An Overview of Carbon Fiber Reinforced Composites in Prosthetic Restoration

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Abstract: ***Purpose of the Article**: To review the use of carbon fiber - reinforced composites in prosthetic restorations in complete and partially edentulous patients. **Background**: Prosthesis reinforcement with the fibers such as carbon fiber mainly improves fatigue behavior and impact strength. Carbon fiber reinforced composites have highly favorable mechanical properties and their strength to weight ratios are superior to those of other materials. When compared to metals and conventional dentures and frameworks, carbon fibers offer many other advantages as well, including non - corrosiveness, low density, greater stiffness, abrasion resistance, high fracture strength, high fatigue and creep resistance, biocompatibility, chemically inert, dimensional stability, low coefficient of thermal expansion and last but not least cost - effectiveness. They also offer the potential for chair side and laboratory fabrication without costly sophisticated equipment. Thus, this article reviews the carbon fiber that is reinforcing various prostheses. **Conclusion**: Carbon fiber reinforced prosthesis is the viable alternative option to the conventional prosthesis providing similar stiffness and rigidity and optimal biocompatibility. The development of a protocol for the fabrication of these prostheses and specific training for dental technicians is recommended to achieve satisfactory results. **Data**: Review articles, Finite element analysis, invitro studies. Source: PubMed, MEDLINE, ResearchGate, Google scholar, https://en.ruthinium.it, http://www.deiitalia.it, Web of Science databases were searched between 1987 and 2020.*

Keywords: Carbon fiber reinforced composites (CFRC), Carbon incorporated Implant plaque removal instrument, Fixed Partial Dentures frameworks, Implant frameworks, Implant over denture, Carbon fiber reinforced posts, Carbon fiber reinforced denture bases

1. Introduction

Rapid and fast changing concepts of composite technology led to the reinforcement of different materials using fibers. Several types of fibers including carbon fibers, glass fibers and ultra - high modulus polyethylene fibers have been employed to reinforce prosthesis. Considerable research has been carried out in this area with an improvement in several mechanical characteristics. However, the ability of fibers to reinforce the prosthesis is found to be dependent on the individual properties of the fibers; impregnation of fibers with resin; adhesion of fibers to the matrix; orientation of the fibers; volume of fibers in the composite matrix and location of fibers in the prosthesis.

Carbon fiber is the union of many thousands of filaments. Each Filament is made of 99.9% chemically pure carbon with a 5–10 μm diameter. The bulk of carbon fibers were made by heating polyacrylonitrile in air at 200˚C - 250˚C. Followed by heating in an inert atmosphere at 1200˚C, that removes hydrogen, nitrogen and oxygen, leaving a chain of carbon atoms and thus forming carbon fibres.1Fibersare united with a matrix to hold the resistant fibers together and to maintain the shape of the product.

There are many manufacturers of carbon fibers who impregnated and reinforced the carbon fiber in various dental prosthesis, few are RUTHENIUM FIBRA, DREAM FRAME [DEIItalia, Mercallo (VA), Italy].

The different orientations of carbon fibers include strand form, woven mat form, layered fibers, arranged randomly, longitudinally and perpendicular to the applied force.[1]

Carbon fibers were mainly used to improve fatigue behavior and impact strength of the prosthesis. They mainly offer a quality restoration with desirable properties.[1]

So, the present study reviews at carbon fibers reinforced in denture prosthesis like conventional denture, over denture, endodontic posts, implant plaque removal instruments, implant and FPD frameworks and their effects on mechanical properties on the restoration.

History and development:

In the late 1860's, **Sir Joseph Wilson Swan** first created carbon fiber to use it in an early incandescent light bulb. In 1879, **Thomas Edison** used cellulose - based carbon fiber filaments for first light bulbs, their considerable tolerance to the heat made these fibers ideal for conducting electricity. In 1958 OH, **Roger Bacon** accidentally produced the first petroleum - based carbon fibers when he tried to measure the triple point of carbon.

In 1980's, **McLaren** racing team introduced the first carbon fiber bodied race car and thus began to use it in the automobile industries.

Since 1980's attempts have been made to use carbon fibers to construct prosthetic frameworks. Use of carbon fibers to improve the strength of denture bases was reported by **Larson et al** in 1991.[1]

Applications of carbon fibers:

a) **In dentistry, carbon fibers are used in fabrication of:**
- Fixed partial denture framework
- Carbon incorporated Implant plaque removal instrument
- Carbon fibre reinforced denture bases
- Implant over denture
- Implant framework
- Carbon fibre reinforced post.

b) In medical field, carbon fibres are used as Carbon reinforced orthopedic implants, MRI scan, Hospital wheel chairs and other surgical uses.

c) In other fields like in acoustics, textile and paper industry, aerospace, automobile, civil engineering, sports equipment, energy production, portable power sources carbon fibers are used.

Fixed Partial Dentures Frameworks
- FPD frameworks are used to improve the prosthesis rigidity and stiffness, reducing possible complications such as prosthesis fractures while rigidly splinting the abutment teeth together.
- The metal frameworks supporting fixed prostheses are expensive, technique sensitive and time - consuming to fabricate. For this reason possible alternatives are emerging.
- Carbon fiber reinforced frameworks are the viable alternative to the metal framework. This newer material is cheaper, faster and better in properties having high stress absorption to occlusal load, high fracture resistance, less density, increased cell viability and high elastic modulus compared to the metal frameworks. (figure: 1)
- Since it is an unesthetic material, before layering/veneering, the framework is masked with a silicon dioxide–based white opaquing agent.

(A)

(B)

Figure 1: (A) Carbon fibre FPD framework. (B) framework after layering

Carbonfiber Reinforced Dentures

- Carbon fibers were mainly used to improve fatigue behaviour and impact strength.
- It is difficult to handle the dry carbon fibers and must be wetted with monomer to form the tows of wet fibre.
- The tows of wet fibre can be laid side by side and enclosed in a thin sheet of PMMA to form a prepeg, which can significantly increase the transverse strength and reduce the fracture of dentures compared to unreinforced acrylic resins.
- However, fibers must be coated with a silane coupling agent to provide proper adhesion between fibers and PMMA resin.
- The different orientations of carbon fibers include strand form, woven mat form, layered fibres, random, longitudinal and perpendicular to the applied force.[1]
- Resins which contain layered fibres of specific orientation exhibit increased resistance to applied stress and significantly increase the flexural fatigue resistance of fibre reinforced acrylics. (figure 2)

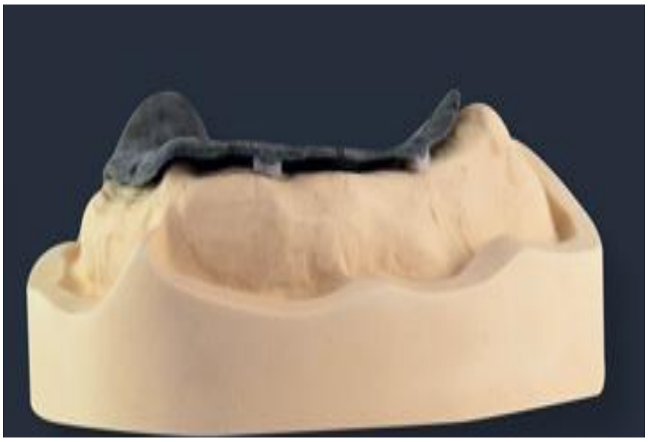


Figure 2: Resin impregnated carbon fibre adapted on crest and palate of the cast to reinforce in the denture bases.

- Isa et al. studied and compared the flexural properties of denture bases reinforced with carbon, aramid and glass fibers, which were arranged in long axis of the specimen and it was found to be the flexural strength of denture base polymers reinforced with carbon fibres were more than the other fibers studied.[1]
- Uzun et al. (1999) observed a significant improvement in the impact strength and elastic modulus of acrylic denture base reinforced with woven carbon fibres.[1]
- Strand form of carbon fiber reinforcement had showed the superior transverse strength than woven mat form.
- Longitudinally oriented fiberstend to increase the resistance to flexural fatigue than the random fiber arrangement.
- Hence, Carbon fiber orientation perpendicular to the direction of the applied stress produced the most favorable combination of increased resistance to bending and to flexural fatigue.[1]
- Studies shown that impact strength of carbon fiber reinforced acrylic denture base resin can be increased by increasing the fiber length and concentration in the polymeric matrix.
- Biological evaluation of carbon reinforced denture base materials has not been evaluated extensively although cytotoxicity of carbon fibers is considered to be a problem. There is a possibility of skin irritation on handling carbon reinforced denture base specimens.
- Ekstrand et al. (1987) assessed the cytotoxicity of leachable elements from carbon - graphite fibres subjected to different surface treatments using agar overlay technique and found that fibers with cleaned surfaces were less cytotoxic than the non - treated ones.[2]
- In comparison with the metal based dentures, carbon fiber reinforced dentures also shows unesthetic behaviour but having superior in all other properties.
- Carbon fibres are not so extensively used currently because of their difficult handling techniques, problems with polishing, poor esthetics due to black color of the fibres and potential toxicity. (figure3)

Figure 3: Carbon Fibre Reinforced Denture Base

Carbon Fiber Reinforced Implant Prosthesis

Implant Framework

Figure 4: Carbon Fiber Reinforced Implant Framework

Implant Overdenture

Figure 5: Carbon Fiber Reinforced Implant Overdenture

Accuracy and rigidity of prosthodontic frameworks have been reported as fundamental prerequisites for the predictable osseointegration of dental implants that are immediately loaded.[3]

- Implant frameworks help in splinting implants with rigid prosthesis and it protects from overloads and micromotions.
- Conventionally, metal frameworks provided sufficient rigidity and stiffness to the prosthesis even if the prosthodontic space is limited. However, they are expensive and time - consuming to fabricate and for this reason possible alternatives are emerging.
- Recent improvements in composite materials have made it possible to fabricate metal - free fixed partial dentures by using various fiber - reinforced frameworks.
- Fiber - reinforced acrylic resin prosthesis offer a cheaper alternative for the patient and ease of use to clinicians and in laboratories.
- Among all, Glass fibers have been mainly used as reinforcement of resinous prostheses, due to their esthetic characteristics. But, their mechanical behavior appeared unsatisfactory compared to metal alloys.
- Carbon fibers may guarantee better mechanical properties when compared to glass fibers with greater stiffness and strength.
- They provide high stiffness, light weight, low density, low coefficient of thermal expansion, low abrasion, good electrical conductivity and vibration damping, biological compatibility, chemical inertness (except in strongly oxidizing environments or when in contact with certain molten metals), elasticity to failure at normal temperature, high fracture strength, high fatigue and creep resistance.[3]
- The properties of the composite are strongly influenced not only by the quantity of carbon but by the orientation of the fibers.
- The full - arch implant - supported fixed dental prosthesis (figure: 4, 5) described as a simple prosthesis with a high esthetic yield, low weight and resistance to wear similar to natural teeth, lower costs than when using many other materials, goodshock - absorption, and no need for post - passivation.
- For this reason, the framework of carbon - fiber composite material is promising for the creation of implant - supported full - arch prosthetic rehabilitations, and it can be a valid alternative to metal or metal - free products.[4]
- These characteristics make Carbon Fiber Reinforced Composites (CFRC) appear excellent for fabrication of frameworks in fixed implant - supported prostheses. However, their application in this field has not been investigated yet.[2]

Carbon Fibre Reinforced Post

- Carbon Fiber - Reinforced (CFR) / Epoxy Resin Posts CFR post system was developed by **Duret** and **Renaud** in France and introduced in Europe in the early 1990s.[7]
- Epoxy resin is reinforced with unidirectional carbon fibers which are parallel to the long axis of the post and forms the matrix for the post. (figure: 6)

Figure 6: Carbon Fibre reinforced post

- The 8 mm fibers are uniformly embedded in the epoxy resin matrix which comprises 64% of the post by weight and are stretched before injection to enhance the physical properties of the post. On application of stress, the post is reported to absorb and distribute it along the entire post channel.[7]
- The CFR post has been reported to exhibit high fatigue strength, high tensile strength, and a modulus of elasticity similar to dentin.

The post which was originally radiolucent is made radiopaque by adding traces of barium sulfate and/or silicate to it.[7]

- Carbon fiber posts being black which can reflect through the all - ceramic restorations, gingiva or tooth and along with its minimal radiopacity makes it less favorable under esthetic considerations.
- However, their ease of use, flexibility, and retrievability makes them favorable and appropriate for gold or porcelain fused to metal crowns.[7]
- Mannocci et al. found that only Composite post and Snowpost posts had uniform radiopacity compared to carbon post.[8]
- On comparison of fiber - reinforced resin posts with a titanium post, Finger et al. found that CFR posts had an acceptable radiopacity.[7]
- The surface roughness of 5 - 10 µm, enhances the mechanical adhesion of post to an auto - polymerizing luting material and the cytotoxicity tests reveal the post to be biocompatible.[7]
- Several studies have indicated that CFR posts exhibit acceptable physical properties when compared to the metal posts.
- King et al. evaluated the physical properties (fracture resistance and modulus of elasticity) of CFR posts and concluded that CFR posts are superior than prefabricated metal posts.[9]
- Novais VR et al. stated that Posts reinforced with carbon fibers have a higher flexural strength than glass fiber posts, although all posts showed similar mechanical property values with dentin.[21]
- Especially when endodontic posts are introduced into the root canal, there is a totally different and unnatural structure that has totally dissimilar stiffness to that of the pulp. Therefore, it is favorable to use materials with mechanical properties closely resembling that of natural dentin.
- According to Galhano et al. Posts reinforced with fibers have modulus of elasticity of approximately 20 GPa, whereas cast metal alloy posts and prefabricated metal posts have about 200 GPa and ceramic posts about 150 GPa.10 Thus, carbon fiber reinforced posts have

mechanical properties similar to that of natural dentin (18 GPa).[22]

- Carbon fiber posts have shown a low failure rate and are clinically satisfactory in 2 - 3 years follow - up cases.
- On the other hand, Sidoli et al. in an in vitro study, found that CFR posts exhibited comparatively poor strength.[10]
- Martínez - Insua et al. reported that the fracture resistance of teeth restored with CFR was lower compared to cast post and cores.[7]
- Multiple studies indicate that there is a decrease in the strength of CFR posts after thermocycling and cyclic loading extraorally.
- On contact of the post with oral fluids has shown to reduce the flexural strength values.
- When the ferrule is small or absent in an endodontically treated tooth restored with a CFR post, loads may cause the post to flex causing a micro-movement of the entire core resulting in a compromised cement seal at margin of the crown accompanied by microleakage of oral bacteria and fluids. As a result, secondary caries may develop in the space and may not be easily detected.[7]
- Despite all the advantageous properties, in vivo applications of the CFR post can be questionable.
- Commercially, carbon fibre reinforced posts are available in different sizes comparative to the G. G drills (figure: 7)
- Available with trade names of MORITA; c - post Bisco. inc.

Figure 7: Various Sizes of Carbon Fibre Posts

Carbon Incorporated Implant Plaque Removal Instrument

- Implant Deplaquer instruments are made of carbon - fiber reinforced plastic material, with sufficient strength to remove plaque and calculus from the implant neck while minimizing scratches on metal surfaces. (figure: 8)
- There are wide choices of plastic currets available and specially shaped blade allows implants to be cleaned from all sides.
- This instrument selection should be determined based on the location and tenacity of the calculus present.

Figure 8: Carbon incorporated implant plaque removal plastic currets

Available in two shapes and they are made of graphite/ carbon fillers to make plastic rigid. Under the trade names of Dream frame, Ruthenium fibra, Kerr dental etc.

- A 4R/4L universal design: Allows the topical reach of all surfaces. Used for light to moderate calculus removal. Due to the fine blade and rigidity of this instrument, breakage can occur when used on heavy calculus.[19]
- A hoe design / Orofacial scaler: Allows the reach of lateral sides with more surface available. This is effective in the presence of severe ridge resorption in the anterior mandible. This instrument is appropriate for areas of heavy calculus with difficult access.[19]

Advantages of carbon fibres:

- High quality
- Light weight
- No special equipments required
- Casting is not done
- Better adhesion
- Economical
- Fracture resistant

Disadvantages of carbon fibres:

- Unesthetic
- Cannot be recycled and reused

Properties of carbon fibres:

- Low density
- Stiffness
- Abrasion resistance
- High fracture strength
- High fatigue and creep resistance
- Biocompatibility
- Chemically inert
- Dimensional stability
- Low coefficient of thermal expansion
- Cost effectiveness

Indications of carbon fibre reinforcement in prosthesis:

- Single complete denture
- Implant supported Overdentures
- Long span bridges
- In High strength endodontic posts
- Full mouth rehabilitation
- Metal free frameworks
- Light weight prosthesis
- Immediate loading fixed full - arch rehabilitations
- Screw retained prosthesis
- Optimal esthetics

Contraindications of carbon fibre reinforced prosthesis:

- High esthetic concern
- Bulky restoration

2. Materials and Methods

Methods of fabrication of the CFRC based denture base and implant frameworks.

Superimposing and Pressure Moulding Technique (Figure: 9)

- In fabrication of carbon fiber framework, first resin patterns are developed. Putty index of the master cast and one of the frameworks should be created.
- Preweighed resin matrix is mixed, applied evenly on carbon fibre sheet (figure: 10) using template, the fibre sheet is cut to obtain multiple pieces and superimposed.
- The carbon multilayer was then cut in a horseshoe form and adapted on the master cast.
- The master cast along with the fibre is vacuum pressed.
- Then tempered in hot water bath at 80 ^{o}c for 1hr. The framework is trimmed using putty index, and finished.

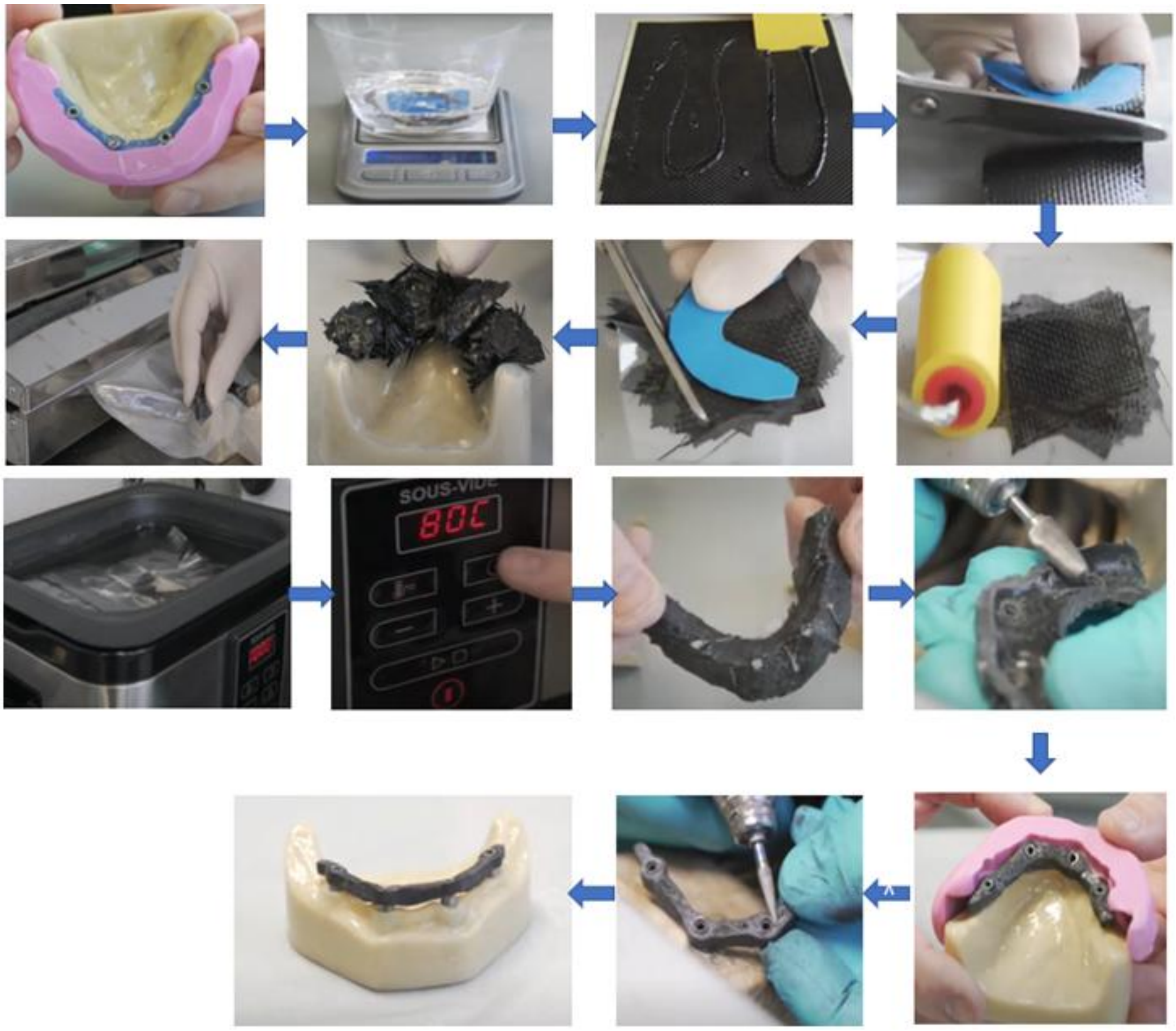


Figure 9: Superimposing and pressure moulding technique

Carbon Fibre Sheet and Resin:

Figure 10: A) Carbon Fibre Frame: youngs modulus: >600 Gpa. B) Epoxy Resin

Finishing and Polishing Kit:

A kit of diamond - coated burs with carbon coating is used for the finishing.

Figure 11: Diamond - coated burs with carbon coating for shaping and finishing

3. Recent Advances

1) Carbon Fiber in Digital Dentistry:

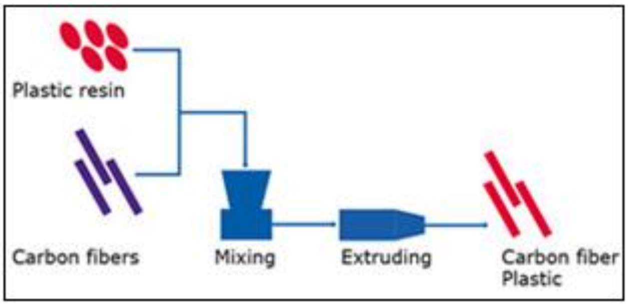
Subtractive manufacturing:

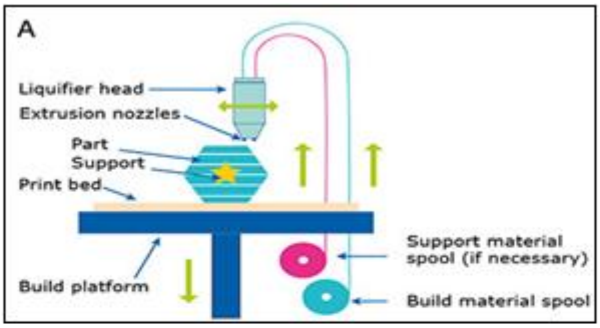
Carbocad 3D discs are a true revolution in the dental field, as a matter of fact they are made of carbon fibre with random braided wires, a patented fibre that can be shaped into any 3D form.[18] (figure: 12) Due to the minimal/ no studies are donerelated to the usage of carbocad 3D, studies yet to be done to conclude its character.

Figure 12: Carbocad 3D discs

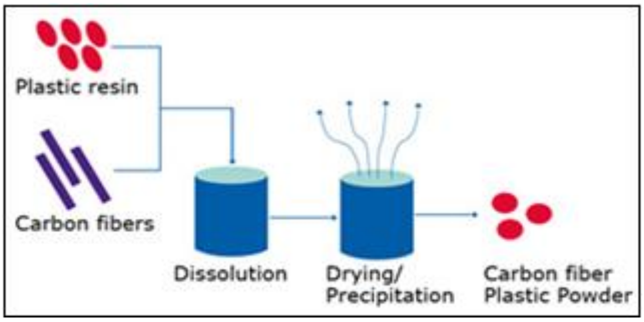
2) Additive Manufacturing:

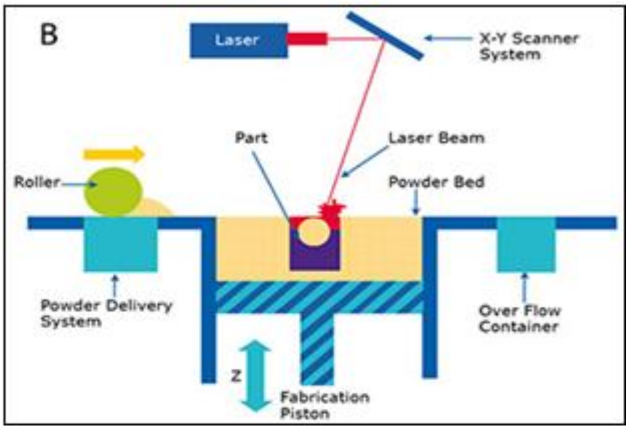
a) Fused deposition melting:





b) Selective laser melting:





4. Discussion

Özen J et al effectively determined the cytotoxic potential of glass and carbon fibers, the particle blending method was used in Groups PGF and PCF, in which the fibers were randomly dispersed in the acrylic resin bulk and surface, to provide a direct contact of the fibers to the cells so as to easily affect their viability.[11] It was determined that glass and carbon fiber reinforced heat - polymerized acrylic resin was found moderately cytotoxic by decreasing the proliferation of gingival fibroblasts by approximately 20%. No difference in cytotoxicity was found between fiber - reinforced groups and the fiber impregnation methods. The unreinforced acrylic resin was significantly less cytotoxic than the reinforced groups. The average decrease in proliferation rates was about 19% at the end of the first 24 hours, and 4.2% at the end of 72 hours incubation periods.[11]

Menini M et al investigated the biocompatibility and mechanical characteristics of dental implant frameworks made of carbon fiber composite. Extracts of CFRC caused no signs of cytotoxicity to L929 mouse fibroblasts and MTT assay. Cell count and cell vitality presented high value both for CFRC intact samples and the fragmented ones. Microscope observation revealed high density of cells grown in contact with the extracts. Cells showed a polygonal morphology and firmly adhered to the bottom of the wells. Very rare multinucleate giant cells were observed.

Carbon fiber - reinforced composites demonstrated optimal biocompatibility and mechanical characteristics. They appear suitable for the fabrication of frameworks for implant - supported full - arch dentures. Great attention must be paid to manufacture technique as it strongly affects the material mechanical characteristics.[3]

Castorina G et al believes that the framework of carbon - fiber composite material is promising for the creation of implant - supported full - arch prosthetic rehabilitations, and it can be a valid alternative to metal or metal - free products such as metal - ceramic and zirconia, due to characteristics of corrosion resistance, high resistance, and lightness. (Figure: 13) The full - arch implant - supported fixed dental prosthesis provides a simple prosthesis with a high esthetic yield, a weight and resistance to wear similar to natural teeth, lower costs than when using many other materials, good shock - absorption characteristics, and no need for post - passivation.[4]

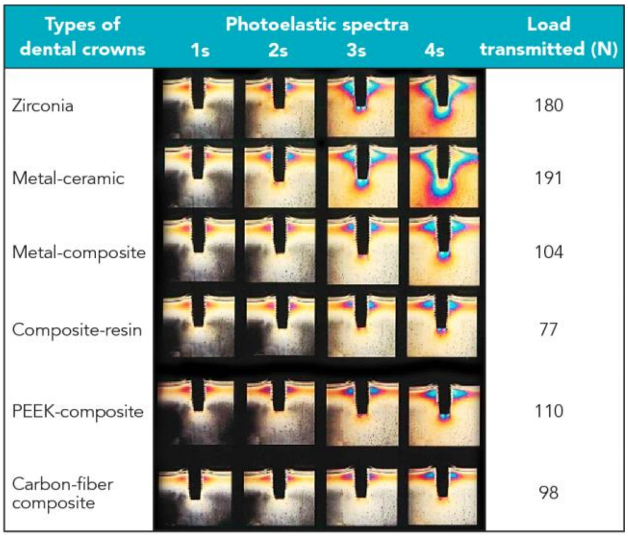


Figure 13: Load transmitted in 3seconds among different types of crowns

Pera F et al considered carbon fibre frameworks as a viable alternative to the metal ones and showed less marginal bone loss around implants and a greater implant survival rate during the observation period.

In implant prosthodontics, the lack of mechanoreception and proprioception of partially and edentulous ridges implies that CFRC may be particularly favorable for these indications due to its good biomechanical capacity to absorb occlusal forces.[12]

A statistically significant difference in the absolute change of bone resorption around the implants was found between the two groups (control and test) with greater peri - implant bone resorption in the control group (mean: 1.0 mm) compared to the test group (mean: 0.8 mm)

Table 2: Properties of metal and carbon fiber framework

Properties	Metal Framework	Carbon Fibre Framework
Cummulative Implant Survival Rate	93.90%	100%
Peri - Implant Bone Resorption	1.0 mm	0.8 mm

A study by Cascos - Sanchez R et al, assessed the bond strength and mechanical failure of carbon - fiber - reinforced composites against cobalt–chrome structures with ceramic veneering.

The study concluded that the chrome–cobalt/ceramic group showed greater bonding strength compared to the carbon - fiber - reinforced composite; most of the fractures within the cobalt–chrome/ceramic group, had no possibility of direct clinical repair. Although carbon - fiber - reinforced composite group showed lower bond strength values, the chipping incidence in this group was as well lower.

The results according to the type of fracture revealed a high statistical difference ($p < 0.01$) and a 57% of effect between the Co–Cr group and the CFRC group. Adhesive failure with fully ceramic veneering chipping was reported in 91.7% of the Co–Cr structures and the remaining failures within this group were of a mixed type (8.3%). On the other hand, 66.7% of the CFCR specimens presented a mixed - type failure, preserving the resin coating to fiber framework. The rest of the failures in this group were cohesive - type fractures in 16.7% of the specimens and adhesive in the remaining 16.7%.

These results are not in the same line with those obtained in a similar study by Taufall et al. who described better results in carbon–resin composite fiber specimens as well as in the carbon–resin acrylic fiber. This difference may have been due to the use of different bond strength testing methods.[13]

A study done by Maria menini et al to assess the bond strength and failure patterns of CFRC veneered with acrylic resin and composites.5Out of 20 samples, 10 CFRCs are veneered with the PMMA, other 10 with composite resins. Shear bond strength was measured and failed samples are microscopically evaluated. Veneering with PMMA showed a higher shear bond strength compared with composites due to the deformation of composites before failure and more rigidity compared to the acrylic PMMA.[5]

Microscopic observation showed an adhesive fracture pattern at the CFRC - adhesive interface in both groups. Specific protocol has to be followed for better adhesion and bonding property between the veneer and CFRC.

Sidoli E et al, [10] stated that a self - contained post and core system, Composipost, comprising an epoxy based carbon fiber post, a composite core material, and a low viscosity Bis - GMA bonding resin, has recently been marketed for the restoration of pulpless teeth. The purpose of this study was to explore the basis of validity of some of these claims by comparing the in vitro performance and failure characteristics of the Composipost system against existing post and core combinations when subjected to compressive loading. The Study concluded that the specimens restored with the Composipost system exhibited inferior strength properties in comparison to the other post and core systems tested ($p < 0.01$) like stainless steel post and composite core; cast gold alloy post and gold alloy core; and endodontically treated tooth only.

5. Conclusion

This article reviews about prosthesis reinforced with Carbon fiberswhich might be a viable alternative to conventional prosthesis in all fields of prosthodontics, providing better mechanical property and ease of use regardless of its unesthetic property.

Though the development of a protocol for their fabrication is different, a specific training for dental technicians is recommended to achieve satisfactory results.

Conflict of Interest:

There was no conflict of interest present during the undertaking of this study. The study did not receive any internal or external fundings.

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