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EVALUATION OF Zr, Ni-Cr, And Au-Ag APPLIED MATERIALS USING FEM ON PROSTHETIC CROWNS

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Abstract: The crown is a steady prosthesis designed to restore the functionality of a damaged tooth along, with its shape and size. They are also used to reinforce the tooth that poses long-term risk due to wide cavities and accidental injuries. The crowns are fixed using dental cement made of different materials such as porcelain cement, ceramics, etc. The present work aims to assess the mechanical properties – stiffness and strength, of the single molar crown prosthetic tooth materials to determine the efficacy of each material under typical masticatory load observed in clinical settings. To this end, the finite element method (FEM) is used to analyze the mechanical behavior of the molar crowns made of Zirconium (Zr), Nickel Chromium (Ni-Cr), and Gold alloy (Au-Ag). The crown models were created in Solidworks and exported to the ANSYS FE package. The exported three-dimensional models were subjected to varying loading conditions – vertical and oblique forces to the tooth axis under suitable displacement boundary conditions. Due to a relatively high elastic modulus, the Zr and Ni-Cr alloy exhibited a higher stress concentration and lower deformation on the crown's intaglio surface compared to the Au-Ag alloy.

Keywords: *Zirconia, nickel-chromium alloy, gold alloy, von-mises, molar crown, finite element method, masticatory load*

1. Introduction

There are many reasons for tooth damage resulting in temporary/permanent loss of tooth functionality. The tooth damage is primarily attributed to caries and non-caries effects. Caries is a disease caused by bacteria in the mouth that break down carbohydrates into sugars and release acids that attack the teeth. On the other hand, non-caries effects include ageing, another common cause of tooth loss. Some people may also develop tooth decay due to night-time clenching or rubbing (Salah et al., 2015; Tan et al., 2001). In all such cases, crowns are used to replace damaged teeth when a significant portion of the tooth functionality is lost owing to decay, wear or old filling errors. A crown is a dental restoration that replaces all or part of a tooth and is fixed to the tooth with cement to create a new outer coating. Patients may regain function, appropriate communication, and aesthetics with various crowns available in the market. It reinforces the damaged tooth while enhancing its appearance, shape, and alignment (Swain et al., 2011).

Prosthetic molar crowns have been manufactured from various metal alloys and are primarily intended to restore the masticatory function owing to the occlusal force generated in that region (Beata Dejak et al.,2012). This restoration functionality is achieved by high-grade alloy crowns such as gold-plated crowns, which were once considered the gold standard for molar prosthetic reconstruction. Long-term trials of such crowns confirm their effectiveness in clinical studies. In recent years, gold alloy crowns have become unpopular due to their esthetics and rising prices. Ceramic crowns made of stainless steel have replaced the gold-plate crowns and are commonly used today (Seong et al.,2007). Ni-based or Co-based pairs have been widely used in the base alloy group, with the recent addition of Ti alloys (Steinemann, 1998). Cr-based alloys are commonly used in Porcelain-fused-to-metal (PFM) pairs, and they facilitates the passage of material into the oral cavity and causes the formation of oxides which improves ceramic adhesion (Geurtsen, 2002; Hensten Pettersen, 2003). Glass-ceramic materials may work well in the frontal area, but the long-term performance of rear crowns is not very promising (Redemagni et al.,2002; Rousson.,2010). For the rear crown, sturdy and durable materials combinations are required, such as zirconia-based ceramics which have a high flexural strength of up to 1200 MPa and fracture toughness of 9 to 10 MPa m1/2 (Raigrodski et al.,2004; Guess et al.,2008).

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Many factors contribute to the functioning of the crown. Fabricating a durable ceramic crown requires an accurate estimation of the stress distribution under various masticatory functions and fracture strength. By separating food using the enamel on the tooth tips, the crown's mechanical function is to start the initial digestion. Therefore, tooth enamel alternatives should have a hardness value equal to or lower than that of tooth enamel. Dentin substitutes must exhibit maximum stress, maximum strain, and modulus equal to or greater than that of dentin. A broken tooth's crown has been repaired using various materials to improve the tooth's appearance and functionality (Erkmen et al.,2012; Matacena et al.,2014). In recent research, virtual models of biomedical devices and analyses of stress distributions in important regions have been developed using parametric FEM and von-Mises analysis. Utilizing models made with engineering software and those recently published in the worldwide literature, current research is conducted (Cervino et al.,2015; Maiorana et al.,2008).

The FEM is one of the popular engineering tools available today for analyzing, modifying, and improving design (Zahedi et al. 2013a, b; Shamsi-Sarband et al. 2012). Currently, this technique is used in biomedical engineering for patient-specific design, reduction of redundant parts of various machinery and structure, visualization, geometric modelling, and performance analysis (Mohamed et al., 2015; Afolabi et al.,2018; Ladapo et al., 2015). To provide high-quality homogeneous dental goods with custom-made implants, a balance between the manufacturing process and lower production costs has motivated several researchers to utilize FEM in the design and development approach. Using the FE tool, the stress distribution of the zirconium coping designs under various loads was computed (Seung-Ryong et al., 2016; Jeong et al.,2013; Oladapo et al.,2015; Christianah et al.,2016). Therefore, FEM can be used as a suitable design technique for identifying the issues leading to dental restorative failure when crowns are used. The primary goal of the present study was to examine the mechanical characteristics of single crowned prosthodontic dental materials under various loading conditions that correspond to the clinical settings.

2. Materials and Methodology

2.1 Pre- Processing Finite Element Analysis (FEA)

The first step in developing a finite element model is to create a 3D geometry from the processed tooth crown. The DICOM (Digital Imaging and Communication in Medicine) data is included in a 3D slicer model structure (Figure 1). The software can separate tissue data from the DICOM files on all three standard geometric planes before rendering the selected data into a 3D digital model. The software works using a series of indicator function areas within a particular set, allowing for rapid separation of different tissue types such as bone and soft tissue. This procedure was used to separate the patient's bone using the automated threshold feature, designed to resolve bone tissue from the CT (Computed Tomography) scans ranging from 500 to 1000. The 3D model is further refined to include the enamel, as well as parts of the lower and upper jaws.

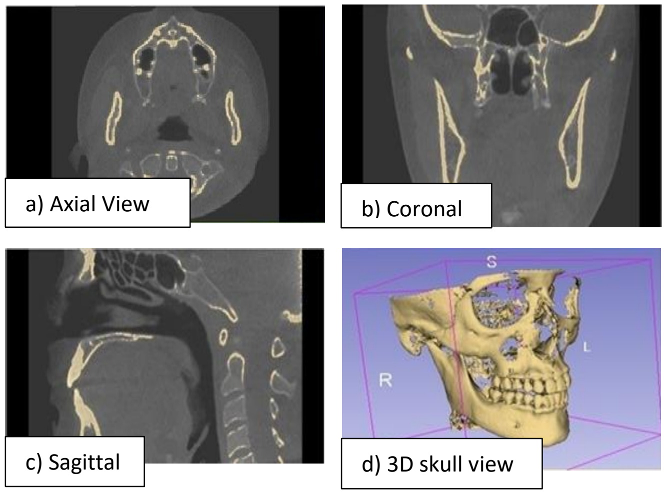

Figure1. (a, b, c) Anatomical MR slices of the head in the 2D slice at axial, coronal, sagittal view and (d) 3D model of the skull in 3D viewer.

As shown in (Figure 2), a single molar crown was extracted from the complete 3D tooth model using a scissors tool to separates the exported 3D mask in STL (stereolithography) file format, and further modifications were made using the AutoCAD 2020 package. The model was exported to the ANSYS FE package in iges format. The solid model was broken down into different parts before the analysis for meshing in the ANSYS workbench. The meshing was done using the four noded tetrahedral elements, as shown in (Figure 3). The meshed model had 2,54,676 nodes, whereas the element count was 1,72,523. The mesh parameters used were sufficient to produce good quality mesh. The materials utilized in the analysis and their mechanical properties are displayed in Table1. Each solid component has been assigned its respective material property in the FE model.

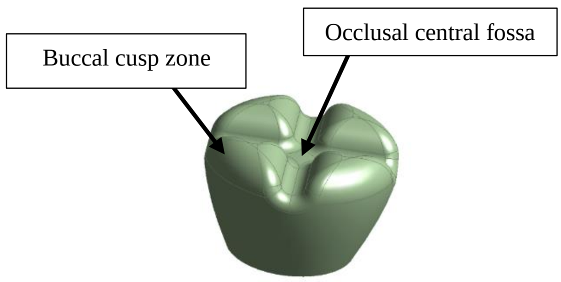

Figure 2. Isometric view of the molar crown

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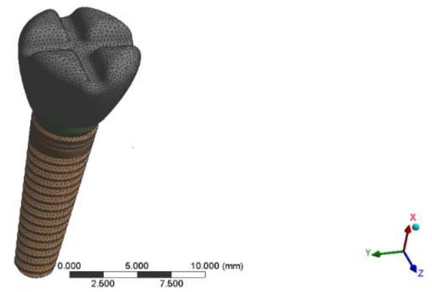

Figure 3. Tetrahedral meshing of a dental crown with abundant screw

2.1 Material and Load Conditions

All the building materials for the dental crown with the abundant screw were considered homogeneous, elastic, and isotropic. The displacement of the nodes corresponding to the surface of the abundant screw was fixed.

The buccal cusp zone and occlusal central fossa received a static load of 100 N. The FE models were subjected to two loading conditions: (1) vertical loading and (2) oblique loading from the buccal side, at 300 and 450 to the tooth axis. The von-Mises stress (Eq.1) and the total deformation parameters were considered for assessing the performance of various dental crowns.

$$\sigma_{vm} = \sqrt{\frac{(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2}{2}} \quad (1)$$

where σ_1, σ_2, and σ_3 are principal stresses and σ_{vm} is the von-Mises stress.

Table 1. Material Properties of Biocompatible materials involved in the study.

Material	Density(Kg/m3)	Poisson's Ratio	Young's Modulus (GPa)	Yield Strength (MPa)
Gold Alloy (Ag-Au)	8000	0.33	91	800
Ni-Cr	8400	0.325	245	2100
Zirconia	4560	0.26	97	810

3. Results and Discussions

The model was examined using the ANSYS workbench for the load applied vertically, at 300 and 450 to the tooth axis, and the resulting von-Mises stress and total deformation distribution were examined. The amount and direction of the applied masticatory force determine the multiaxial stress distribution of the treated tooth that has been repaired. The von-Mises stress under one applied load is depicted in (Figures 4 and 5) in terms of its values and patterns. Dark blue (the lowest stress) to red (the highest stress) colour banding is used to depict the stress profile. Following vertical contact with neighboring teeth, the stress progressively shifts away from the stress point and toward the remainder of the crown. However, the maximal load is confined to the crown and barely penetrates the underlying teeth. For each material, (Figures 6 and 7) illustrate the maximum von-Mises and the total deformation, respectively. According to the static analysis, the Au-Ag alloy had a maximum von-Mises stress of 20.01 MPa and a maximum displacement of 0.00143 mm when the axial load was applied. The maximum von-Mises stress for the Ni-Cr alloy material was 39.6 MPa and the material deformed by 0.00687 mm in response to an applied axial load. When the oblique load was applied, Zr was subjected to the maximum stress of 24.96 MPa and a maximum deformation of 0.00143 mm. For the Ni-Cr alloy model material, (Figure 6) displays the maximum equivalent stress profile observed.

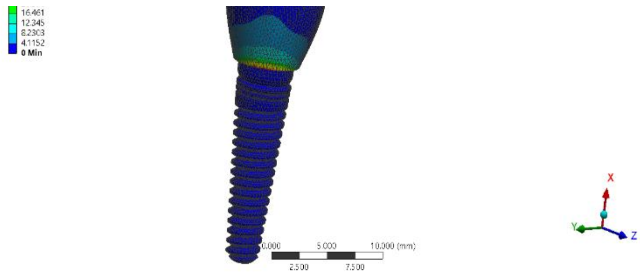

Figure 4. Equivalent Load at the axial condition for Zirconia

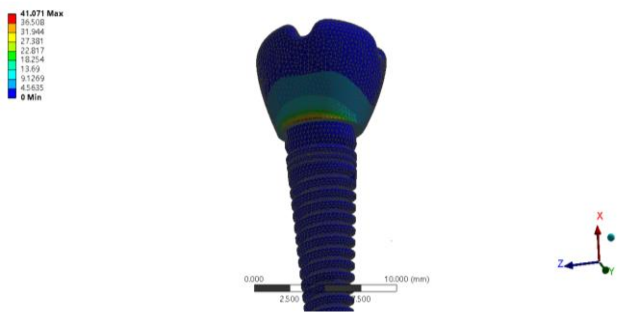

Figure 5. Equivalent Load at the axial condition for Nickel-Chromium alloy.

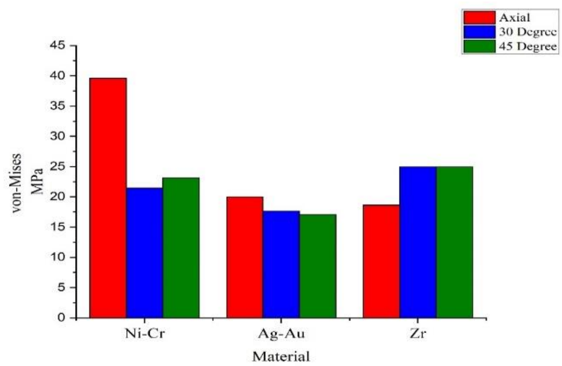

Figure 6. von-Mises stress at 100N load (axial, 30o, and 45o).

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(Figures 8 and 9), demonstrate that the region immediately above the fixed basal region had the highest stress values because, when subjected to force, this region was unable to deform because all degrees of freedom for the base were locked. On the other hand, the crown curved around the base when oblique force (300 and 450) was applied. As a result, under the second load condition, the anterior region was compressed, while the posterior region was stretched, resulting in a high-stress zone around the base in both the front and back views shown in (Figure 5). For the following reasons, it was also shown in (Figure 4), that the entire anterior top portion of the crown was a zone of significant stress under vertical force. High irregularity, multiple uneven contours, and significant stress concentration factors were identified in this region of the crown. The issue of stress distribution and masticatory force, which affects the periodontium and replaces the tooth material such as veneer porcelain on zirconia, has received a lot of attention in recent research (Vaidyanathan et al.,2013; Granell-Ruiz et al.,2012).

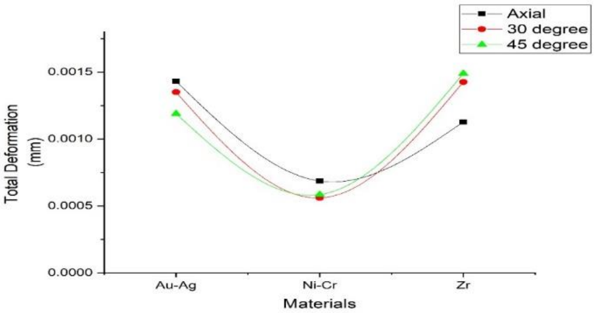

Figure 7. Total Deformation for masticatory load of 100 N (axial, 300, and 450).

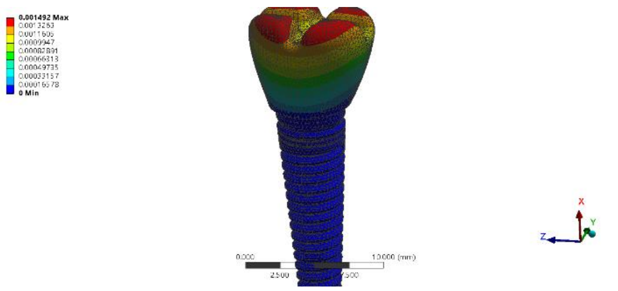

Figure 8. Total Deformation of Gold alloy (Au-Ag) at axial

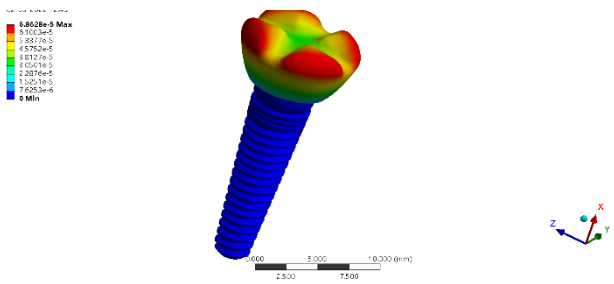

Figure 9. Total Deformation of Ni-Cr at axial load

The results of this study clearly supports the recent literature findings. There is no ideal material to replace the anatomical features of a natural tooth. For fixed prostheses, creating temporary restorations from dental resins is a necessary step. The pulp capping protection, position stability, occlusal function, cleanability, marginal accuracy, wear resistance, strength, and aesthetics standards must all be met by temporary resin crowns. They serve an essential role in providing a template for the final restoration after being evaluated in the oral cavity. However, these research findings indicate that dental resins have a low fracture resistance, and a high risk of destruction, and cannot be used for prolonged chewing cycles. Significant efforts have been made to strengthen the strength and dependability of dental ceramic systems in response to the patient's aesthetic demand for a white metal-free, tooth-colored prosthesis. According to (Regish et al.,2011), restoring missing teeth has become one of the most critical requirements for patients visiting the clinic to restore aesthetics and function. There are numerous procedures that can replace a single lost crown. Each surgical procedure has distinct advantages and disadvantages that can be thought of as a predictable long-term treatment option.

The clinical results of using gold or Ni-Cr alloys are predictable and safe, and their use is well documented in contemporary research (Lauritano et al.,2016). The high degree of fracture, uniformity, and gradual consumption of gold alloys, when compared to the findings of recent investigations, suggest that they are more resilient to long-term stress distribution. The Ni-Cr alloy has an excellent tensile strength as well. With no fractures across numerous extended masticatory cycles, the von-Mises stress distribution demonstrated similar results for Au-Ag and Ni-Cr. From another perspective, recent research has focused on assessing the consistency and durability of metal-free prosthetic single crowns. These materials highlighted the fantastic results of the anterior teeth, but the posterior region, which was influenced by the strong masticatory force, resulted in crown fractures with no long-term benefits.

For front free-contact teeth, zirconia can be considered the best framework ceramic, but for posterior restorations using Ni-Cr alloys, the masticatory cycle is crucial to predicting long-term performance prior to clinical usage. The current model was validated and confirmed in accordance with the goal of the study using the static finite element analysis, according to earlier research published by (Tsouknida et al.,2013). A crucial criterion for model reliability is the application of realistic loads and boundary conditions since the predictive capacity of the simulation is linked to the interaction variables taken into account during the analysis. The created model is thought to offer a respectable level of reliability for qualitative risk assessment of procedural variables related to the masticatory cycle based on specified parameters. Each operative procedure can be assumed to be a long-term treatment option with pros and cons. And the final goal is to make technical suggestions related to virtual models, not clinical recommendations.

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4. Conclusion

From the present investigations, three biocompatible materials, Au-Ag, Ni-Cr and Zr alloys, were chosen based on the patient functional requirements and other preferences such as location of the dental implants, duration of the treatment, and the cost. The position of the force greatly influenced the stress distribution pattern. However, the von Mises stress were found to be low to cause crown failures. Zirconia has the advantage of being aesthetically pleasing, but one has to take into account its low fracture toughness during the dental restoration procedure to avoid fractures during mastication especially in molar and posterior regions. The elastic modulus of the Ni-Cr alloy is higher among the three materials, and therefore the deformation will be low. In terms of durability, gold crowns are preferred, but they are costly. The presented model is a 3D virtual model; therefore, additional research is needed to ensure the durability and long-term clinical success of the materials used.

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