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Analysis of Al_2O_3/Al FGM as Biomaterial of Artificial Human Femoral Bone and Compare with Ti6Al4V Alloy through Computational Study

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ANALYSISOFAL2O3ALGMASBIOMATERIALOFARTIFICIALHUMANFEMORALBONEANDCOMPAREWITHTI6AL4VALLOYTHROUGHCOMPUTATIONALSTUDY

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Abstract - A finite element model of bones with accurate geometry and material properties generated in CAD softwares are being widely used to make realistic investigations on the mechanical behavior of bone structures. The aim of this study is to create a model of real proximal human femur bone for evaluating the finite element analysis (FEA) and investigate the use of Ti6Al4V and Al_2O_3/Al FGM for artificial femur. Here, behavior of femur bone is analyzed in ANSYS 13 workbench under physiological load conditions and compared with artificial femur composed of Ti6Al4V and Al_2O_3/Al FGM. The CAD model was imported in Ansys 13.0 workbench, meshed and analysed in Ansys mechanical APDL workbench under the loading conditions. It was found that both material are suitable for artificial bone material. Human femur with Al_2O_3/Al FGM showed better mechanical properties and less weight compared to Ti6Al4V. In the biological environment, the demands of biomaterials are challenging. This study will be useful to surgeon in femur surgeries and bone prosthesis. These better synthetic bone substitutes will most probably be commercially available for orthopaedic applications in the near future.

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I. Introduction

Titanium alloys are considered to be the most attractive metallic materials for biomedical applications. In biomedical applications Titanium alloys specifically Ti6Al4V is mostly favoured. But a matter of great concern that this alloy has possible toxic effect resulting from released vanadium and aluminum in case of permanent implant applications [13].

This unique study is conducted to analyze the prospect of Al_2O_3/Al FGM which is a relatively new * concept as biomaterials. As, FGM has relatively less decompose rate over time, this is one of the most prospective materials in permanent implant applications.

Mechanical properties of human bones and implant devices are of prime interests to Clinicians and engineers for decades. Researches are going on to findout a material that copes with human body well, hasgood mechanical properties and of course low price.To do this the use of three dimensional (3-D) finiteelement analysis (FEA) for orthopedic application iswell accepted for more than three decades [1]. Boneexhibits elastic linear behavior at macro level for the normal range of regular daily activities [9]. As a result, although the bone is a complex biological tissue, theuse of FEA is attractive. The need for reconstructive surgery of bones is continuously increasing along with the ageing of the population as well as the increase of traumatologic injuries. In 2001 350,000 bone grafting was conducted only in USA. Nowadays, over 500,000 bone graft procedures are performed annually, and approximately 2.2 million world wide (Giannoudis et al., 2005) [10]. Per year total cost of this process excceds billions of dollers. Hence, solely donor material cannot meet this surplus amount of bone replacement. Autografts are still regarded as optimal reconstruction material, because of the lack of good enough synthetic materials. However, highly engineered structures can fulfil the demand of synthetic biomaterials to a great extent. In fact, it is possible to mimic better the structures of living materials, like bone, cartilage or teeth using substitute materials. Therefore, the search for better synthetic bone substitute is consistant.

II. Femur's CAD Model Generation Methodology

The 3D model was generated using Solid works 12, a highly efficient and easy to use CAD modeling software. Using a reals bones sketch and dimensions the 3D model was generated using different advanced features of Solid works.

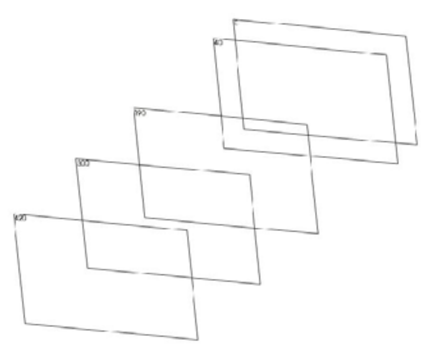

Figure 1 : Planes defined for sketching

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A total of five planes was created to generate different major features on the specified plane. All planes were offset of the base plane at different distances as shown in Figure 1. Figure 2 shows the drawing sketched onthe plane 40.

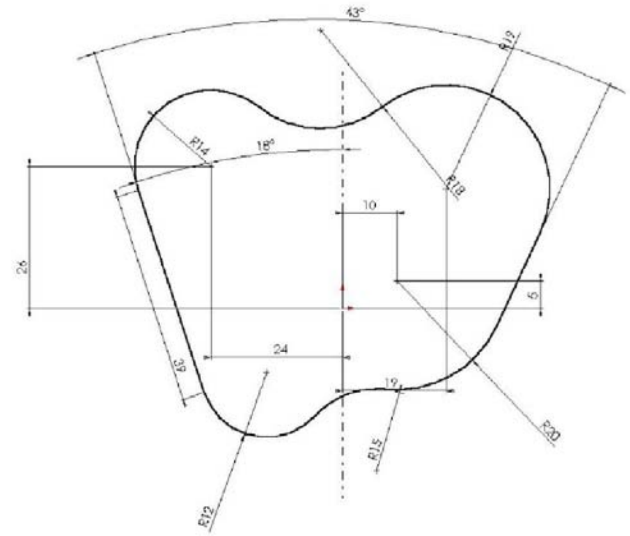

Figure 2 : The shape defining sketch

Similarly, in planes 190, 300 and 420 sketches in Figure 3 were drawn.

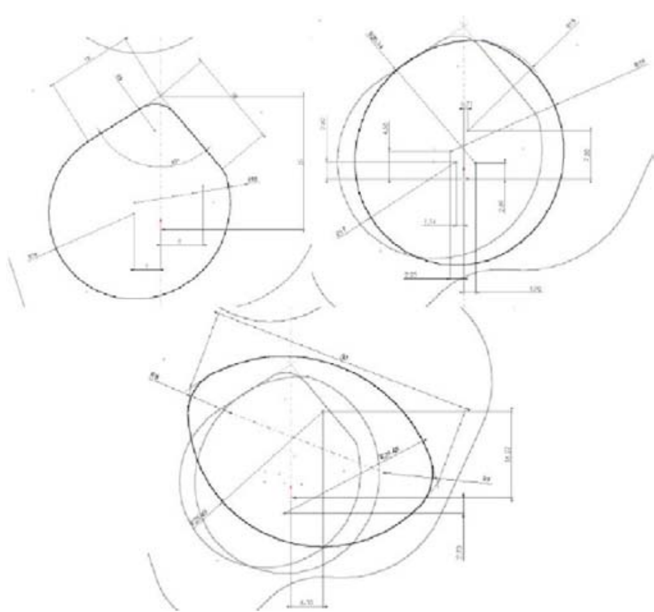

Figure 3 : Sections for defining the full profile

Figure 4 presents the base shape generated using Loft feature.

Figure 4 : The base shape

Revolve feature was used to generate the specific feature shown in Figure 5.

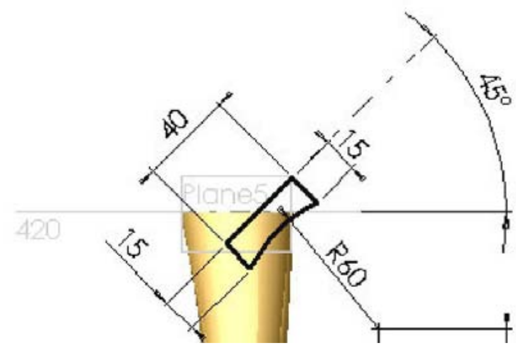

Figure 5 : Generation of femur head support

At that feature it was attached a secondary shape using Dome command (Figure 6).

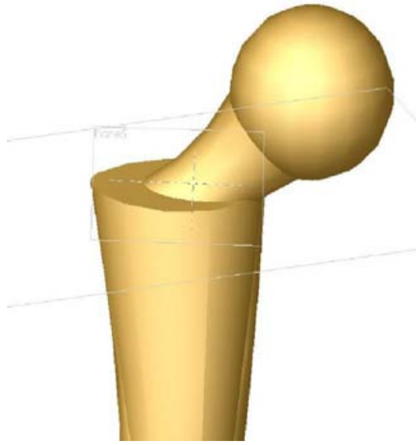

Figure 6 : Generation of head by dome feature

The features shown in Figure 7 were obtained by using Extrude feature in Insert manu twice.

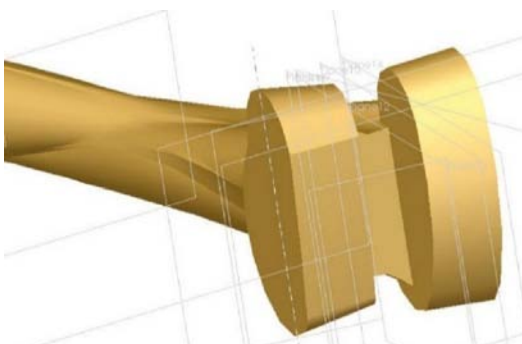

Figure 7 : After bose extrude

Figure 8 shows the modelling done by Loft feature in Solidworks.

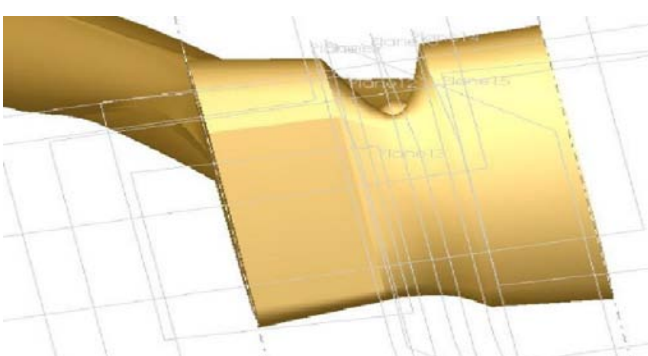

Figure 8 : Loft feature definoing in the mid plane

Two Dome shapes were attached at the two extruded shape and fillets were introduced after that (Figure 9).

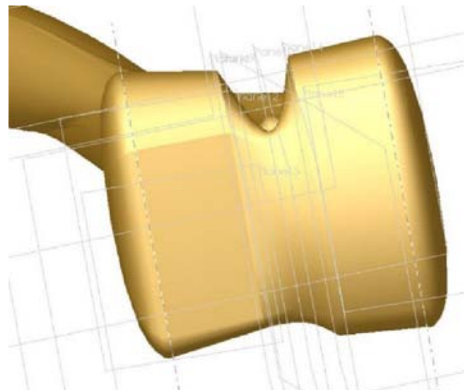

Figure 9 : Dome feature for accurate shape generation

In an inclined plane with 120 degrees it was drawn the sketch presented in Figure 10. 4

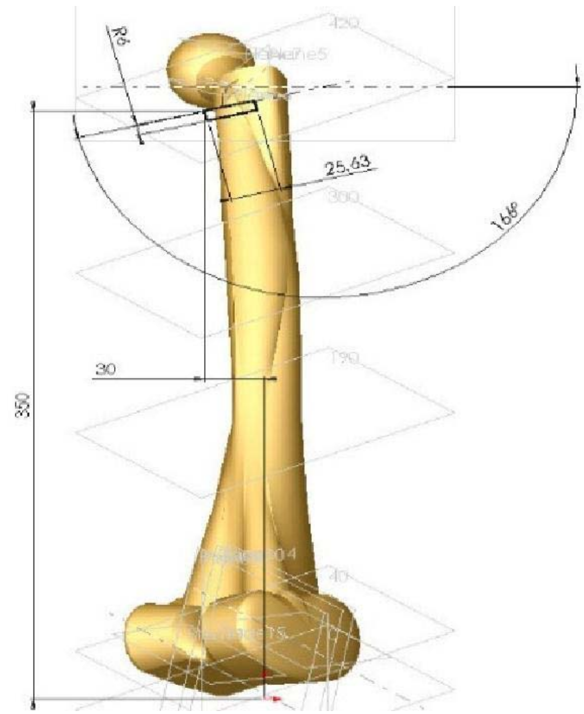

Figure 10 : The sketch drawn in inclined plane

Revolve feature was applied to the previous sketch in Figure 10. The output is shown in Figure 11.

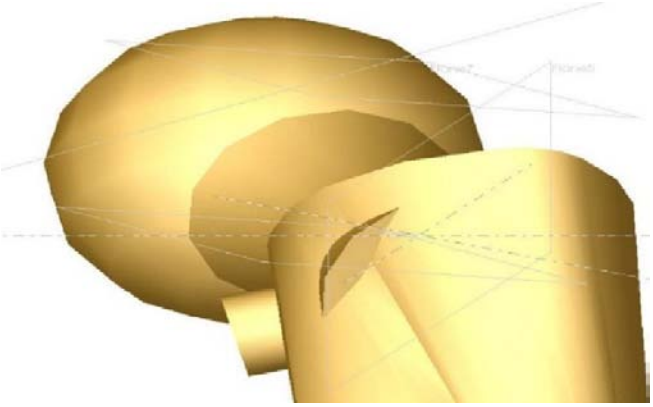

Figure 11 : The Revolve Feature

Fillet of 3mm radius was introduced to the selected areas (Figure 12).

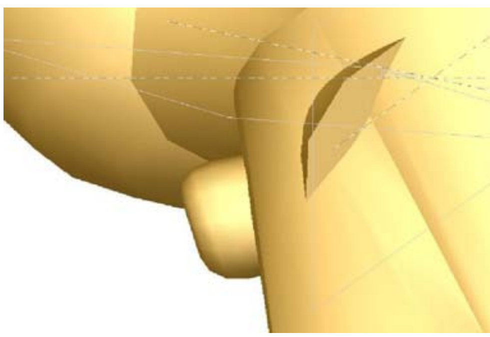

Figure 12 : Fillet of 3 mm radious for obtaining the precedent feature

After some minor operations and editings the femur bone was fully generated as shown in Figure 13.

Figure 13 : Complete 3D femur model

III. Modeling of Materials' Properties

a) Al_2O_3/Al FGM

For modeling Al_2O_3 /Al FGM methodology of Debabrata Chakraborty, Manish Ranjan and Anil Kumar was adapted [3]. In this study, the functionally graded material of thickness h, consisting of two constituent materials has been considered. The effective material properties of FGM shell is obtained by power law distribution where P(z), the material property at any location z was related with Pt and Pb are the material properties of the top surface (Al_2O_3) and bottom surface (Al) respectively.

$$P(z) = P_t - P_b \left\{ \frac{2z+h}{2h} \right\}^{\lambda} + P_b \qquad (1)$$

In the equation (1) if λ is set to 0, a component fully made of ceramic will be formed. On the other hand content of metal increases as λ increases. Poisson's ratio, ν is assumed to be constant throughout the material. The stress-strain relationship can be expressed as

$$\begin{Bmatrix} \sigma_{xx} \\ \sigma_{yy} \\ \tau_{xy} \\ \tau_{yz} \\ \tau_{zx} \end{Bmatrix} = \begin{bmatrix} 1 & \nu & 0 & 0 & 0 \\ \nu & 1 & 0 & 0 & 0 \\ 0 & 0 & \frac{1-\nu}{2} & 0 & 0 \\ 0 & 0 & 0 & \frac{1-\nu}{2} & 0 \\ 0 & 0 & 0 & 0 & \frac{1-\nu}{2} \end{bmatrix} \begin{Bmatrix} \varepsilon_{xx} \\ \varepsilon_{yy} \\ \gamma_{xy} \\ \gamma_{yz} \\ \gamma_{zx} \end{Bmatrix}$$

This methodology was validated by the study of dynamic response of a simply supported square isotropic plate subjected to suddenly applied uniform load q = 100 kN/m^2 .The outcomes were compared with the results published by Kant et al. [6] as shown in Figure. 14. T2he dimensions and material properties of the plate are a = b = 250 mm, h = 50 mm, E = 21 GPa, ν = 0.25, ρ = 800 kg/m . It is observed from Figure.2 that the result from the present code converges well with 88 mesh size and in excellent agreement with the already published results of Kant et al. [6].

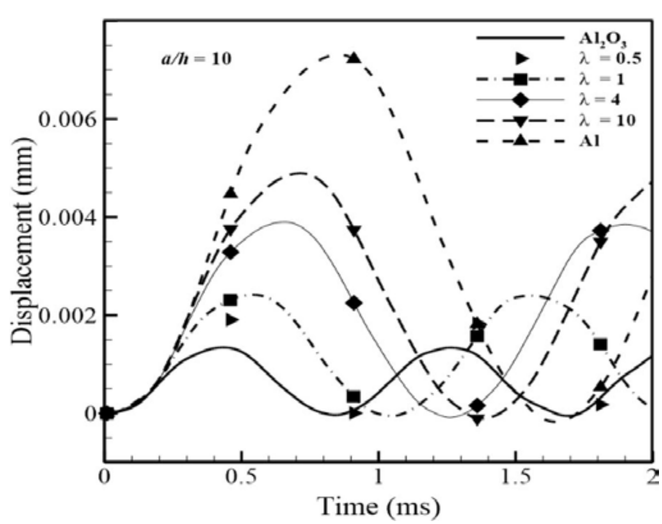

Figure 14 : Effect of power law gradient on central deflection of Al_2O_3/Al FGM cylindrical shell [3]

b) Ti6Al4V Alloy

"Ti6Al4V, Ti-6Al-4V or Ti 6-4, is the most commonly used Titanium alloy. It has a chemical composition of 6% aluminium, 4% vanadium, 0.25% (maximum) iron, 0.2% (maximum) oxygen, and the remainder titanium. It is significantly stronger than commercially pure titanium while having the same stiffness and thermal properties (excluding thermal conductivity, which is about 60% lower in Grade 5 Ti than in CP Ti). Among its many advantages, it is heat treatable. This grade is an excellent combination of strength, corrosion resistance, weld and fabricability.This alpha-beta alloy is the workhorse alloy of the titanium industry. The alloy is fully heat treatable in section sizes up to 15mm and is used up to approximately 400°C (750°F). Since it is the most commonly used alloy – over 70% of all alloy grades melted are a sub-grade of Ti6Al4V, its uses span many aerospace airframe and engine component uses and also major non-aerospace applications in the marine, offshore and power generation industries in particular.Generally, Ti-6Al-4V is used in applications up to 400 degrees Celsius. It has a density of roughly 4420 kg/m3, Young's modulus of 110 GPa, and tensile strength of 1000 MPa. By comparison, annealed type 316 stainless steel has a density of 8000 kg/m3, modulus of 193 GPa, and tensile strength of only 570 MPa. And tempered 6061 aluminium alloy has 2700 kg/m3, 69 GPa, and 310 MPa, respectively." [11]

IV. A Case Study: Typical Femur Under Load

To demonstrate the behavior of the femur modeled for Al_2O_3/Al FGM and TI6AL4V, a simple example is presented here. This example is not a best case or worst case scenario but rather just a pseudo random example to see if and how much proper the materials are for artificial bone.

Relevance Center set to medium. A fine relevance center would yield better results but it causes very high amount of RAM consumption which was unavailable. The Inflation Option settings determine the heights of the inflation layers. Smooth Transition was set for obtaining desired mesh refinement. The Smooth Transition option uses the local tetrahedral element size to compute each local initial height and total height so that the rate of volume change is smooth. Each triangle that is being inflated will have an initial height that is computed with respect to its area, averaged at the nodes. This means that for a uniform mesh, the initial heights will be roughly the same, while for a varying mesh, the initial heights will vary. Increasing the value of the Growth Rate control reduces the total height of the inflation layer. The total height approaches an asymptotic value with respect to the number of inflation layers. Span Angle Center sets the goal for curvature based refinement. The mesh will subdivide in curved regions until the individual elements span this angle. The following choices are available:

- Coarse - 91o to 60o
- Medium - 75o to 24o
- Fine - 36o to 12o6

For this study Curvature Normal Angle was set to 18O. Figure. 15 shows surface mesh of femur bone.

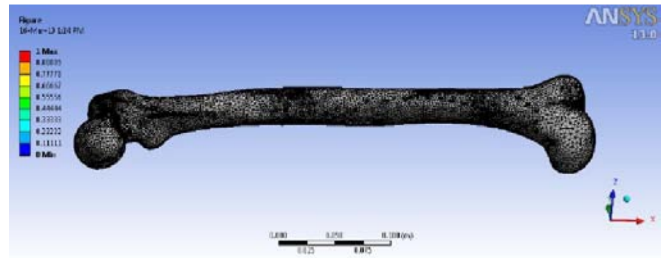

Figure 15 : Surface mesh of the femur bone

The three dimensional model of femur bone was imported in ANSYS and was meshed with Ansys default mesh tool. An eccentric and concentrate load of 300N applied at the head of femur bone and fixed support is provided at lateral condyle, medial condyle and patellar surface in Ansys Mechanical workbench. The boundary conditions are shown in Figure. 16 and load applied is shown in Figure. 17

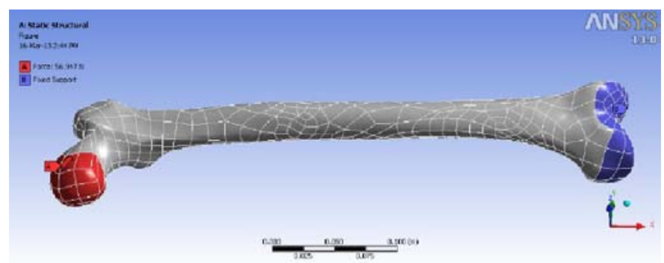

Figure 16 : Bourdary Conditions

The load applied here was ramped load which was applied for 1 second varying linearly 0N to 300N. Figure.5 shows ramp load applied on the femur.

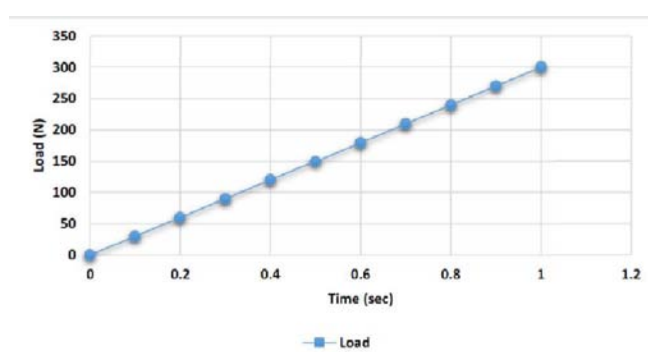

Figure 17 : Applied load on the femur

V. Results and Discussion

It may be noted that only static load applied on Femur. Though Al_2O_3/Al FGM is relatively new concept compared to TI6Al4V, it has higher reliability and less weight. From the properties of Ti6Al4V and Al based FGM (i.e. Al_2O_3/Al FGM) we can see that FGM has slightly less strength than Ti6Al4V. But from aluminum based FGM sudden release of Al is less frequent and safe. As a result Al based FGM has become a strong competitor in the field of artificial bone material.

Figure.18 and 19 shows the deformation pattern of the femur for Ti6Al4V and Al_2O_3/Al FGM respectively.

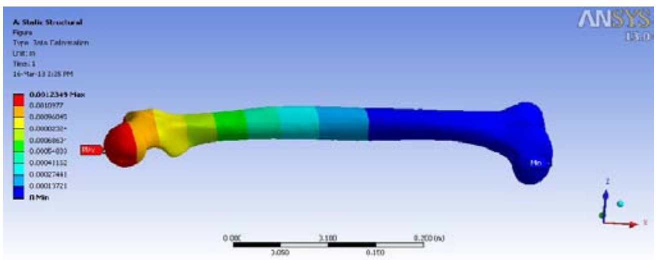

Figure 18 : Deformation Contour for Ti6Al4V

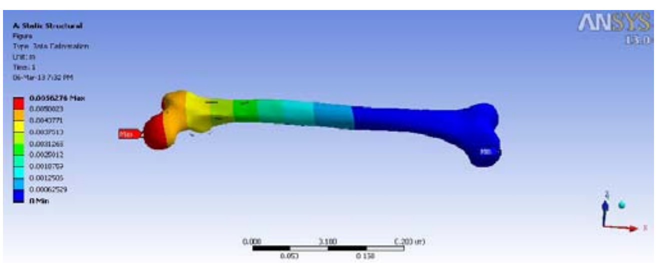

Figure 19 : Deformation Contour for Al_2O_3/Al FGM

These Figures shows similar patterns of deformation both for Ti6Al4V and Al_2O_3/Al FGM. From the max-min deformation probe label it is observed that at the head of the femur deformation is maximum and at the lateral condyle deformation is zero. Maximum and minimum deformation of the femur in both cases are shown in table 1.

Table 1 : Maximum and Minimum Deformation

Material	Deformation (m)	
	Maximum	Minimum
Ti6Al4V	1.2349e-003	0.0
Al_2O_3/Al FGM	5.6276e-003	0.0

Observed maximum and minimum values of deformation from table 1 are in acceptable range compared to the values of deformations for actual femur bone studied by Raji Nareliya with a fector of safety 15 [7].

Figure. 20 shows variation of deflection of the bone under load along the path shown in Figure. 21

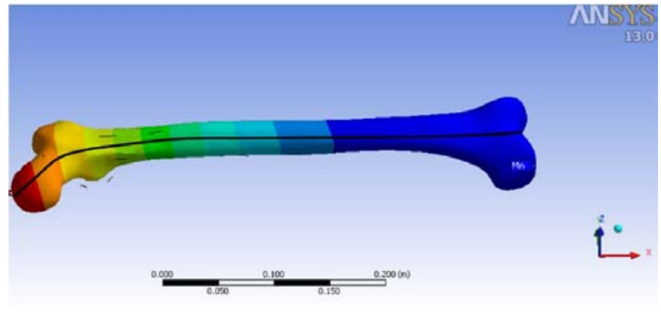

Figure 20 : Path along which deflection is measured

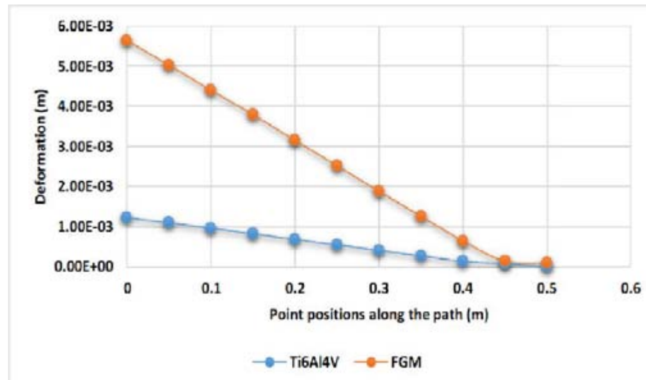

Figure 21 : Deflection Curve

From the deflection curve it is observed that Al_2O_3/Al FGM gives 9 times less deflection than Ti6Al4V for same loading criteria. As, load applied to the femur bonr was varied linearly with time (Figure. 5), we got the deformation almost linear along the path shown. Moreover, this curve is almost identical to Figure. 22 which was obtained by Somkid, Benchawan and Kamonchat's research work [8].

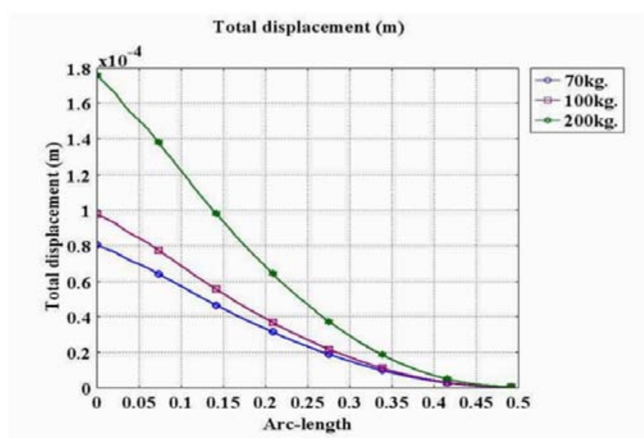

Figure 22 : Profile of total displacement along the axial of femur bone [8]

Stress development contour due to concentrated load apply on the femur head for Ti6Al4V and Al_2O_3/Al FGM can be observed from Figure. 23 and Figure. 24 respectively.

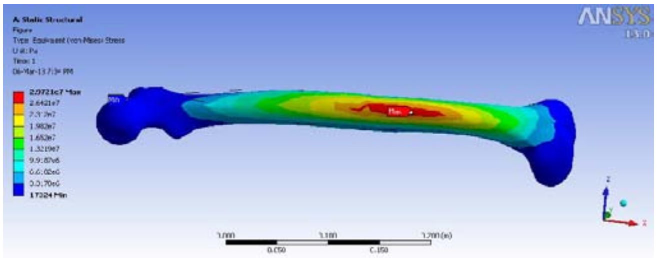

Figure 23 : Stress Contour for Ti6Al4V

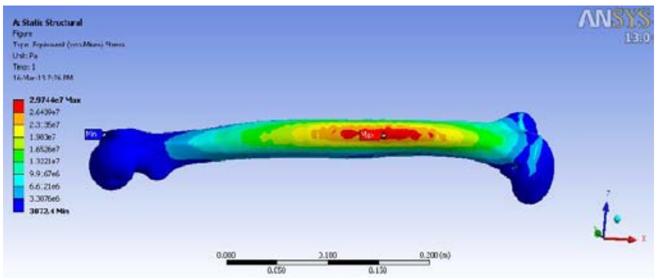

Figure 24 : Stress Contour for Al_2O_3/Al FGM

It is observed from max-min stress probe lebel that minimum stress occurs at the both ends of the femur and gradually increases to the middle portion of the bone. Mximum and minimum stress of the femur in both cases are shown in table 2.

Table 2 : Maximum and minimum stress

Material	Equivalent (Von Misses) stress (Pa)	
	Maximum	Minimum
Ti6Al4V	2.9744e+007	3072.4
Al_2O_3/Al FGM	2.9721e+007	17324

V. Conclusion

In the field of biomedical, research on biomaterial is of utmost important. Typically, in the reconstruction of bone defects, clinicians use autograft bone, based on the fact that the commercially available synthetic materials are not optimal for the reconstruction of bone. Moreover, as stated earlier for total bone replacement the need for specialized biomaterial is of utmost importance. This study deals with Ti6Al4V and Al_2O_3/Al FGM as prospective candidate of femur bone material. Both of these materials has friendly behavior with MRI. This computational study reveals mechanical characteristics of Ti6Al4V and Al_2O_3/Al FGM under a random loading. Overall study shows that Al2O3/Al is more suitable than TI6AL4V in case of both strength and weight of the bone. This study will be useful to surgeon in femur surgeries and bone prosthesis. These better synthetic bone substitutes will most probably be commercially available for orthopaedic applications in the near future.

Acknowledgments

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