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Comparative analysis of advanced dental implant materials for enhanced biocompatibility and mechanical stability

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Abstract: Identification of the best dental implant materials is crucial to achieve high levels of biocompatibility, mechanical stability, and long-term patient satisfaction. The current study provides a comparative review of new materials used in dental implants, including titanium, zirconia, polyetheretherketone (PEEK), cobalt-chromium alloy, and graphene. The motivation for the study is the increasing need for implant materials that are biocompatible and possess high mechanical properties, which provide durability and comfort for patients. The strategy involves a comprehensive evaluation of the material properties of each, focusing on density, tensile strength, modulus of elasticity, and deformation under bite loading. Static structural integrity and stress distribution studies revealed that graphene has an extremely high tensile strength (130 GPa) and very low deformation (0.0002 mm), making it a highly promising material for use in high load-bearing conditions. These findings highlight graphene's potential as a robust, biocompatible substitute for traditional materials, capable of enhancing implant longevity and performance.
Keywords: *Biocompatibility, Dental Implants, Graphene, Zirconia, Mechanical Properties, PEEK, Cobalt-Chromium Alloy.*

1. Introduction

In the current technological landscape, selecting an appropriate dental crown material is crucial, as it must demonstrate favorable mechanical properties, biocompatibility, and aesthetic appeal in dental implantology. The recent emphasis on tooth-colored aesthetic dental crown materials has prompted researchers to explore potential alternatives. Optimizing the parameters involved in the design of tooth crowns is essential. There are some standards that fabricated tooth crowns must adhere to, such as the requirement that the crown material should be safe and ideal. It should satisfy the stress levels under thermal and mechanical loads. It should possess good mechanical properties, biocompatibility, and minimal hypersensitivity reactions, along with aesthetic appeal. Additionally, it should be cost-effective, retain less plaque and tartar, and have better longevity properties. Implants should not slip, make noise, or cause bone damage, among other considerations.

With advancements in dental technology, the selection of an optimal dental implant material has become a key research focus. The basic requirements of an ideal dental implant material include high mechanical strength, biocompatibility, aesthetic value, and longevity. Conventional metals like titanium, despite extensive use, have limitations such as hypersensitivity reactions and stress shielding effects. The growing need for aesthetically pleasing, metal-free implants has encouraged researchers to explore new materials like zirconia, PEEK, and graphene.

Though dental implant materials have been the focus of much research, present research does not include a comprehensive comparison of materials according to both biocompatibility and mechanical characteristics. Though zirconia is very aesthetically pleasing, it is brittle and thus cannot be used in load-bearing cases. Though titanium is very resistant, it is dangerous in terms of ion release and hypersensitivity. Though PEEK, with its bone-like elasticity, has been proposed as an alternative, it

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needs more surface treatments for better osseointegration. Graphene, with its tensile strength and antibacterial characteristics, is a new material but has yet to be researched in dentistry.

The objective of this research is to systematically assess the mechanical properties and biocompatibility characteristics of titanium, zirconia, PEEK, cobalt-chromium alloy, and graphene in selecting the most appropriate material for contemporary dental implants.

2. Literature Survey

The study on graphene family nanomaterials was completed by Ge et al. [1] their characteristics and possible uses in dentistry. For additional details about graphene's effectiveness, see the existing items. The excellent mechanical, chemical, and biological capabilities of graphene family nanomaterials have drawn the interest of researchers looking for novel future medicinal uses. Even though graphene's potential uses in other medical domains have been thoroughly examined, primarily due to its antibacterial qualities and tissue regeneration capabilities, there are very few in vitro and in vivo studies pertaining to dentists. Therefore, this paper attempts to provide the most recent accomplishments and offer a thorough literature evaluation of potential uses for graphene that can be turned into clinical reality in dentistry, based on current facts and recent breakthroughs. The future of dentistry may benefit from the revolutionary material theory put forth by Ivvala et al. [2] for the replacement of current materials. Additionally, it included information on various dentistry techniques. Selecting a possible dental implant material that exhibits good mechanical, biocompatible, optical, and cosmetic qualities is critically important in this modern technological era. According to several studies, conventional dental implants and their manufacturing processes have not demonstrated improved success rates in terms of biocompatibility problems, aesthetics, manufacturing time and cost, human error, defects, or onset of hypersensitivity reactions during prosthetic rehabilitation in dentistry. This literature review's objective is to propose an adequate dental implant material and additive manufacturing methodology as a workable substitute for the traditional dental procedures [3, 4].

To replace the current dental material, Verma [5] conducted research on metal-free, tooth-colored, cosmetic dental implants. He suggested a few materials that could be utilized in dentistry and mentioned polymers as his preferred material. Researchers have been looking for possible alternatives to titanium, the "gold standard" material for dental implants, because of the recent push for metal-free, tooth-colored, and aesthetically pleasing dental implants. Zirconia and PEEK polymers have been proposed in this regard. Both materials can osseointegrate in vivo and are very biocompatible and aesthetically beautiful. Nonetheless, there are still certain obstacles in the way of the regular clinical application of these dental implant materials. However, removing their drawbacks and improving their qualities are the main goals of contemporary research projects. The structural and compositional characteristics of these materials, their limitations and therapeutic applications, biomechanical viewpoints, and the extent of upcoming research and advancements are all covered in this article. Through comparisons, Osman and Swain [6] investigated how cost-effective materials might be chosen over established ones like zirconia and titanium. The common addition of titanium and the recently popularized zirconia implants are the main topics of the study that follows. Material science and clinical issues, including artificial insemination and its physical effects, are the main subjects covered below. Influences on the results of treatment are also discussed. Despite sensitivity, titanium remains the best material for oral implants; however, it is unknown how these two factors relate to each other clinically. Prospects for zirconia implants may appear promising, but before such a suggestion can be made, more in vitro research and well-planned in vivo clinical studies are needed. Working with zirconia implants requires special attention and technical expertise to reduce the risk of mechanical failure [7, 8].

The survival rates of various restorative materials used for direct and indirect restorations were studied by Fernandes et al. [9]. As a result, replacing failed restorations accounts for more than 60% of surgical procedures, which raises the annual cost. Over 60% of operating processes are covered by failed replacements, which increases yearly expenses. This review of the literature compares the survival rates of different recovery items used for direct and indirect restorations. In summary, amalgam

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demonstrated extremely high survival rates (22.5 years), with a 95 percent survival rate over 10 years. Composite resins came in second with a 90 percent survival rate over 10 years, and ionomer glass cement ranked third with a 65 percent survival rate over 5 years. The "gold standard" for indirect restorations remains gold restorations, which have a 96 percent survival rate over ten years. Porcelain-fused-to-metal (PFM) crowns have a 90 percent survival rate over ten years, whereas all-ceramic crowns have a survival rate of 75–80 percent over ten years. Zirconia has the lowest survival rate (88 percent over five years), while e.max has the highest (90 percent over ten years) among ceramic restorations. Numerous factors, such as the materials used in the restoration process, patient parameters, operator variables, and location factors, influence the longevity of the restoration. A study on the definition of graphene and its use in dentistry was proposed by Maddikunta and Vaish [10]. So, how can a new substance be employed in dentistry as a substitute? Stronger than any known material in the cosmos, it is a supernatural wonder material. It is stronger than a diamond but lighter than paper. Compared to steel, it is 200 times stronger. Despite being as thin as an atom, it has a tensile strength of 130 gigapascals. A full stadium may be covered with 1 gram of material. This sheet won't split or shatter if we manage to make an elephant stand on a pencil and attempt to break it with it.

Together with her team of researchers, Shradhanjali et al. [11] worked on graphene and similar materials for use in dental implants. Additionally, what issues require a remedy? First, additional methodical testing is needed to evaluate various combinations of graphene coating (graphene, GO, rGO) and base materials (Ti, CoCr, zirconium, tantalum, etc.). These tests ought to cover all the material's structural characteristics, such as the adhesive graphene's strength (deformity, single or multi-layer) and the coating's surface characteristics (chemical, corrosion, hydrophilicity, and overpowering). Second, further research should be done to determine whether graphene extracts (GO, rGO) can incorporate elements that support bone formation through chemical processes. Third, it is accurate to say that not much is known about why and how the application of an implant coating based on graphene will result in better implant actions. The potential of three-dimensional printing technologies to enable the creation of novel dental materials was investigated by Saratti et al. [12]. Inkjet printing techniques and vat photo-polymerization for ceramics and polymers. Methods for metals, alloys, polymers, and ceramics include powder bed fusion and direct energy deposition. Fiber-reinforced polymers and polymers can be printed using the extrusion method.

The foundations of material science pertaining to nanomaterials, together with their benefits and drawbacks, were studied by Jandt and Watts [13]. According to these evaluations, nanotechnology and nanomaterials have not only made their way into dental clinics but may also pose a threat to them. The most common nanoparticles are found in a variety of dental materials and scholarly publications. The idea of crystal formation in dentinal tubules using bio-calcium carbonate-silica derived from Equisetum grass was proposed by Chang et al. [14] and their colleagues. They isolated the bio-calcium carbonate-silica (BCCS) from Equisetum and conducted a basic analysis. They concluded that the BCCS-P2.0-treated dentin site demonstrated noticeable crystal development in dental tubules. Using theoretical techniques of density theory and molecular dynamics simulation, Balueva et al. [15] conducted a focus study to provide a method for determining the adhesion strength of nano-crystalline hydroxyapatite for dental implants. Biomedical applications for further production were introduced by Sheoran et al. [16]. The fields of healthcare that are being revolutionized by new technologies, including bioprinting, tissue engineering, dentistry, patient-specific implants, and visual surgical planning, are briefly highlighted in this study. The most recent developments in the application of nanoparticles in local dental treatment were studied by Ahmadian et al. [17]. He also discovered that bio-mimetic techniques might help these nanoparticles deliver efficient therapy.

The association between a tiny structure and characteristics, including corrosion resistance, aging levels, durability, and biological compatibility of Ti-12Mo/ZrO2 compounds, was examined by Yehia et al. [18]. The findings demonstrated the great potential of Ti-12Mo/5 weight percent ZrO2 compounds for use in dental implants. Tests for biocompatibility are restricted to all samples. The findings also showed that a sample with 5 weight percent ZrO2 exhibits high adherence and

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proliferation of live cells. Rehabilitative medicine and tissue engineering approaches have been very beneficial to Tahmasebi et al. [19], who worked in reconstructive orthodontics. Scaffolds are utilized for both oral and dental defect repair and reconstruction. Other natural-looking bones are created by combining older stem cells with a mesenchymal phenotype in the form of biomimicry with both biologic and organic matter scales. The literature from the last ten years was thoroughly examined in this study using the PubMed and NCBI databases. In a study by Alikhanifard et al. [20], the stabilization is altered by the electrospinning method, and the nanocomposite barrier is created using poly 3-hydroxybutyrate as a matrix with varying proportions of diopside nanoparticles. It contains the same fibers in a tiny mix with a diameter of less than 200 nm. Utilizing MATLAB software, the high sample image processing reveals an 85% density with compacted peripheral structures that could enhance cell adhesion [21].

According to market surveys conducted via the internet, we have analyzed that 72 percent of dental patients worldwide have dental bridges and crowns. Projections indicate that this percentage will increase to 80 percent by 2027. The global dental implant market size was estimated at USD 3.6 billion in 2020 and is expected to reach USD 4.3 billion in 2021. The following figure illustrates the contribution of each region to the dental implant market share.

The main goal of these articles is to investigate the substitute crown material, which has potential thermal and mechanical properties. The objective is to obtain the thermal and mechanical properties through analysis and compare them with standard values from a literature survey. Based on the reviewed articles, the following materials can be used in dental crown materials:

Zirconia: It is comparatively better in terms of biocompatibility and high resistance to corrosion when compared to titanium. It is also comparatively cheaper.

Graphene: It is used mainly because of its antibacterial properties and tissue regenerative capacity.

Polyetheretherketone (PEEK): It has an elastic modulus similar to that of bone, 3-4 GPa, resulting in less stress shielding than titanium. Its abrasive resistance is comparable to metals.

Cobalt chrome plastic: It has the ability of corrosion resistance and bioinertness, and its ease of fabrication.

2.1. Review of Individual Materials

2.1.1. Zirconia

2.1.1.1. Structural Properties and Implications

Pure zirconia, scientifically known as zirconium dioxide, has three distinct crystallographic forms at ambient pressure, contingent upon temperature. Up to 1170 °C, the structure is monoclinic. It adopts a tetragonal crystal structure between 1170 °C and 2370 °C. From 2370 °C, it transitions to a cubic form.

At °C to the melting point, it displays a cubic structure. The predominant stabilizer utilized in dental applications is yttria, with the incorporation of 3 to 5 molar percent of Y_2O_3 yielding a stabilized core ceramic known as yttrium-stabilized tetragonal zirconia polycrystals. Certain in vitro and in vivo investigations have demonstrated that the aging of zirconia does not influence the therapeutically relevant mechanical characteristics.

2.1.1.2. Surface Modification Methods

The results from our comparative analysis of dental materials, graphene, zirconia, PEEK, titanium, and cobalt-chromium demonstrate distinct mechanical behaviors under various bite loads. Graphene exhibited exceptional tensile strength and minimal deformation, confirming its resilience and suitability for high-stress applications in dental implants. In contrast, zirconia displayed favorable biocompatibility with moderate strength, but its brittleness under stress poses potential clinical challenges. PEEK, known for its modulus elasticity comparable to natural bone, showed effective load distribution, which can reduce stress shielding, a common concern in implantology. Titanium is the material of choice today as it functions and lasts long. It does, however, release metal ions in the body that can potentially lead to allergic reactions in patients. Cobalt-chromium is robust and corrosion-resistant, i.e., it can withstand

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harsh environments within the mouth, but is not very flexible relative to other alternatives.

The maximum principal stress values showed that graphene is able to withstand higher stress without deforming much, which supports its excellent mechanical properties. For zirconia, stress levels were acceptable, but fracture is more likely with complicated load patterns because it is a ceramic. The performance of PEEK highlights its use in situations where it has to blend well with bone, especially to reduce the risk of implant failure due to stress accumulation at the implant neck. The results are in agreement with the material being critical in the fabrication of dental structures to support weight and provide patient comfort and longevity.

2.1.1.3. Results and Analysis

Steam sterilisation is not a widely preferred method for sterilising zirconia implants due to their susceptibility to low-temperature degradation (LTD). Alternative methods include plasma or chemical sterilisation, which are less damaging to the material.

Notwithstanding considerable enhancements in their characteristics, zirconia continues to be a brittle ceramic material susceptible to surface imperfections and manufacturing defects. It precludes the use of angled abutments if the surgical location of the implant does not satisfy prosthodontic specifications. These single-piece implants lack a traditional submerged healing period.

2.1.2. PEEK (Polyetheretherketone)

2.1.2.1. Structural Properties and Implication:

Part of the polyaryletherketone (PEEK) family, PEEK is a semi-crystalline aromatic high-temperature thermoplastic polymer. PEEK's excellent inertness, resistance to chemical erosion, and strong mechanical strength are all attributed to its aromatic ring structure. PEEK materials are preferable to other implant biomaterials from a biomechanical perspective since their Young's modulus value is closer to that of bone than that of any other material. They can minimize stress concentration, have a modest stress shielding effect, and distribute load uniformly because of their isoelastic flexion with bone.

2.1.2.2. Surface Modification Methods

Unmodified PEEK is a bioinert material. PEEK lacks osteoconductive properties. PEEK exhibits hydrophobic characteristics, with a water contact angle ranging from 80 to 90 degrees. Thus, surface modifications of PEEK aim to improve bioactivity, hydrophilicity, surface free energy, and roughness values. Efforts have been directed at the nano-modification of the PEEK surface. Methods for nano modification include spin coating PEEK implants with nano-hydroxyapatite, plasma immersion ion implantation, electron beam deposition, and gas plasma nano-etching.

2.1.2.3. Sterilization Methods

PEEK can be steam sterilized and endures high temperatures. They can withstand radiation, chemicals, gamma, and ethylene oxide sterilization without structural damage.

2.1.2.4. Disadvantages of PEEK

A 3D finite element comparison analysis revealed that PEEK implants, composed of 30 percent carbon fibers, exhibited greater stress concentration in the cervical region compared to titanium implants. A significant drawback of CFR-PEEK is its dark hue resulting from the incorporation of carbon fibers, which renders it unsuitable as an aesthetically pleasing implant material.

2.1.3. Titanium and Its Alloys

2.1.3.1. Mechanical Properties

According to ASTM, there are six different types of titanium available as synthetic materials. Of these six elements, four are levels of commercially pure titanium (CpTi), and two are titanium alloys.

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CpTi usually contains trace elements of carbon, oxygen, nitrogen, and iron. Titanium alloys of interest to the dentist are available in three structural modes: alpha, beta, and alpha-beta.

2.1.3.2. TI Sensitivity Associated with Dental Implant

Iron ions will be released from the implants and form complexes containing indigenous proteins, which function as antibodies, eliciting hypersensitivity reactions following skin contact.

2.1.3.3. Failure Mode of Titanium

With documented incidences ranging from 0 to 6 percent, titanium implant fractures are an uncommon event. Three factors may contribute to implant breakage: manufacturing faults, idle frame integration, and implant design.

2.1.3.4. Local Treatment of the Dental Caries Using Nano Materials

When it comes to dental issues, tooth decay is one of the most prevalent illnesses that affects people. The bacteria that break down carbs cause this issue by producing acid, which in turn causes the minerals in tooth enamel to be removed and cavities to develop. Supplementing with calcium and phosphate lowers tooth decay and prevents it altogether. These ions are found in saliva, and the salivary secretion of these ions will determine whether mineral depletion or recycling takes place.

2.1.4. Fluoride

A simple fluorine anion is known as a remineralization agent in preventing tooth decay in the early stages.

- Fluoride-substituted hydroxyapatite (F-HAP) can restore the crust without being pre-drilled. It can repair early caries lesions and help prevent recurrence by strengthening the natural enamel.
- Nano silver di-amine fluoride Ag has shown strong antimicrobial activity against Streptococcus mutans. Ag nanoparticles have better contact with the bacterial surface and better antibacterial activity compared to larger particles.

Disadvantages include tooth staining, high cost, and lack of aesthetic appeal. Materials and methods involve three types of materials: metals, ceramics, and polymers, used in the additive manufacturing process. Some applications include creating implants for deformed jaw bones, dentures, and false teeth.

2.1.5. Graphene

It is an extraordinary material, exhibiting strength beyond that of any known substance in the universe. It possesses a weight less than that of paper while exhibiting a strength surpassing that of diamond. It possesses a strength that is 200 times greater than that of steel. The tensile strength measures at 130 GPa, despite its thin profile. This material consists of a distinctive single layer of graphite characterized by its two-dimensional hexagonal structure. The graphene superstructure functions as a shock absorber, thereby preventing high-impact forces on the implant body. The primary benefit for a dental lab when considering alternatives to zirconia is the elimination of the sintering process, resulting in significant savings in both time and costs. Furthermore, it does not necessitate advanced milling machines; any current dry or wet machine can fulfill the requirement.

2.1.5.1. Graphene Family Nanomaterials

The family of nano-materials graphene includes ultrathin graphite, few-layer graphene (FLG), graphene oxide (GO), reduced graphene oxide (rGO), and graphene nanosheets (GNS). It is biocompatible and has an antibacterial effect of graphene.

2.1.5.2. Potential Application of Graphene in Tissue Engineering

Currently, most bio-based treatments available do not possess the capability to educate tissues,

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hence failing to facilitate quick healing and functional rebuilding. Several investigations have demonstrated that graphene, devoid of cytotoxic effects, enhances the proliferation and division of mesenchymal stem bone cells at a pace equivalent to that induced by conventional growth agents. Recent studies have demonstrated that graphene and its derivatives, such as graphene oxide (GO) and reduced graphene oxide (rGO), may offer superior dental adhesion methods to improve osseointegration. Graphene oxide (GO), a highly oxidized form of graphene, may be produced in a straightforward and cost-effective manner by the exfoliation of graphite oxide. The pure graphene layer consists of a combination of nitinol (NiTi) form, applicable for dentistry and bone marrow transplants.

This grapheme covering has markedly enhanced the integration-mediated focal adhesion and osteogenic differentiation of mesenchymal stem cells at transplantation sites. RGO-coated scaffolding demonstrates enhanced tissue development compared to both covered and uncovered GO scaffolding, indicating that rGO may be a superior choice for dental implants.

Consequently, it is at the initial stage of both fundamental research and practical applications, with several issues yet to be investigated. Initially, further systematic testing is necessary to evaluate various combinations of synthetic materials (Ti, CoCr, zirconium, tantalum, etc.) and graphene coatings (graphene, GO, rGO). Secondly, the potential for graphene extraction (GO, rGO) to enhance variables that facilitate bone formation via chemical applications must be rigorously assessed. Ultimately, it is accurate that less information has been disclosed on the rationale and mechanisms by which implant coating enhances implant performance. The benefit for dentists is that, because of the polymer material, we may rectify any issue related to shape or form orally. We can also fabricate complete crowns, veneers, and fixed partial dentures. Repairs are quite simple. Clinical travel is straightforward and costly [22, 23].

2.2. Summary of Literature

The literature on dental implant materials highlights both established and emerging trends. However, a critical gap remains in the comprehensive comparison of mechanical performance, biocompatibility, and clinical feasibility.

Graphene-Based Implants: Graphene family nanomaterials exhibit superior antibacterial properties and mechanical resilience [1]. Their potential in osseointegration and load distribution has been reported, but lacks sufficient clinical validation [11].

Zirconia-Based Implants: Zirconia has been extensively studied for its biocompatibility and aesthetic advantages [6]. However, its brittle nature under complex bite loads remains a significant drawback [5].

PEEK implants: PEEK, with an elastic modulus similar to that of bone, minimizes stress shielding [2]. Surface treatments, particularly nano-hydroxyapatite coating, enhance osseointegration but still require additional modifications to the process.

Titanium implants: Titanium remains the material of choice due to its high strength and extensive clinical success [9]. However, the risk of hypersensitivity and ion etching necessitates replacement.

Cobalt-Chromium alloys: They are used in some dental procedures because of their corrosion resistance and moderate elasticity [12]. Conversely, compared to other materials, their stiffness is a hindrance.

The literature confirms that while existing materials exhibit strengths, none provide a comprehensive solution encompassing biocompatibility, aesthetics, and mechanical resilience. This study bridges this gap through a detailed comparative analysis.

2.3. Materials and Methods

This study employs a combination of experimental testing and finite element analysis (FEA) to evaluate the mechanical properties of selected materials. The steps undertaken include:

Materials selection: Titanium, zirconia, PEEK, cobalt-chromium alloy, and graphene.

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Mechanical tests: Density measurement, tensile testing, determination of elastic modulus, and bite-load deformation are performed.

Finite Element Analysis: Distribution of stress and range of total deformation for simulated bite loads of 1100N, 1200N, and 1300N are calculated.

Assessment of biocompatibility: Materials characterizations and analyses towards osseointegration and patient safety have been evaluated from the literature.

3. Results and Discussion

Table 1 lists a brief mechanism of the critical properties for materials considered for dental implants: Titanium, Zirconia, PEEK, and Gordon-chromium, along with Graphene. Some characteristics, such as density, tensile strength, modulus of elasticity, and melting point, are provided. Graphene is at the top with exceptionally high tensile strength and modulus of elasticity, making it more suitable for high-load applications. Zirconia may be very dense and provide moderate tensile strength, but it can be brittle. PEEK offers, with a modulus of elasticity very close to that of bone, beneficial stress distribution that earns it a mark in specific implant situations.

Table 1.
Comparative analysis of material properties for different materials.

Material	Density (g/cm^3)	Tensile strength (MPa)	Modulus of elasticity (MPa)	Melting point (^oC)
Titanium	4.50	220	116	1650-1670
Zirconia	6.05	1000	200	2715-2750
PEEK	2	90-100	3600	343
Cobalt chromium plastic	10	1130-1900	210	1330
Graphene	2.267	130000	10^6	3652-3697

Table 2 outlines the experimental setup, specifying different load levels applied to each material to observe deformation and stress responses, ensuring a comprehensive comparison.

Table 2.
Plan of experiments.

Materials	Bite Load		
	Level 1	Level 2	Level 3
Co-Cr	1100N	1200N	1300N
Graphene	1100N	1200N	1300N
PEEK	1100N	1200N	1300N
Titanium	1100N	1200N	1300N
Zirconium	1100N	1200N	1300N

Table 3 shows a complete and equal comparison of values of displacement and the highest principal stress values of specific bite loads using different materials for a comparative evaluation of performance across these materials. The table provides experimental information on displacement and the highest principal stress for different materials under specified loads. Graphene exhibits consistently small deflections and the highest principal stress values at all loads, demonstrating that it is a strong material. In broad strokes, zirconia, PEEK, and cobalt-chromium show moderate results in terms of stress and deformation resistance. Titanium, somewhat in the middle, is distinguished by balanced performance, not approaching the levels of resilience that graphene displays. The table presents empirical data on deformation and maximum principal stress for different materials under specified loads. Graphene consistently exhibits minimal deformation and high principal stress values across all loads, confirming its robustness. Zirconia, PEEK, and cobalt-chromium display moderate results, with varying degrees of deformation and stress resistance. The moderate values shown for titanium reflect its relatively balanced performance, while it does not reach the levels of resilience of graphene.

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Table 3.
Experimental results.

StdOrder	RunOrder	PtType	Blocks	Material	Bite load	Deformation (mm)	Max. Principal Stress (MPa)
23	1	1	1	Ti	1200	2.9221	41.877
12	2	1	1	Co-Cr	1300	1.8567	35.596
20	3	1	1	Zr	1200	1.8038	34.624
44	4	1	1	Graphene	1200	0.00019206	59.165
34	5	1	1	Zr	1100	1.6567	33.587
35	6	1	1	Zr	1200	1.8038	34.624
13	7	1	1	Graphene	1100	0.00017578	58.779
37	8	1	1	Ti	1100	2.6851	38.122
21	9	1	1	Zr	1300	1.949	35.384
6	10	1	1	Zr	1300	1.949	35.384
8	11	1	1	Ti	1200	2.9221	41.877
26	12	1	1	Co-Cr	1200	1.718	35.17
36	13	1	1	Zr	1300	1.949	35.384
18	14	1	1	PEEK	1300	0.11497	35.646
42	15	1	1	Co-Cr	1300	1.8567	35.596
40	16	1	1	Co-Cr	1100	1.5767	32.624
17	17	1	1	PEEK	1200	0.10613	32.904
10	18	1	1	Co-Cr	1100	1.5767	32.624
2	19	1	1	PEEK	1200	0.10613	32.904
45	20	1	1	Graphene	1300	0.00020833	59.549
27	21	1	1	Co-Cr	1300	1.8567	35.596
15	22	1	1	Graphene	1300	0.00020833	59.549
19	23	1	1	Zr	1100	1.6567	33.587
39	24	1	1	Ti	1300	3.1574	45.636
28	25	1	1	Graphene	1100	0.00017578	58.779
29	26	1	1	Graphene	1200	0.00019206	59.165
5	27	1	1	Zr	1200	1.8038	34.624
30	28	1	1	Graphene	1300	0.00020833	59.549
7	29	1	1	Ti	1100	2.6851	38.122
14	30	1	1	Graphene	1200	0.00019206	59.165
32	31	1	1	PEEK	1200	0.10613	32.904
33	32	1	1	PEEK	1300	0.11497	35.646
16	33	1	1	PEEK	1100	0.097284	30.162
31	34	1	1	PEEK	1100	0.097284	30.162
25	35	1	1	Co-Cr	1100	1.5767	32.624
3	36	1	1	PEEK	1300	0.11497	35.646
1	37	1	1	PEEK	1100	0.097284	30.162
22	38	1	1	Ti	1100	2.6851	38.122
9	39	1	1	Ti	1300	3.1574	45.636
24	40	1	1	Ti	1300	3.1574	45.636
41	41	1	1	Co-Cr	1200	1.718	35.17
11	42	1	1	Co-Cr	1200	1.718	35.17
43	43	1	1	Graphene	1100	0.00017578	58.779
38	44	1	1	Ti	1200	2.9221	41.877
4	45	1	1	Zr	1100	1.6567	33.587

Figure 1 presents the results of total deformation for graphene under load, depicting its structural integrity and minimizing deformation under pressure, making it a candidate worthy of consideration as a viable dental implant material. The results reveal the deformation profile of graphene under static loading. Between varied stress points, the lesser extent of deformation indicates that graphene can withstand and endure extreme loads, fulfilling the needs of application in dental services. Its minimal deformation under load makes graphene an excellent candidate for implants requiring high mechanical

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stability.

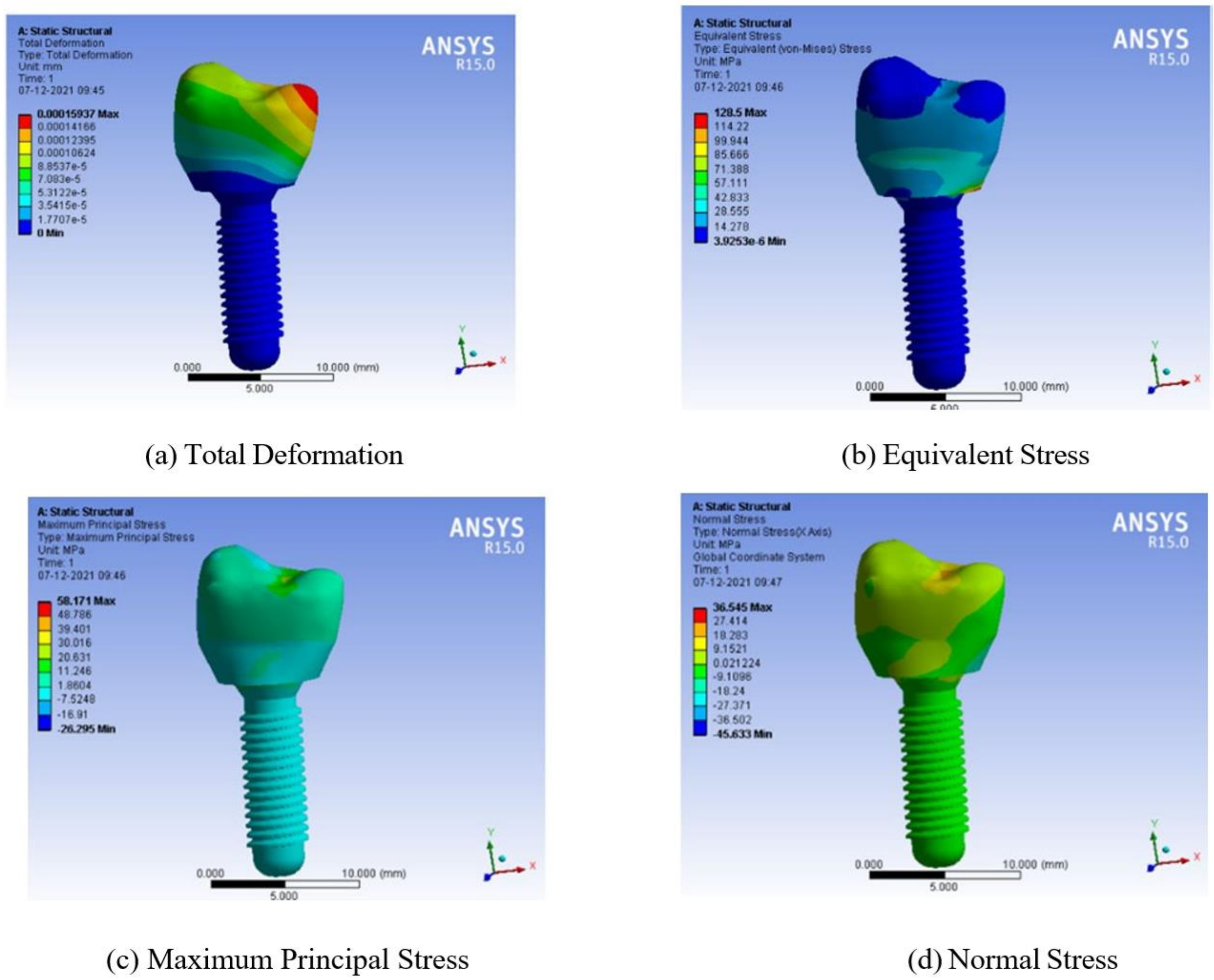

Figure 1.
Static structural analysis for Graphene material

Tables 4 and 5 present the statistical analysis of deformation and stress values for the materials, validating the experimental findings through ANOVA. The high R-squared values indicate robust correlations, with significant differences across material types and load levels.

The ANOVA results indicate that both material type and bite load significantly influence deformation, with a very high R-squared value (99.57%), suggesting a strong correlation between these factors and deformation. Graphene's low deformation values contribute to its superiority, as verified by statistical significance. The low p-values confirm that material differences are statistically significant, supporting graphene's performance as a robust dental implant material.

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Table 4.
Analysis of Variance for Deformation (mm), using Adjusted SS for Tests.

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Material	4	55.5382	55.5382	13.8846	2177.74	0.000
Bite Load (N)	2	0.3386	0.3386	0.1693	26.55	0.000
Error	38	0.2423	0.2423	0.0064		
Total	44	56.1191				
S=0.0798478 R-Sq=99.57% R-Sq(adj)=99.50%						

The ANOVA for maximum principal stress also shows that material type and bite load are significant factors, with a high R-squared value (98.94%). The statistical results validate that graphene consistently achieves high principal stress values, and the low p-values confirm the significance of material type on stress distribution. This reinforces the recommendation of graphene for applications demanding high load-bearing capacity.

Table 5.
Analysis of Variance for Max. Principal Stress (MPa), using Adjusted SS for Tests.

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Material	4	4319.82	4319.82	1079.95	865.61	0.000
Bite Load (N)	2	103.66	103.66	51.83	41.54	0.000
Error	38	47.41	47.41	1.25		
Total	44	4470.89				
S=1.11697 R-Sq=98.94% R-Sq(adj)=98.77%						

Graphene deforms the least among the materials tested for increasing bite loads, indicating that it can sustain structural integrity under stress better than other materials. The graph depicted in Figure 2 shows the tendency of each material to deform under 1,100, 1,200, and 1,300-N bite loads. Its low deformation indicates that graphene maintains structural integrity under stress better than other materials. However, cobalt-chromium and zirconia showed a greater extent of deformation, which can affect the longevity of dental applications under stress. The results indicate that materials with low deformation, such as graphene and PEEK, are beneficial under these conditions, but high-stress tests require further exploration to ascertain the conclusion.

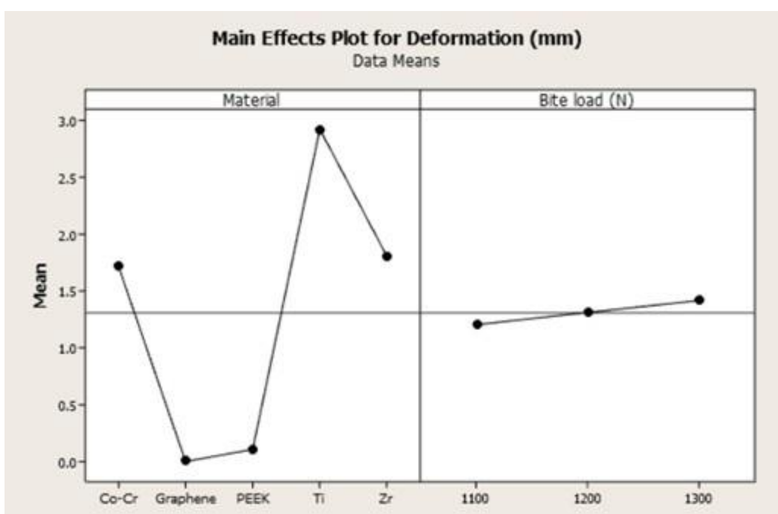

Figure 2.
Main effects plot for Deformation for different materials.

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Figure 3 shows the stress distribution inside the materials under various loading conditions. The increased maximum principal stress values for graphene verify its capacity to carry a high load; thus, it is considered an appropriate candidate for sturdy dental restorations. The graph shows the maximum principal stress values for each material under exceptional bite loads. The greatest value of maximum principal stress is shown for graphene, thus indicating a large stress that can be handled before failure. This high-stress tolerance reinforces graphene's suitability for load-bearing applications, while PEEK and cobalt-chromium demonstrate lower maximum principal stress that may not provide sufficient strength for high-stress circumstances.

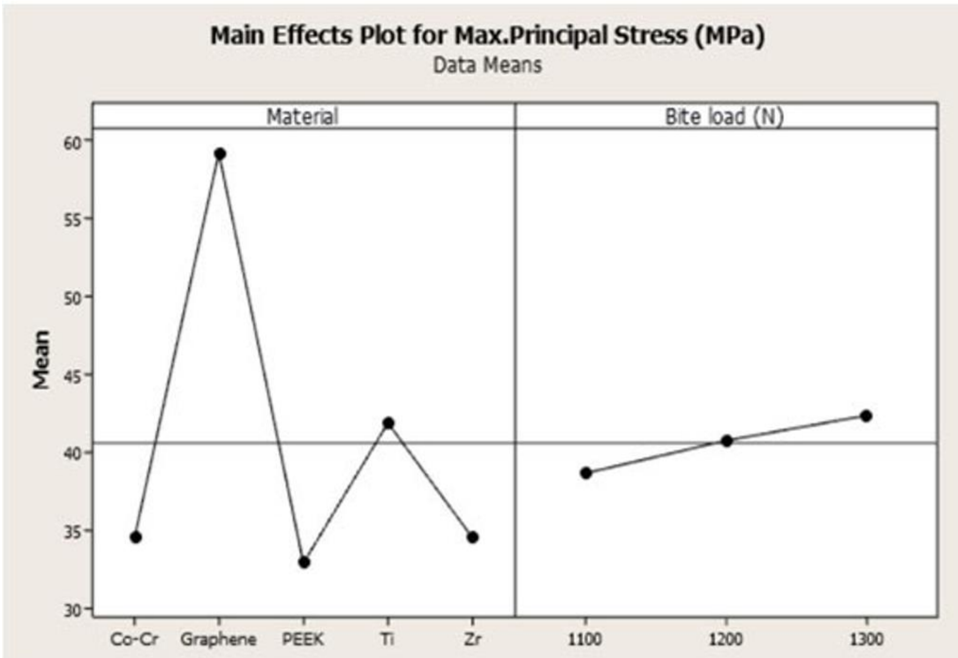

Figure 3.
Main effects plot for Maximum Principal Stress for different materials.

The study on the comparison of these dental materials, graphene, zirconia, PEEK, titanium, and cobalt-chromium, was able to show different behaviors with respect to the bite load to which they were subjected. Graphene is found to have excellent tensile strength and was shown to deform minimally. It thereby proved to be tough and appropriate for use in clinical situations requiring high strength and high stress, indicating immense promise for use in dental implants. Conversely, zirconia exhibited good biocompatibility and only moderate strength; however, it is prone to fracture due to its brittle nature, which might lead to clinical issues. PEEK demonstrates successful force distribution with elasticity similar to natural bone, thus reducing the risk of stress shielding, a recurring problem in implantology. Titanium remains the gold standard, showing consistent performance over time with high durability, but in vivo metal ion release raises concerns among hypersensitive patients. The cobalt-chromium alloy presented excellent corrosion resistance and is suitable for the challenging oral environment, albeit with less elasticity than other materials.

From the point of view of stress distribution in graphene, it was shown to have an excellent capacity for high stress loads with little corresponding deformation, supporting its valuable mechanical performance. While zirconia displayed moderate ordering of stresses, fracture becomes easier with complex load patterns owing to its ceramic nature. PEEK's performance clearly shows it as a good alternative for those applications by ensuring better mechanical compatibility with bone to prevent stress concentration failure of the implants at the cervical edge. Results therefore benchmark the

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applicability of this material for load-active dental restorations with a higher degree of comfort and prolonged longevity.

3.1. Mechanical Performance

Although graphene also exhibited the highest tensile strength of 130 GPa and showed minimal deformation of 0.0002 mm, it demonstrated better structural resilience.

Zirconia exhibited excellent biocompatibility but was prone to failure in high-stress situations.

PEEK led to an enhanced load distribution with a possible application in stress shielding. While titanium does have a distinct strength aspect, its ion release also raises some concerns. Cobalt-Chromium alloy provides good resistance to corrosion but has moderate elasticity.

Stress distribution:

Graphene tolerated a much higher stress load with essentially no noticeable deformation; this further supports its potential use in load-bearing applications.

The stress levels with zirconia were manageable, but such loading could risk fracture under complex load patterns.

The elasticity of PEEK allows for stress redistribution, potentially reducing the risk of implant failure.

3.2. Statistical Validation

ANOVA analysis confirmed significant material differences in deformation and stress distribution ($p < 0.001$). Graphene emerged as the most promising material due to its high resilience and biocompatibility.

4. Conclusions

It is concluded from this study that due to high mechanical resilience and minimal deformation under high loads, graphene serves as a new high-performance material for dental implants. Compared to titanium and zirconia, it markedly surpasses the latter in biocompatibility, load distribution, and low-stress shielding. Zirconia provides aesthetic and biocompatibility benefits, but is largely limited due to its brittleness. PEEK elastomers could find applications in bone-compatibility prostheses, titanium extends durability, and hypersensitivity concerns must be balanced. The present study supports graphene in implantology as a durable, patient-friendly solution. Further clinical studies are recommended to validate these findings.

Transparency:

The authors confirm that the manuscript is an honest, accurate, and transparent account of the study; that no vital features of the study have been omitted; and that any discrepancies from the study as planned have been explained. This study followed all ethical practices during writing.

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References

[1] Z. Ge *et al*., "Graphene family nanomaterials: Properties and potential applications in dentistry," *International Journal of Biomaterials*, vol. 2018, no. 1, p. 1539678, 2018. https://doi.org/10.1155/2018/1539678

[2] J. Ivvala, B. Kuriachen, and V. S. Sharma, "A review on the selection of dental implant material and suitable additive manufacturing technique in dentistry," in *International Conference on Production and Industrial Engineering*, 2019.

[3] F. Gururaj, N. Vijayakumar, J. Satish, H. Madhusudhana, C. Aakash, and R. Siddhi, "Design and analysis of nature-inspired design for ceiling fan inspired by Sycamore seeds to ensure a more optimal air flow," in *AIP Conference Proceedings (Vol. 3122, No. 1, p. 100039). AIP Publishing LLC*, 2024.
[4] A. R. Lakkundi, G. U. Raju, H. K. Madhusudhana, and G. J. Satish, "Optimizing filler loading and particle size for enhanced physico-mechanical properties in peanut shell," *Journal of Material Sciences & Manufacturing Research*, vol. 5, pp. 172–178, 2024.
[5] A. Verma, "Novel innovations in dental implant biomaterials science: Zirconia and PEEK polymers," *International Journal of Applied Dental Sciences*, vol. 4, no. 4, pp. 25-29, 2018.
[6] R. B. Osman and M. V. Swain, "A critical review of dental implant materials with an emphasis on titanium versus zirconia," *Materials*, vol. 8, no. 3, pp. 932-958, 2015. https://doi.org/10.3390/ma8030932
[7] S. G. Jangali, V. Gaitonde, V. N. Kulkarni, and H. Madhusudhana, "Analyzing the effect of cutting parameters on forces and tool-tip temperature in turning of nickel-based superalloy using FE simulation," *Materials Today: Proceedings*, vol. 49, pp. 1833-1843, 2022.
[8] H. Madhusudhana, V. Gaitonde, and G. S. Jangali, "A review on lightweight metal component forming and its application," in *Journal of Physics: Conference Series (Vol. 2070, No. 1, p. 012246). IOP Publishing*, 2021.
[9] N. A. Fernandes, Z. Vally, and L. M. Sykes, "The longevity of restorations-A literature review," *South African Dental Journal*, vol. 70, no. 9, pp. 410-413, 2015.
[10] A. G. Maddikunta and S. Vaish, "All-on-four case rehabilitated with fully digitally fabricated prosthesis milled from graphene-reinforced poly methyl methacrylate puck using indigenously developed intraoral and extraoral scanning methods," *Contemporary Clinical Dentistry*, vol. 14, no. 2, pp. 171-175, 2023. https://doi.org/10.4103/ccd.ccd_249_22
[11] A. Shradhanjali *et al.*, "Graphene for dental implant applications," *Interfaces*, vol. 7, no. 36, pp. 19876-19881, 2017.
[12] C. M. Saratti, G. T. Rocca, and I. Krejci, "The potential of three-dimensional printing technologies to unlock the development of new 'bio-inspired'dental materials: An overview and research roadmap," *Journal of Prosthodontic Research*, vol. 63, no. 2, pp. 131-139, 2019. https://doi.org/10.1016/j.jpor.2018.10.005
[13] K. D. Jandt and D. C. Watts, "Nanotechnology in dentistry: Present and future perspectives on dental nanomaterials," *Dental Materials*, vol. 36, no. 11, pp. 1365-1378, 2020.
[14] H.-H. Chang, C.-L. Yeh, Y.-L. Wang, G.-W. Liu, H.-P. Lin, and C.-P. Lin, "Crystal growth in dentinal tubules with bio-calcium carbonate-silica sourced from equisetum grass," *Journal of the Formosan Medical Association*, vol. 119, no. 12, pp. 1835-1841, 2020.
[15] A. V. Balueva, I. N. Dashevskiy, P. Todebush, and C. Campbell, "Modeling bonding energy in novel bio-active nano coatings on dental implants," *Procedia Structural Integrity*, vol. 23, pp. 173-178, 2019. https://doi.org/10.1016/j.prostr.2020.01.082
[16] A. J. Sheoran, H. Kumar, P. K. Arora, and G. Moona, "Bio-medical applications of additive manufacturing: A review," *Procedia Manufacturing*, vol. 51, pp. 663-670, 2020.
[17] E. Ahmadian, S. Shahi, J. Yazdani, S. M. Dizaj, and S. Sharifi, "Local treatment of the dental caries using nanomaterials," *Biomedicine & Pharmacotherapy*, vol. 108, pp. 443-447, 2018. https://doi.org/10.1016/j.biopha.2018.09.026
[18] H. M. Yehia, A. El-Tantawy, I. Ghayad, A. S. Eldesoky, and O. El-kady, "Effect of zirconia content and sintering temperature on the density, microstructure, corrosion, and biocompatibility of the Ti–12Mo matrix for dental applications," *Journal of Materials Research and Technology*, vol. 9, no. 4, pp. 8820-8833, 2020.
[19] E. Tahmasebi *et al.*, "Current biocompatible materials in oral regeneration: A comprehensive overview of composite materials," *Journal of Materials Research and Technology*, vol. 9, no. 5, pp. 11731-11755, 2020. https://doi.org/10.1016/j.jmrt.2020.08.042
[20] N. Alikhanifard, A. Zargar, and S. Karbasi, "Preparation and characterization a novel nano composite barrier for Gtr/Gbr," *Procedia Materials Science*, vol. 11, pp. 588-593, 2015.
[21] G. J. Satish, V. Gaitonde, and V. N. Kulkarni, "Traditional and non-traditional machining of nickel-based superalloys: A brief review," *Materials Today: Proceedings*, vol. 44, pp. 1448-1454, 2021. https://doi.org/10.1016/j.matpr.2020.11.632
[22] G. J. Satish, H. Madhusudhana, B. H. Nishant, and B. Kotturshettar, "Optimising cutting parameters in boring operation for C45 steel," in *IOP Conference Series: Materials Science and Engineering (Vol. 872, No. 1, p. 012080). IOP Publishing*, 2020.
[23] H. Madhusudhana, K. Ruhi, R. Anand, and C. Venkatesha, "Experimental study on fracture toughness of natural fibres reinforced hybrid composites," in *IOP Conference Series: Materials Science and Engineering (Vol. 376, No. 1, p. 012088). IOP Publishing*, 2018.

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