NUMERICAL STUDY OF STRESSES IN DENTAL MATERIALS BY USING FINITE ELEMENT ANALYSIS

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Abstract—

Dental tooth is made of different materials such as soft, hard and intermediate materials. PMMA is the softer material but it is associated with poor mechanical properties. It has been documented that the strength of PMMA is increased by incorporation of Zirconia as filler material. The objective of this study is to find out the optimum or best material which overcome the disadvantages of both PMMA and Zirconia and gives the optimum composition with increased mechanical properties. For this purpose 3D model of tooth is generated and for different materials as per there mechanical properties such as modulus of elasticity density and Poisson's ratio this tooth model is analyzed in finite element analysis at constant loading condition.

Keywords—*FEA, PMMA, Zirconia, Reinforcement, Composition*

I. INTRODUCTION

A dental crown is tooth-shaped cap that is placed over a tooth to cover the tooth to restore its shape and size and also to improve its strength and appearance. Dental crown may also be needed to protect the weak tooth from breaking because of large biting forces during mastication, to restore fractured tooth and also to cover the implant. Dental materials are basically classified as hard materials (ceramics), Intermediate materials (porcelain-fused-metal) and soft materials (resins).

Now a day's most commonly used dental materials are acrylic resins (PMMA) and ceramics (zirconia) both materials have some of the advantages and disadvantages. PMMA has been the most popular denture base material because of its advantages including low cost, good aesthetics, ease of application, stability in the oral environment, easy laboratory and clinical manipulation and inexpensive equipment etc. one of the major disadvantage of the PMMA is that its fracture resistance is not satisfactory [12].

PMMA is very soft material therefore it has very low modulus of elasticity. As PMMA is very soft material it may failed due to biting forces during mastication due to micro- fragmentation. Therefore, life cycle of dentures made of PMMA is very short [5]. Zirconia is also another most commonly used dental material because of its advantages. The most common advantages of zirconia is that it is 100% Biocompatible, it is similar to the natural tooth in aesthetics and have high strength. The main disadvantages of zirconia is that because of its high strength and hardness it may damages the opposing tooth during mastication after some period.

The main goal of research and development of dental material is to develop the ideal restorative materials. The ideal restorative material would be identical to natural tooth structure in strength, adherence and appearance. The properties of ideal restorative material can be divided into four categories: Physical property, Biocompatibility, Aesthetics and applications. Dental materials requires physical properties which includes low thermal conductivity and expansion, resistance to chemical erosion and also it must be resistant to different types of forces and wears such as attrition and abrasion. Ideal restorative material should be highly biocompatible, Biocompatibility refers to the how well material coexists with biological equilibrium of tooth and body system. Also, it is required that dental material should match the surrounding tooth structure in shade, translucency and texture. i.e, it should be nearly similar to the natural tooth.

In general fracture of denture base in the mouth occurs via fatigue mechanism over a certain period of time. In this even the relatively small flexural stresses lead to the formation of microscopic cracks in areas of stress concentration or the area where stress is concentrated during chewing or mastication. With continued load bearing, these cracks fuse to ever growing fissure that weakens the material. Catastrophic failure occurs from the final loading cycle that exceeds mechanical capacity of remaining portion of the material. In addition to this, denture fracture is also frequently related to the faulty design, fabrication and material choice. Many attempts have been done previously to improve the mechanical properties of PMMA including its chemical modification by the addition of various reinforcing materials like metals, metal fillers, glass fibers, aramid fibers, carbon fibers and ultra high modulus polyethylene [10].

From literature it is observed that addition of varying amount of metal fillers such as copper, aluminium and powder silver into PMMA at particular concentration not only gives it an advantage of improved thermal conductivity and increased strength, but also decrease the warpage, reduces the polymerization shrinkage, inhibits the growth of bacteria over the denture surface and makes the material radiopaque. Compromised aesthetics is the major disadvantage of reinforcing the PMMA by using different metal fillers.

Recently it is observed that, reinforcement of zirconia (ZrO2) as filler into PMMA also improves the mechanical properties of PMMA efficiently. As discussed earlier zirconia is biocompatible and additional advantage of zirconia as filler over metal filler is superior aesthetics [11].

While selecting dental materials two factors are needed to be considered in which bone interface stress distribution and load transfer to the jaw bone during mastication or chewing. Therefore, most important thing is that using soft (less rigid) dental material reduces the stresses generated on the jaw bone, that it absorbs more energy from applied load and transfers very small amount of energy to jaw bone. Hence, softer material is acts as the damper and absorbs the large amount of energy of applied load. Similarly, by using harder dental materials when load is applied during biting it absorbs very small amount of energy of applied load and transfers more amount of energy of applied load to the jaw bone [5].

In dentistry, for analysis of effect of stresses in tooth for different material FEA has become an increasingly useful tool. Transvers and vertical loads from the biting during mastication induce bending moment and axial forces that result in the stress gradients at the interface of tooth and bone. Because of complex geometry of the tooth FEA has been viewed as the most suitable tool from the biomechanics point of view to study the effects of stresses in different tooth crown materials [4].

The aim of this study is to analyse the value of stresses in different tooth crown materials and also evaluation of effect of 10% and 20% zirconia reinforcement on the properties of PMMA.

II. MATERIALS AND METHODS

Poly methyl methacrylate (PMMA) is used as the base material in this study as control group. Zirconia (ZrO_2) is used as the reinforcing material.

The materials used for analysis purpose involves PMMA, Zirconia, Composition A (PMMA reinforced with 10% of Zirconia), Composition B (PMMA reinforced with 20% of Zirconia). From literature it is observed that neither PMMA nor zirconia individually sufficient to get the superior tooth. Hence, it is proposed to form a composite in which acrylic is the base material and zirconia is used for reinforcement. From the review it was observed that when PMMA is reinforced with 10% of Zirconia the transverse strength of composition is increased by 32% than the PMMA but impact strength was reduced by 10%. Similarly, when PMMA is reinforced with 20% of Zirconia the transverse strength of composition is increased by only 23% but its impact strength was reduced by only 6% [10]. From this, it was observed that composition A gives transverse strength more than composition B but its impact strength is less than that of composition B. In general, transverse strength counteracts the biting forces during the mastication and impact strength counteracts the forces which are raised only during accidental cases [10]. Therefore, as composition A gives transverse strength more than composition B from review composition A was selected as best material for manufacturing of tooth.

The study was conducted using 3D finite element model and were analysed by using finite element analysis (FEA). The standard 2D design of the molar tooth is as shown in the figure 1 which is available from the review of journal of prosthetic dentistry [13]. The model were composed of parabolic tetrahedron solid elements. The 3D model of this standard 2D design was fabricated using commercially available software Solidworks 2014 as shown in figure 2. The 3D model created in Solidworks 2014 was then imported in the ANSYS APDL R15.0 for further analysis. The model in ANSYS was then simulated with the help of an Intel core i5 processor, with 4 GB ram, 64 bit operating system. The materials used in this study were assumed to be homogenous and isotropic. The properties such as modulus of elasticity, density and Poisson's ratio are required for the analysis of tooth made of particular material in FEA [8]. Therefore, modulus of elasticity, density and Poisson's ratio of PMMA and Zirconia are shown in the Table 1.

Table 1. Properties of PMMA and Zirconia

Properties	PMMA	Zirconia
Modulus of elasticity (GPa)	3.2	200
Density(Kg/m³)	1180	5680
Poisson's ratio	0.37	0.27

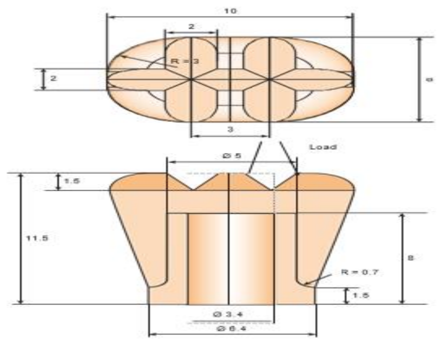

Fig.1. 2D design of tooth

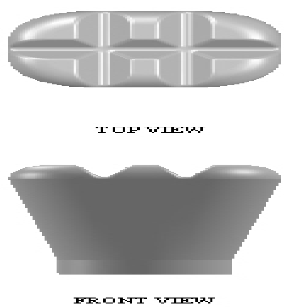

Fig.2. 3D design of tooth generated in Solidworks

The properties such as modulus of elasticity, density and Poisson's ratio of composition A and composition B are required for the analysis of tooth made of these compositions by using FEA. Therefore, these properties of composition A and composition B which are not already available are found out by using formulas which are obtained from the book of 'Mechanics of composite materials' written by Robert m. Jones.

Analytical calculation for finding the properties of composition A and composition B-

The following properties of composition A and composition B are calculated

1. Axial modulus of elasticity of composition
2. Density of composition
3. Poisson's ratio of composition

Composition A- PMMA (90% by vol.) + Zirconia (10% by vol.)

=90% and = 10%
Axial modulus of elasticity of composition A-
= +
= 3.2*0.9 + 200*0.1
= 2.88 + 20
= 22.88 GPa
Density of composition A-
= +
= 1180*0.9 + 5680*0.1
= 1062 + 568
= 1630 Kg/m³
Poisson's ratio of composition A-
= +
= 0.37*0.9 + 0.27*0.1
= 0.36

Composition B- PMMA (80% by vol.) + Zirconia (20% by vol.)

=80% and = 20%
Axial modulus of elasticity of composition B -
= +
= 3.2*0.8 + 200*0.2
= 2.56 + 40
= 42.56 GPa
Density of composition B-
= +
= 1180*0.8 + 5680*0.2
= 944 + 1136
=2080 Kg/m³
Poisson's ratio of composition B-
= +
= 0.37*0.8 + 0.27*0.2
= 0.35

Materials / Properties	Composition A PMMA (90%) + Zirconia (10%)	Composition B PMMA (80%) + Zirconia (20%)
Axial modulus of elasticity (GPa)	22.88	42.56
Major poisons ratio	0.36	0.35
Density(Kg/m³)	1630	2080

Table 2. Properties of composition A and composition B

From above calculations of properties it is seen that, composition A has lower axial modulus of elasticity than composition B. As we know that softer materials have lower modulus of elasticity and harder material have higher modulus of elasticity [5]. Therefore, composition A is softer material than composition B. Hence, composition A absorbs large amount of energy of applied load during mastication and transfers small amount of energy to the jaw bone than composition B. Therefore, composition A (10% reinforcement of Zirconia) is selected from analytical calculations as best material for manufacturing of tooth than composition B (20% reinforcement of Zirconia).

The maximum amount of load that each molar tooth can experience is 150N which is obtained from the review [5]. For numerical analysis this value of load is required to be converted into the pressure. The value of the pressure is obtained by the formula as given below,

$$\text{Pressure} = \frac{\text{Load}}{\text{Area}}$$

Area of each side blocks of 3D tooth design is 0.68 mm^2 and area of that of the each middle block of 3D tooth design is 0.91 mm^2

Pressure on each side block is given by,

$$\text{Pressure} = \frac{150}{0.68}$$

=220.58 Mpa

Pressure on each middle block is given by,

$$\text{Pressure} = \frac{150}{0.91}$$

=164.84 Mpa

The complete model is meshed after importing it in ANSYS APDL R15.0 by element tet 4 node 285 which is used for 3D meshing of tetrahedron [13]. After meshing of 3D design of molar tooth in ANSYS the load is given on the top surface of tooth in the form of pressure and lower end of the tooth is in fixed position.

III. RESULTS

In this study, the distribution of von Mises stresses in the molar tooth for PMMA, Zirconia, composition A (PMMA reinforced with 10% of Zirconia by vol.) and composition B (PMMA reinforced with 20% of zirconia by vol.) were investigated. The von Mises stress is good representative of state of stress because it is scalar variable that is defined in the form of all individual stress components [4]. The distribution of stresses for the tooth were shown under the effect of axial compressive loading in the Y-direction. In FEA, a qualitative and quantitative analysis was performed, based on the progressive visual scale, pre-defined by the software used, ranging from dark blue colourr to red [4].

The stress and strain are generated in the tooth due to the applied load during the mastication. Therefore, there is some amount of deformation in the tooth structure due to its properties. Generally due to change in material properties, change in position, direction and value of applied load there will be new results of stress and deformation are obtained. Finite element analysis produces number of results that can be presented graphically and tabulated as stress, strain, deformation distribution.

The finite element analysis showed the deformation and stress distribution in Y-direction for PMMA, Zirconia, composition A and composition B tooth as follows,

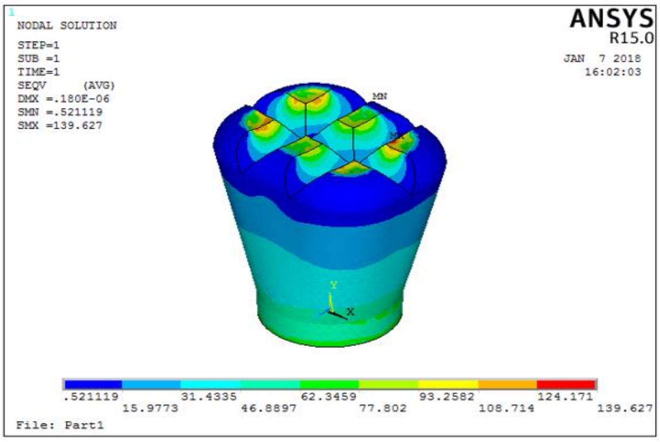

Fig. 3. von Mises stress distribution for PMMA tooth

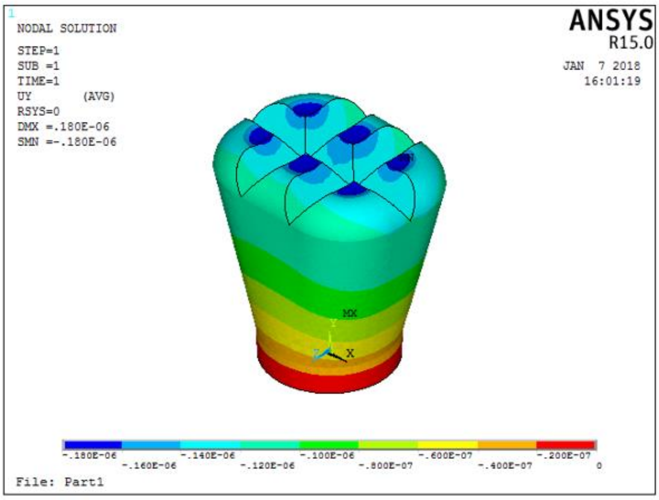

Fig. 4. Stress distribution in Y-direction for PMMA tooth

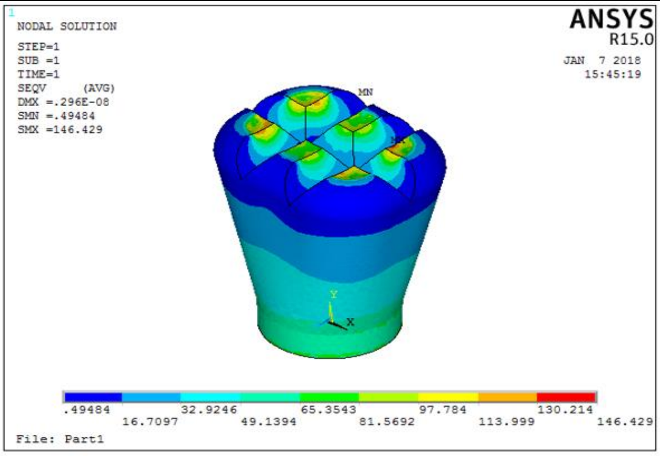

Fig. 5. von Mises stress distribution for Zirconia tooth

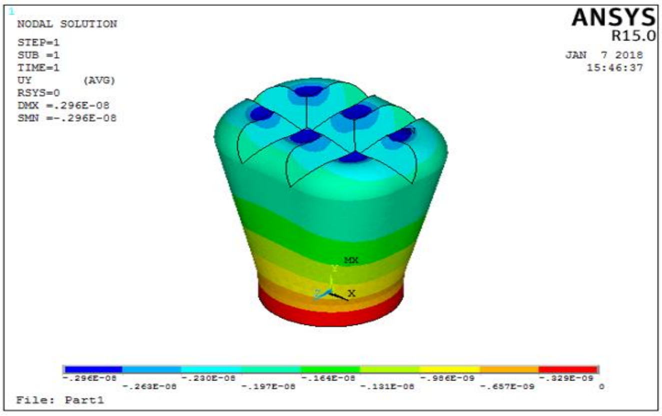

Fig. 6. Stress distribution in Y- direction for Zirconia tooth

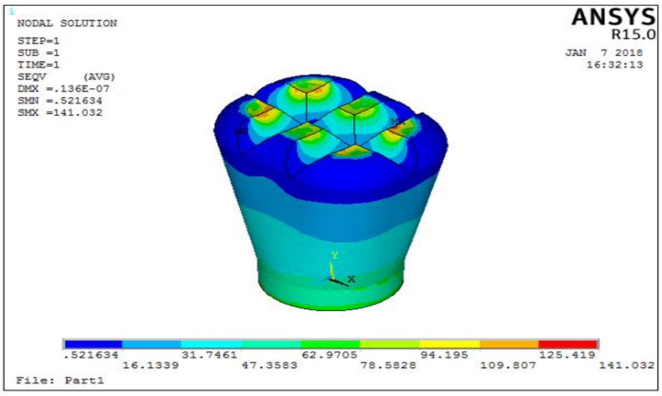

Fig. 7. von Mises stress distribution for composition A tooth

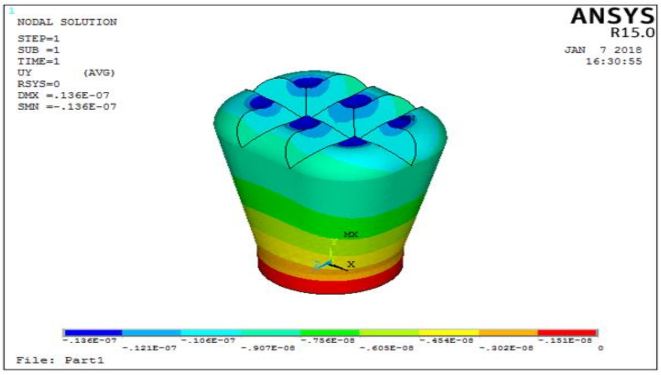

Fig. 8. Stress distribution in Y- direction for composition A tooth

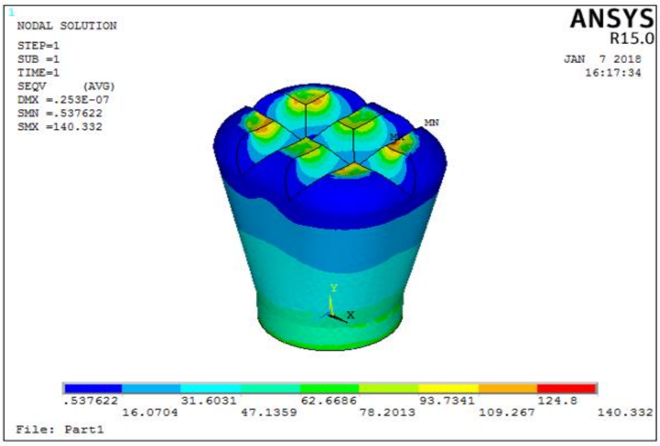

Fig. 9. von Mises stress distribution for composition B tooth

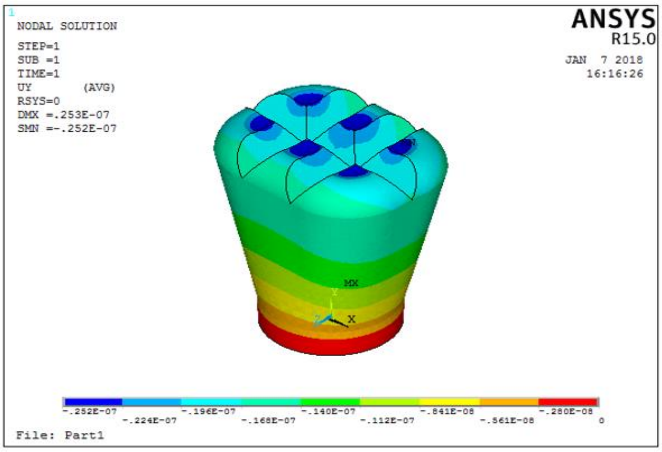

Fig. 10. Stress distribution in Y- direction for composition B tooth

IV. *DISCUSSION*

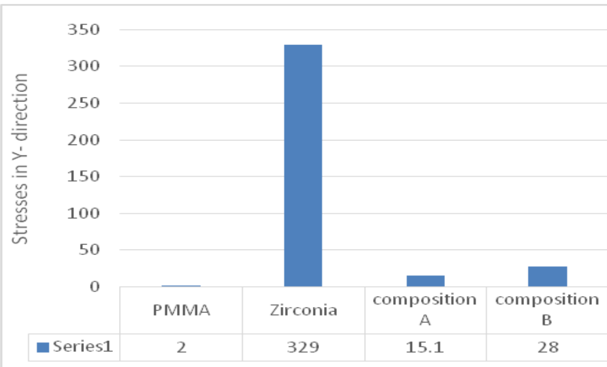

Fig.11. Chart of stresses in Y- direction for given materials

The aim of this study was to predict the stress distribution and from that stress distribution we have to select the optimum material composition for manufacturing of tooth. The tooth design is modelled as homogeneous and linearly elastic materials, and completely static load is assumed. The material properties mentioned above in the Table 1 and 2 and boundary conditions have been reported to provide a good indication of actual situation similar to biting during mastication. The finite element analysis has been used by various investigators for analysis of stresses in various dental parts such as implants, crowns etc. Previously, other methods like photo- elasticity have been used to analyze the stress concentration in dentistry. The experimental condition can be kept identical to that of the actual condition is one of the major advantage of the finite element analysis. From FEA analysis of above result it is observed that value of the stress distribution changes as material properties changes by keeping load constant (150N).

The results of FEA for PMMA, Zirconia, composition A and composition B are shown in the form of chart as shown in figure 11. From above results of finite analysis it is observed that, as PMMA is soft material because its low modulus of elasticity it absorb maximum amount of energy (2 MPa) of applied load and transfers very low amount of energy to the jaw bone or next system. In addition to this highest deformation is observed in the softer material (PMMA). Similarly, as Zirconia is harder material because of it higher modulus of elasticity it absorbs very low amount of energy of applied load and transfers maximum energy to the jaw bone (329 MPa). Also, value of deformation is smaller in the zirconia because it is harder material. As composition A involves the 90% of PMMA as base material and only 10% of Zirconia as reinforcement, the results of FEA shows that it absorbs slightly less amount of energy of applied load and transfers slightly more amount of energy than PMMA to the jaw bone (15.1 MPa). The composition A deform slightly more than PMMA when load is applied. Similarly, as composition B involves 80% of PMMA and 20% of Zirconia as reinforcing material, the result of FEA shows that it absorbs less amount of energy than PMMA and composition B and transfers more amount of energy (28) of applied load as compared to the PMMA and composition A to the jaw bone. In addition to this, it is observed that its deformation is less than the PMMA and composition A.

V. CONCLUSION

From the above finite element analysis study, it is observed that as composition A is softer material than composition B it absorbs the more amount of energy of applied load and transfers very small amount of energy to the jaw bone. Therefore, as composition A overcomes all the disadvantages of PMMA and Zirconia and also absorbs the more amount of energy of applied load it is selected as the optimum composition of the dental material for manufacturing of the restorative tooth.

Also, from review of the materials it is observed that the composition A gives the more transvers strength than the composition B as compared to PMMA. Therefore, composition A is selected as the superior material for manufacturing of the tooth.

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