 12 mm, thickness of 1.9 mm tapering to 1.25 mm, and width of 2.8 mm tapering to 2.2 mm at the tip (Figure 6). Clasps made to these specifications required a 1 kg force to displace the clasp tip by 0.5 mm, which was deemed as adequate retention for a removable partial denture [41].

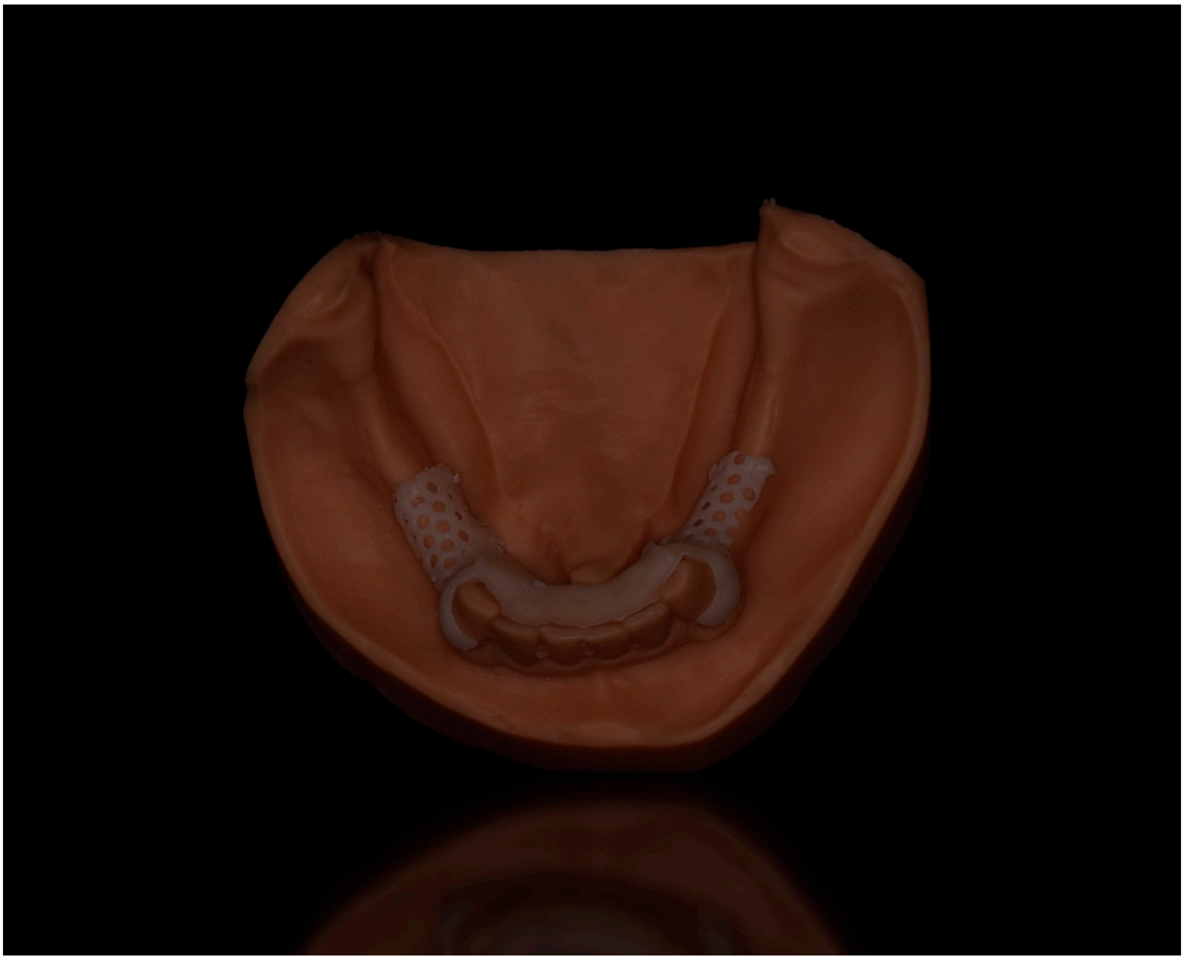

Figure 6. Although size and taper of clasp arms vary between materials and manufactures, coverage of the abutment teeth significantly increases with polymer-based clasps.

The greater cross-sectional diameter required for acetal clasp assembly results in the coverage of a larger surface area of an abutment tooth as compared to metal clasps. Increased coverage of tooth surfaces may promote increased food and plaque accumulation with subsequent gingival inflammation and periodontal disease [41]. In a study comparing microbial adhesion to acetal resin and cobalt chromium frameworks, it was noted that the soft tissue beneath acetal frameworks harbored more microorganisms. In comparison, the intaglio surfaces of cobalt chromium frameworks retained higher levels of microorganisms. This study recommended the use of metal-based frameworks for patients with gastrointestinal and pulmonary diseases to help minimize the risk of potential infection, as tissue debris and microorganisms may be eliminated with the removal and cleansing of the denture [50].

No studies were found that compared the fit of frameworks fabricated from acetal resin to those made from cobalt chromium or other polymers.

4.4. Polyamide

Polyamides, or nylons, represent another class of thermoplastic polymers. Due to its crystalline structure, nylon's properties include high strength, heat resistance, and significant flexibility [51]. Watt first suggested using polyamides as a denture base material in 1955 [52]. Since then, different companies have produced nylon denture base materials, each with their own method of molding and polymerization. Marketed under many brand names, including Lucitone FRS, Deflex, Flexite Supreme, and others, it is perhaps most commonly known to clinicians by the brand name Valplast (Figure 7).

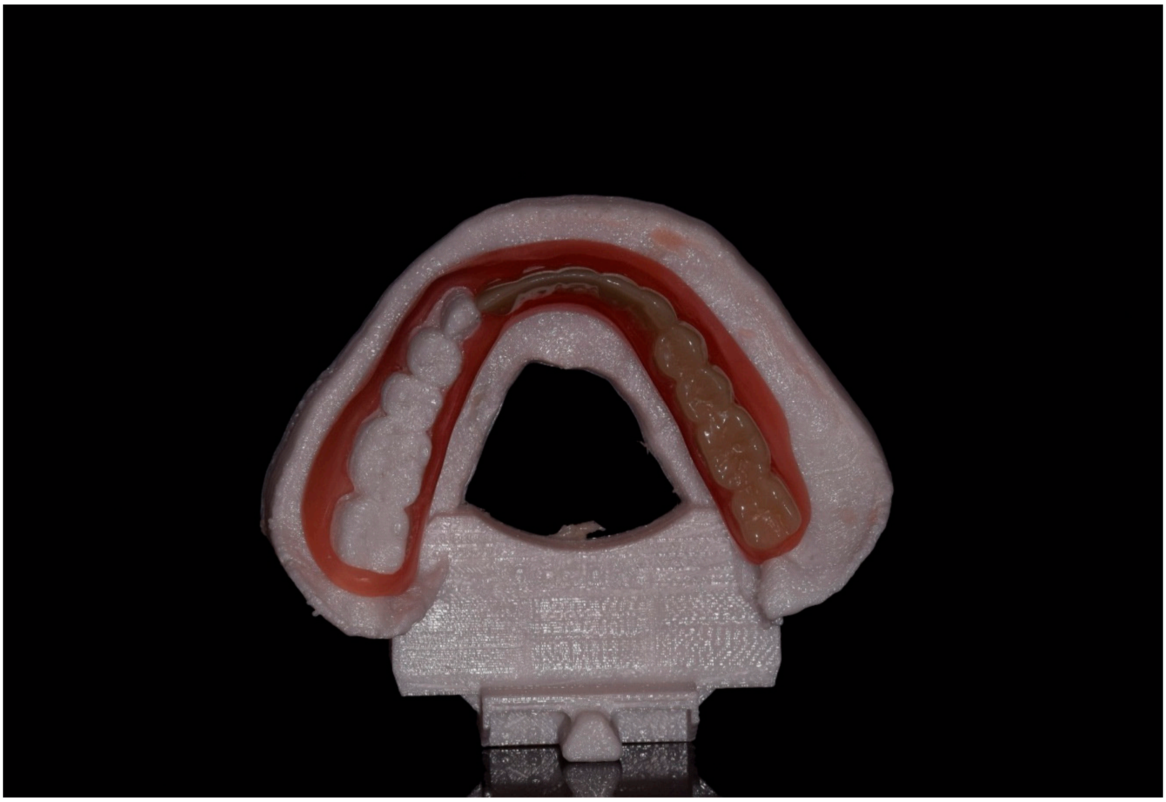

Figure 7. 3D printed polyamide (Valplast) removable partial denture. The prosthesis lacks rest seats and clasp assemblies and relies on engaging retentive undercuts of the remaining teeth.

Multiple studies have been conducted to compare the flexural strength of nylon to other partial denture materials [53–56]. The results of these studies showed that nylon partial denture bases exhibit the lowest flexural strength overall. In a related study, Takabayashi found that polyamides failed to meet the ISO standard for Type III denture base materials which requires more than 65 MPa of flexural strength [54]. He attributed nylon's low flexural strength to the absence of an aromatic ring within the polyamide structure which allows water molecules to penetrate the polymeric structure. Despite its low flexural strength, nylon demonstrates significant resistance to fracture, toughness, and resistance to stresses through deflection. This property allows nylon to provide sufficient retention by engaging undercuts on remaining teeth, thereby eliminating the need for clasp assemblies [51]. A study by Wadachi et al. showed that polyamide partial dentures exerted significantly higher forces on the supporting soft tissue compared to other resins [57]. This is likely due to the material's flexibility and the lack of tooth support, as rests seats are not usually incorporated in polyamide partial dentures. Subsequently, the authors suggested that nylon be reinforced with metal substructures [57].

Disadvantages of nylon-based partial dentures include color instability, surface roughness, and subsequent microbial adhesion. In comparison to other resins, polyamide partial dentures showed the greatest color changes when soaked in curry and coffee [54]. Similar staining occurred when nylon-based partial dentures were soaked in beverages that included red wine and cola [58]. Studies on surface roughness showed that polyamide produced rougher surfaces when compared to PMMA, both before and after polishing [59]. Polyamides surfaces proved to be softer and more easily damaged with a scratch test when compared to PMMA [60].

Multiple studies have shown that the polymerization shrinkage of nylon is greater than that of PMMA, but that water sorption may cause it to expand [61,62]. However, the expansion that occurs does not equal polymerization shrinkage, and is therefore not compensatory [61]. The water sorption properties result in dimensional instability that affects the fit of nylon removable partial dentures [51]. No studies were found that compare the fit of polyamides to cobalt chromium or other metal alloys.

4.5. Polyaryletherketone Polymers (PAEK)

Several high-performance polymers have been developed in an attempt to overcome the limitations of currently available materials. Most if not all of these polymers are derived from the polyaryletherketone (PAEK) family. These polymers are composed of aryl, ether, and ketone molecules that are arranged in different polymeric arrangements to form various amorphous and semi-crystalline structures. PEEK is perhaps the most well-known member of the PAEK family currently used for dental applications [63,64]. While the medical and dental literature cites many studies on PEEK resins, data is limited on other PAEK polymers. This review will attempt to cover some of the available studies on these polymers.

4.6. Aryl Ketone Polymers (AKP)

Solvay Dental 360 released a high-performance aryl ketone polymer (AKP) marketed under the name Ultaire AKP. According to the manufacturer, Ultaire AKP has high impact and flexural strengths, which are superior to other available removable partial denture materials [65]. In contrast to polyamides, Ultaire AKP is resistant to water sorption and resists cleaner-induced surface roughness. The manufacturer claims that its elastic properties result in clasps that outperform those made from cobalt chromium in fatigue testing [65]. Marie et al. compared the deformation and retention of Ultaire AKP clasps to cobalt chromium clasps [66]. They found that although cobalt chromium clasps had higher retentive values, there was a reduction in retention with time due to permanent deformation. Ultaire AKP clasps showed lower but consistent retentive forces over 15,000 cycles and underwent minimal deformation even when subjected to non-ideal paths of removal.

Ultaire AKP was further evaluated against polyetherketoneketone (PEKK), another polymer from the PAEK family [67]. Clasps from Ultaire AKP, PEKK and cobalt chromium were tested under similar 15,000 cycles in a fatigue test to assess retention and deformation. As with previous studies, both Ultaire AKP and PEKK clasps demonstrated significantly lower retention when compared to cobalt chromium. Fluctuating retentive values were noted for all three groups. Cobalt chromium clasps demonstrated the highest retentive values after 15,000 cycles. Baseline retentive values for polymer clasps were maintained, thus supporting their clinical use for removable partial dentures [67].

When comparing biofilm formation and microbial adhesion to Ultaire AKP and cobalt chromium frameworks, an in vitro study showed that Ultaire AKP resulted in significantly reduced *Candida albicans* and *Streptococcus mutans* biofilm attachment at 6 h [65]. A biofilm consisting of a *Streptococcus mutans*/*Streptococcus sanguinis* mixture proved to be less differentiated on Ultaire AKP as compared to cobalt chromium and POM. The authors concluded that Ultaire AKP may be an attractive removable partial denture framework material since it has excellent mechanical properties while promoting less microbial adhesion, particularly of cariogenic *Streptococci* [65].

4.7. Polyetheretherketone (PEEK)

Polyetheretherketone, or PEEK, is another synthetic, thermoplastic polymer with a semi-crystalline structure [68]. It has been used in orthopedics for many years as a spinal cage and joint replacement material [69,70]. In dentistry, PEEK has been studied as a potential material for dental implants, implant abutments, fixed crowns and bridges, and removable partial denture components [71]. PEEK has been shown to be biocompatible, wear resistant, water insoluble, and shows low reactivity with other materials. It has a modulus of elasticity that is similar to enamel, dentin, and human bones, and has a low plaque affinity compared to metals and other resins [71,72]. These properties suggest PEEK as an alternative material for the fabrication of removable partial denture frameworks.

Peng et al. conducted a finite element analysis study to assess PEEK as a material of choice for the fabrication of clasp assemblies [72]. As with acetal resin, the authors found that clasp specifications recommended for cobalt chromium alloys did not apply to PEEK clasps. They found that PEEK clasps made having a width of 3 mm, a thickness of 2.25 mm at the base and a taper ratio of 0.5 that engage a 0.50 mm undercut provided acceptable retentive and mechanical properties. PEEK and cobalt chromium clasps cycled to simulate a 10-year clinical use life span showed varying deformation profiles in early cycles, but no significant differences in the long-term deformation of either material [72]. Clinical reports of cobalt chromium frameworks using PEEK clasp assemblies showed no complications and very little color or texture changes during follow-ups at six months and two years [73,74].

Removable partial denture frameworks milled out of PEEK have also been examined by multiple authors. One study compared milled PEEK frameworks to cobalt chromium frameworks made by different methods including the lost wax technique, milled/printed castable patterns and selective laser melting. The results showed that PEEK frameworks showed the lowest distortion and best fit [18]. In a finite element analysis, Chen et al. compared the mechanical function of frameworks made from cobalt chromium alloys, titanium alloys (Ti-6Al-4V) and PEEK. In this study, PEEK frameworks exerted lower stress on the periodontal ligaments of abutment teeth and showed a more uniform distribution of masticatory forces as compared to metal alloy frameworks. However, they noted higher stresses and displacement of supporting tissues beneath distal extension PEEK frameworks [75]. Another study comparing residual ridges of patients with distal extension PEEK removable partial dentures to edentulous patients not wearing a prosthesis showed no significant three-dimensional differences [76]. These findings suggest that PEEK frameworks may have a reduced impact on supporting soft tissues and alveolar bone, and that they may help to preserve residual ridges in edentulous patients. It must be noted that this was a short-term study lasting only one year. Several case reports showed high patient satisfaction and occlusal stability with PEEK frameworks [77,78]. Interestingly, patients who had previously worn partial dentures with cobalt chromium frameworks reported reduced retention upon insertion of their newly made PEEK removable partial dentures. Some authors have suggested engaging deeper undercuts, such as 0.50 mm, or using bulkier clasps to enhance retention, if necessary [49,72,78].

A randomized controlled trial was conducted to compare oral health related quality of life (OHRQoL) in partially edentulous patients treated with cobalt chromium and PEEK removable partial dentures. The study found that both materials significantly improved

OHRQoL after four weeks, six months, and one year [68]. While patient satisfaction scores were better for PEEK removable partial dentures, the differences in scores were not statistically significantly. Further, periodontal examinations revealed no difference in periodontal probing depths, gingival bleeding indices or plaque indices between the two materials. The trial concluded that PEEK removable partial dentures and cobalt chromium partial dentures had a similar effect on the periodontium [68]. As with previous studies on PEEK removable partial dentures, the trial had a short follow-up period of one year as well as a small sample size of 26 patients.

Table 1 provides an overview of the digitally fabricated framework materials discussed in this review.

Table 1. An overview on the different removable partial denture framework materials, their method of fabrication and mechanical properties.

Framework Material	Fabrication Method	Properties
Cobalt chromium	Conventional lost wax technique Milled/3D printed castable patterns SLS and SLM	High strength, heat resistance and light weight with favorable resistance to wear, corrosion, and staining.
Titanium	Conventional lost wax technique Milled/3D printed castable patterns SLS and SLM	Biocompatible, resistant to corrosion, ductile, light weight and high strength.
Acetal	Injection molding Milling	Biocompatible, high wear resistance and impact strength, low thermal conductivity, and marked flexibility.
Polyamide	Injection molding 3D printing	High strength and fracture resistance, heat resistance, stress deflection and significant flexibility.
PAEK (AKP)	Milling	High impact and flexural strength, resistance to water sorption and better resistance to microbial adhesion.
PEEK	Milling	Biocompatible, unreactive with other materials, wear resistant, and has a modulus of elasticity that is similar to dentin and bone.

5. Considerations and Limitations

5.1. Design Principles and Guidelines

A review of case reports and studies involving digitally fabricated polymer frameworks reveals that rests are often omitted from clasp assemblies. Rigid rests are critical components of framework design as they provide vertical support to resist settling of the denture and subsequent impingement of underlying soft tissue [79]. Even when incorporated, rests made from flexible polymers will not effectively transmit vertical forces to the abutment teeth unless they are of adequate thickness [80]. This is seldom possible without aggressively preparing abutment teeth, and rests are therefore omitted. Consequently, many of the reported complications seen with polymer-based removable partial denture frameworks stem from poor removable partial denture designs and deviation from established principles [4].

To minimize plaque retention and metal display, design principles for metal clasp arms specify minimal abutment tooth contact and the importance of maintaining an adequate distance between the clasps and free gingival margins. In contrast, due to their inherent flexibility, attaining adequate retention with polymers requires clasp arms of greater dimension. This increases abutment tooth contact and may locate clasps closer to gingival margins. Polymer clasp dimension recommendations varied among studies, making it difficult to objectively compare outcomes. Further, it remains questionable whether wider and thicker polymer-based clasps provide better esthetic outcomes despite matching the shade of abutment teeth (Figure 8).

Figure 8. The unconventional size and shape of clasps required to provide adequate retention when fabricating frameworks from thermoplastic polymers.

5.2. Rigidity of the Major Connector

Major connectors join components of the removable partial denture on opposite sides of the arch. Major connectors must be rigid to provide cross arch stability and provide resistance to the forces of mastication [81]. Rigidity is diminished in major connectors made from polymers with low flexural moduli. A study assessing chewing capabilities with PMMA, acetal, and polyamide removable partial dentures found that a lower modulus of elasticity was associated with reduced chewing ability and food fragmentation levels [82]. The authors attributed this finding to the lack of rigidity of acetal and polyamide. Flexible materials may attain greater rigidity with appropriate dimensional modifications. The question then becomes how thick a major connector should be to attain sufficient rigidity, and what implications would the increased material bulk have on patient comfort, weight of the prosthesis, and interference with speech and deglutition.

5.3. Repair and Bonding

It is well established that the ongoing process of ridge resorption is not halted by the use of conventional removable partial dentures. As resorption progresses, cobalt chromium frameworks with heat processed acrylic resin denture bases may be relined using heat or self-curing acrylic materials. Relining these removable partial dentures is predictable and requires no special surface treatment as PMMA forms a strong chemical bond with itself. The composition of the polymers discussed may make bonding with acrylics or composites difficult due to a lack of chemical bonding. Peng et al. investigated methods of bonding denture base acrylic (PMMA) to PAEKs using various surface treatments [83]. They found that sandblasting and priming the PAEK material prior to bonding denture acrylic provided shear bond strength that fulfilled clinical guidelines. Other studies have examined bond strength to different polymers, but no definitive guidelines or recommendations for long term bonding have been made [84–89].

5.4. Clinical Studies and Long-Term Follow-Up

In this review, the majority of studies on digital frameworks and removable partial dentures made from technopolymers were in vitro in nature. There is a lack of clinical studies or trials with long term follow-up using sintered titanium or polymers as removable partial denture frameworks. Further, the information currently available regarding the mechanical and chemical properties of thermoplastic polymers may not apply to clinical settings [4]. Consequently, it is unknown how durable these partial denture frameworks will be, and what complications may arise in the long term. Critical issues, such as debonding, peeling, or discoloration at the junction between thermoplastic polymers and acrylic, have not been studied [4]. Further, none of the studies assessed the stability of polymer-based clasps and frameworks. Poor stability, defined as the excessive movement under function, is the most common complaint amongst removable partial denture users. The lack of definitive long-term clinical studies combined with the lack of adequate design principles should make clinicians cautious when using the aforementioned polymers for definitive prostheses.

As the CAD/CAM and material science worlds advance, research efforts should perhaps be directed towards studying alternative design principles that may be better suited to the properties of newly developed polymers. Some authors, for example, have suggested obtaining support and resistance to vertical displacement from components placed above the survey line [80]. Different clasp assembly designs that engage both above and below the survey line have been introduced [80,90]. The impact of clasp design on load distribution with polymers such as PEEK has been shown to be substantial. When this was studied further, certain clasp designs displayed similar load distribution patterns to removable partial dentures designed with the RPI concept [91]. Such findings highlight the importance of carefully assessing the mechanical and chemical properties of novel framework materials. By doing so, clinicians are able to advantageously utilize these unique properties to fulfil fundamental principles of removable partial denture design.

6. Conclusions

Digital technology has revolutionized the removable partial denture fabrication process. The development of alternative methods, such as SLS and SLM, for the additive construction of cobalt chromium and titanium frameworks is promising as they reduce fabrication errors and inaccuracies. The introduction of esthetic thermoplastic polymers as potential framework materials has challenged many aspects of the design and fabrication of removable partial dentures. Within the limitations of this review, the following conclusions can be drawn:

1. While promising, clinical studies on additively manufactured titanium frameworks are required to determine their overall fit, function, and impact on supporting abutment teeth.
2. Clasp arms made from thermoplastic polymers require additional bulk to serve as retainers.
3. The inherent flexibility of novel polymers limits their use as major connectors, minor connectors, and rest seats.
4. Removable partial dentures made from novel polymers are difficult to reline and repair.
5. Currently, removable partial dentures made from thermoplastic polymers are best used as interim prostheses as long-term evidence of their function is lacking.
6. Future improvements in high performance polymers and digital manufacturing methods may help to address the need of the growing partially edentulous population.

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