Design and Analysis of HIP Stem using Finite Element Modeling

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Abstract—The objective of this research work is to analyze the biomechanical behavior (stress and deformation) of cementless THR made up of β-phase Ti alloy at static and dynamic loading conditions using the finite element modeling (FEM). In the present research work, the surface of β-phase Ti based cementless THR is modified or treated by powder mixed electric discharge machining (PMEDM) process. PMEDM provides a vehicle to interface implant with large scales cell and tissues. In other words, PMEDM promotes bone ingrowth (osseiointegration). In this paper, a three dimensional FEM model of CT-scanned bone of a patient and implant was constructed using ANSYS 14 software. The bonded contact was used to simulate the full bone ingrowth and long term stability of THR. The study predicts the potential risk of failure of the implant at static and dynamic loading condition. The results obtained from this study indicate that no risk of failure of implant arises further the results are helpful for the prosthesis surgeons to understand the biomechanical behavior of the β-phase Ti based cementless THR. The results clearly indicate that PMEDM process can be used as a surface modification technique for Ti based bio-implant in future.

Keywords— Total hip replacement (THR), β-phase Ti alloy, PMEDM, finite element model, bone ingrowth, stress and deformation.

I. INTRODUCTION

Ti based metallic implants ate the ultimate choice for the replacement of dysfunctional or damaged joint such as hip and knee due to its excellent mechanical properties and biocompatibility. Inspite of these excellent mechanical properties, their wear resistance, bone ingrowth, stability, stress shielding and performance in loading environment are very poor. In order to improve the biological and tribological properties of implant materials for promotion of osseointegration, surface modification is often required [1]. According to the different clinical needs, various surface modification schemes such as CVD, PVD, Sol-gel, Anodisation, Ion implantation and Electric discharge machining (EDM) process [2-5]. Among these techniques, EDM process is the potential candidate to modify surface of substrate. EDM is a non-traditional concept of machining which has been widely used to machine hard and tough materials irrespective of their hardness and toughness. It uses thermal energy to machine electrically conductive parts. In EDM process, there is no direct contact between the tool and the workpiece. So, vibration and stresses chatters are zero and thus any conductive and complex shapes within very close tolerances can be machined/ manufactured/ modified [6]. EDM suffers from some serious drawbacks of instability and arcing. To overcome these problems; number of researchers have done many efforts in the past [7-8]. The recent advancement in this direction is mixing of powders particles into the dielectric fluid of EDM [6]. This technique is termed as powder mixed EDM (PMEDM). In PMEDM, the suspended powder enlarged and widened the discharge gap which in turn improves the stability and thus efficiency [9].

Many researchers in the literature have studied the results of machining of Ti and its alloy by EDM [10-12]. However; few research studies are reported for machining of Ti and its alloy by PMEDM. The research which is reported in literature for PMEDM have studied the machining of Ti alloy just for measurement of material removal rate (MRR), tool wear rate (TWR) and surface roughness (SR) etc. No research studies have been available that presented the PMEDM machining/modification of Ti alloy used as an implant for the biomedical purpose.

In this research paper PMEDM is tried first time to machine and modify the surface properties of Ti based β-phase alloy. PMEDM supposed to provide excellent interface between implant surface and large scale cells and tissues. The biocompatibility is prime requirement for the successful all surgeries including HIP and Knee joints. The best way to check the biocompatibility and osseiointegration is the experimentation. In experimentation; one has need to insert the implant in the body of carrier (Rabbit etc.) and after certain time period; then to evaluate the bone ingrowth. It is assumed that good bone in-growth provides the guarantee for successful implantation. Surface characteristics of implant have been reported to significantly influence on bone in-growth [13]. The other way to check the biomechanical behavior of inserted implants is to do the modelling and simulation under both static and dynamic loading conditions.

Biomechanical behavior of THR or hip prosthesis is studied by finite element analysis (FEA) to predict the performance and potential risk of failure of Ti implant at static and dynamic loading condition [14]. It was found that stem made up of Ti material are safe against fatigue failure. A finite element simulation and analysis of model for bone remodeling around cementless stem. Bone ingrowth simulated by contact condition [15]. Authors found the model represents the novel approach for prediction of bone ingrowth on cementless stem. Bougherara H. et al studied the biomechanical assessment of modular and monoblock revision hip implants at sub clinic axial load by finite element analysis. Bonded contact was assumed for full bone ingrowth. They found that modular implant was 3 to 4.5 times mechanically stiffer than the monoblock [16]. A finite element analysis of biomimetic hip stem on hydroxyapatite (HA)-coated carbon fiber composite was performed by C Caouette et al [17]. They studied the biomechanical behavior of stem at slow walking, stair climbing and gait conditions. They found that composite stem allowed better stress shielding and micromotions than Ti-6AL-4V. M. Tarala et al proposed a methodology to simulate the bone ingrowth as a time dependent process. They developed an algorithm to calculate the strength of bone-implant interface based on the micromotions and gaps. The results shows that as bone ingrowth increases with time the micromotions and gap are less, this simulation shows that how implant successfully adopted the phenomena of bone ingrowth [18]. B. R. Rawal et al designed and manufactured a Ti based cementless femoral stem for Indian population. The FEA of the stem was conducted and compared with medical steel to predict the risk of failure at loading conditions. They found that Ti is stiffer than steel and no risk of fracture [19]. C. Prakash et al investigated the stress shielding and micro-motions for the β-phase Ti based cementless THR. The result shows that stress shielding is reduced and micro-motions are reduced as bone grow around implant. Micromotions remained below 40μm at full bone ingrowth which further indicates the proper fixation of implant.

The aim of present study was to investigate the biomechanical behavior of PMEDMed β-phase Ti based cementless THR. Finite element modeling (FEM) and analysis of femur- implant was conducted in ANSYS-14.0 software. The study predicts the potential risk of failure of the implant at static and dynamic loading condition. The results obtained from this research work would be helpful for the prosthesis surgeons.

II. MATERIALS AND METHODS

A. Geometry of femur-implant

The three dimensional geometry of a femur of hip joint was obtained from CT scan image of bone of a 62 years old male patient. CT- scanned image was obtained from orthopaedics department, PGIMER, Chandigarh, India. The CT scanned image of hip joint femur geometry standardized format IGES data file. The IGES file of femur was imported into CATIA software and solid model femur was created. The head of femur was removed and then implant was inserted into femur to form a single piece model. The combined geometric model of femur and the implant was created by using software CATIA-V5R17. β-phase Ti biomaterial was used as stem material. The surface of β-phase Ti implant is assumed to be modified/treated by PMEDM process. Then the solid implanted femur model was imported in ANSYS 14.0. In the current study the behavior of β-phase Ti implant was assumed linearly isotropic and cortical bone and cancellous bone were assumed homogeneous, isotropic and linearly elastic.

Young's modulus of elasticity (GPa) and passions ratio of bone 17 GPa and 0.33 and for β-phase Ti implants are 55 GPa and 0.3 respectively.

B. Load and boundary conditions

The implant-femur assembly subjected to loading condition assuming an average weight of 70 Kg. 2000 N load is acting on femur neck, 1570 N is acting at abductor muscle and the bottom of femur connected to knee is fixed in static load condition. Dynamic load on neck of femur is considered for 5 seconds and rest of conditions are same as statics.

C. Finite element model

The Workbench is used for Finite element analysis (FEA) of assembly. Its simulation module automatically generates contact between the femur and implant. A 8 node tetrahedron surface to surface frictional contact was defined between the implant and bone using contact elements CONTA174 and TARGE170. The augmented Lagrange method was used for solving the contact problem. Fine mesh was applied to the implant-femur assembly. Bonded contact was assumed for full bone ingrowth and long term stability of implant. Fig 1(a) shows finite element model and Fig 1(b) shows the femur-implant assembly with boundary conditions. The finite element model for this study contains 83988 nodes and 52174 elements.

III. RESULT AND DISCUSSION OF FEA

To investigate how biomechanical behavior differ from each other, THR is analyzed under static load and dynamic walking load. Total deformation and Von Mises stresses are calculated analyzed. The results indicates that the use of material with a lower modules (55 GPa) is more stiffer than Ti-6Al-4V (110 GPa) and stain steel (200 GPa).

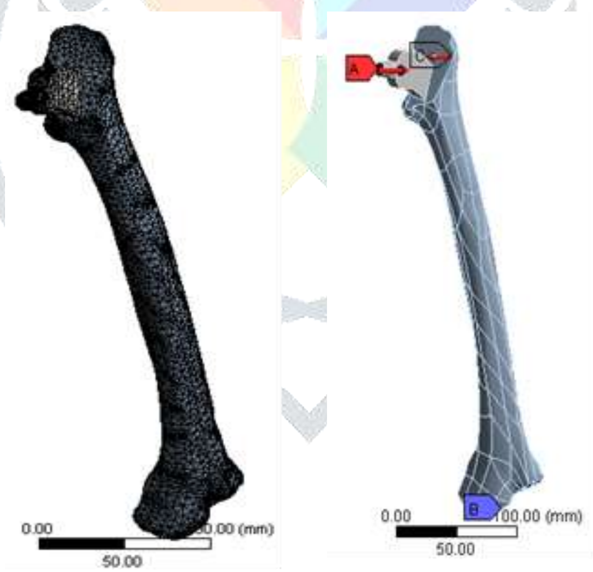
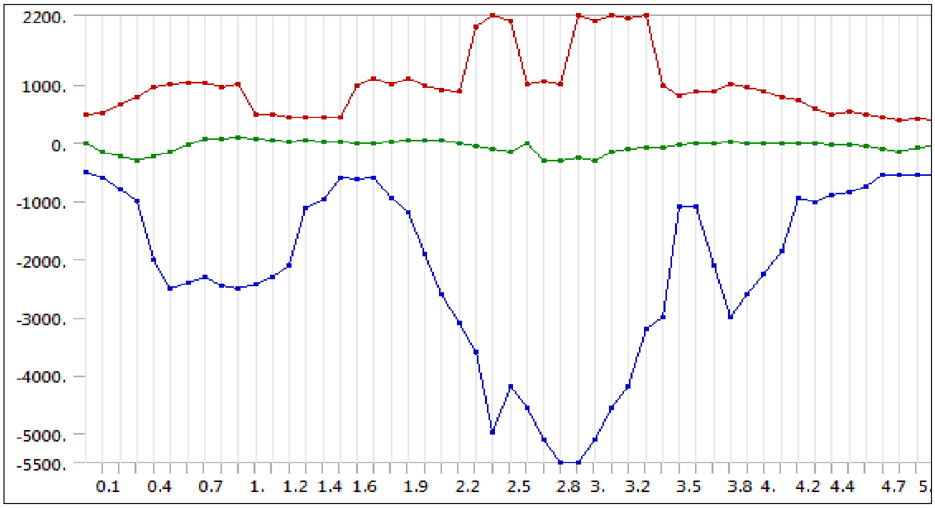


Fig. 1 Bone-femur assembly in ANSYS workbench (a) FEA model (b) model with boundary conditions



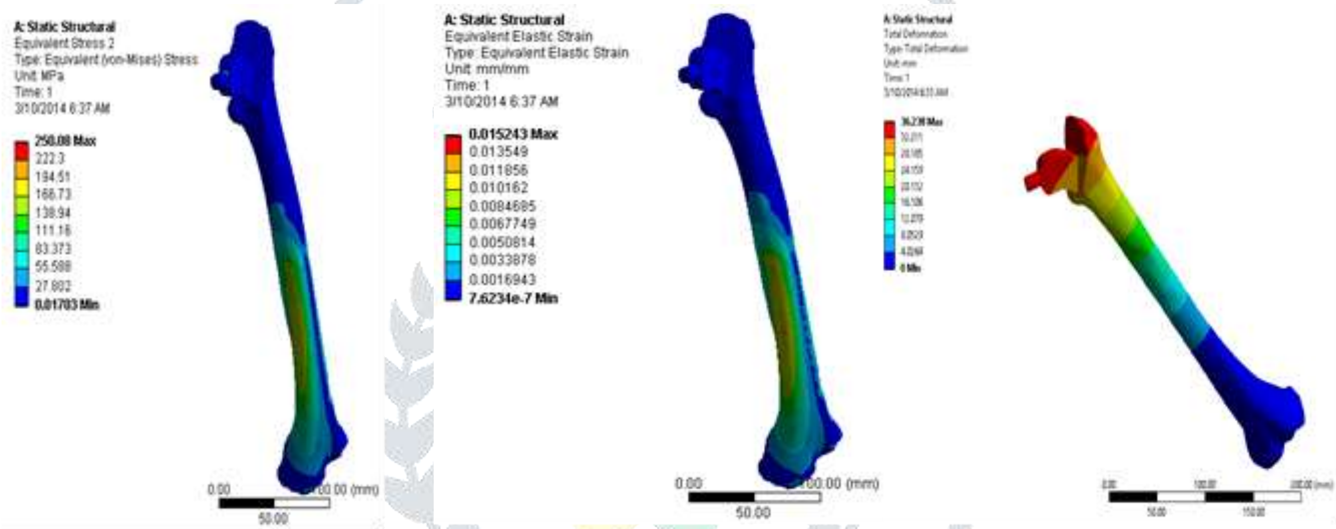


Fig. Contour plots of (a) Von-Mises stresses (b) strain (c) total deformation on bone-stem at static condition using 316-L cementless Hip replacement

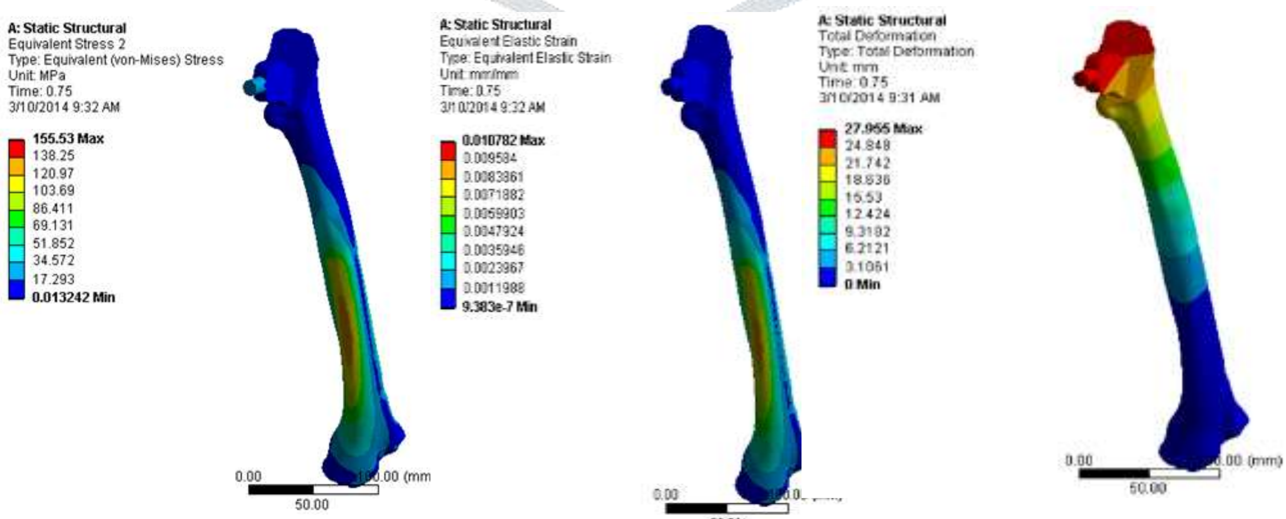


Fig. Contour plots of (a) Von-Mises stresses (b) strain (c) total deformation on bone-stem at static condition using Ti-6Al-4V cementless Hip replacement

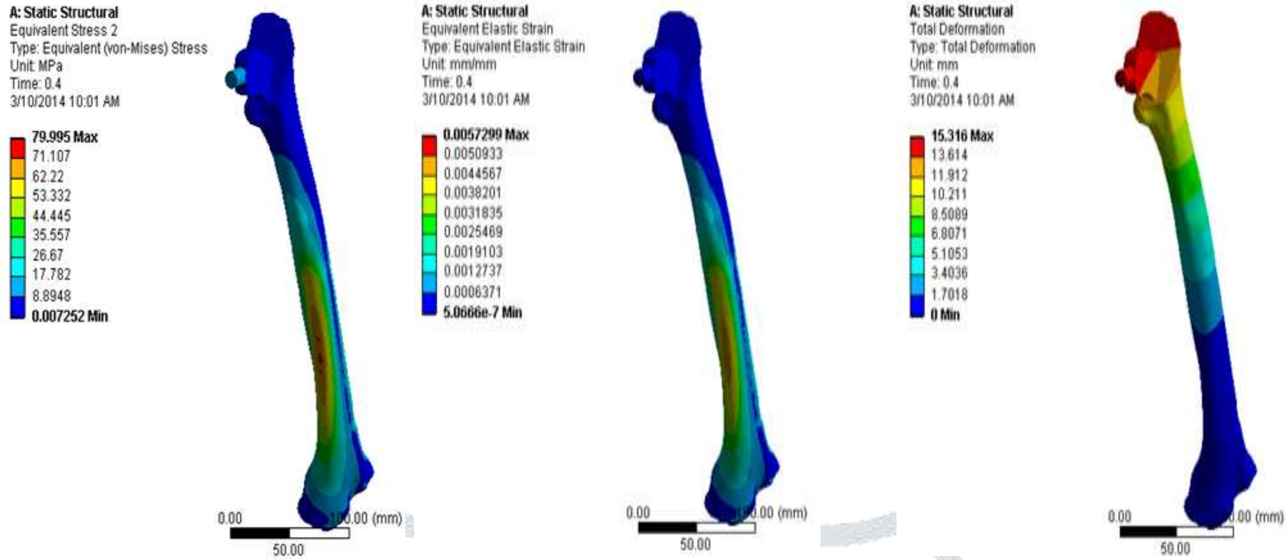


Fig. Contour plots of (a) Von-Mises stresses (b) strain (c) total deformation on bone-stem at static condition using β-phase Ti (TNTZ) cementless Hip replacement

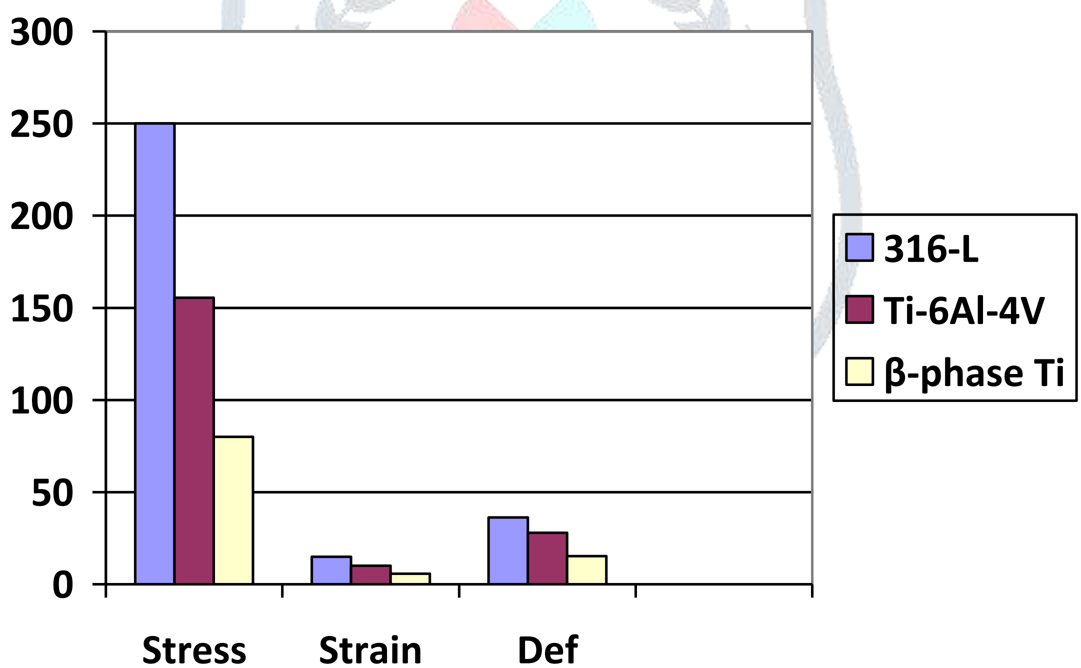
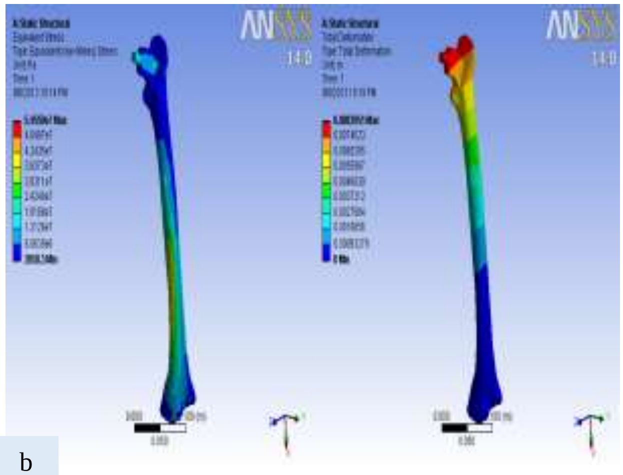


Fig. Comparison of stress, strain and deformation at static load condition corresponding to 316-L, Ti-6Al-4v and β-phase Ti alloy

A. Results at static load condition

The results are presented for FEA analysis of PMEDMed β-phase Ti based cementless THR at static load condition. The model recognizes regions of deformation and Von Mises stresses. Fig 2 (a) and Fig 2 (b) shows the distribution of Von Mises stresses and total deformation developed in the assembly in color coded maps. Dark blue color represents area with minimal stress while red color represents area with maximum stress. The maximum and minimum Von Mises stresses is 5.45 x 10^7 Pa and 2050.3 Pa respectively. Results shows that the higher deformation occurs at the neck of implant.



a b

Fig. 2 Contour plots of (a) Von-Mises stresses (b) total deformation on bone-stem at static condition

B. Results at dynamic load condition

The results are presented for FEA analysis of PMEDMed β-phase Ti based cementless THR at dynamic load load condition. The model recognizes regions of deformation and Von Mises stresses at dynamic load condition. Fig 3 (a) and Fig 3 (b) shows the distribution of Von Mises stresses and total deformation developed in the assembly in color coded maps. Dark blue color represents area with minimal stress while red color represents area with maximum stress. The maximum and minimum Von Mises stresses for 5 seconds is represented in fig 4. Results shows that the variation in the magnitude of deformation for 5 second in fig 5.

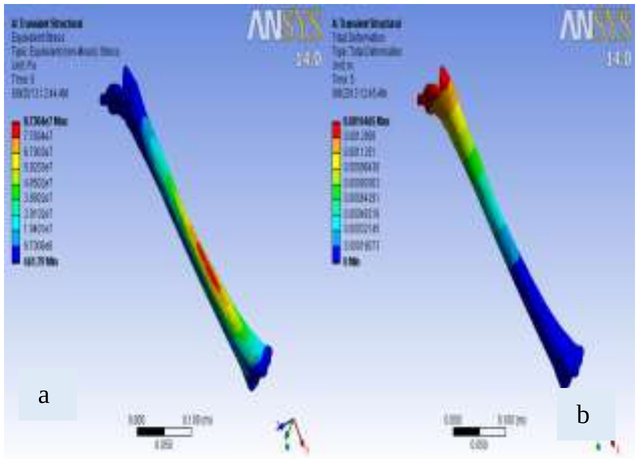


Fig. 3 Contour plots of (a) Von-Mises stresses (b) total deformation on bone-stem at dynamic condition

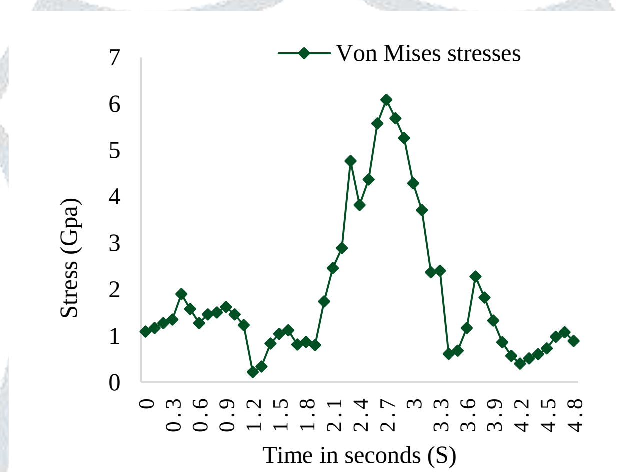


Fig. 4 Variation in magnitude of Von-Mises stresses on bone-stem at dynamic load condition

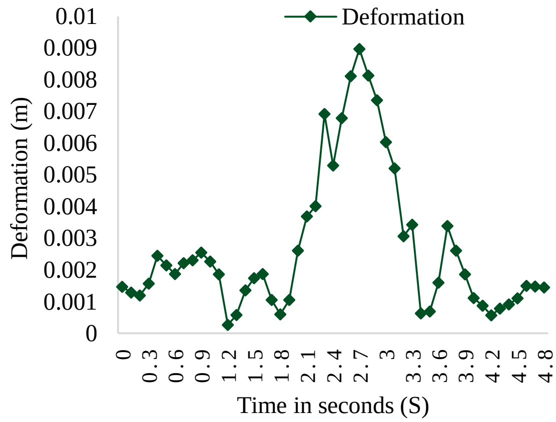


Fig. 5 Variation in magnitude of deformation on bone-stem at dynamic load condition

IV. CONCLUSIONS

In this present study, FEA analysis of PMEDMed β-phase Ti based cementless THR was conducted at static and dynamic load condition. Implant of β-phase Ti alloy was found stiffer, reliable and bio-compatible for prosthesis. The results obtained from the study indicating no risk of fracture at static and dynamic loading conditions. The results obtained from this research work helpful for the prosthesis surgeons to understand the biomechanical behavior of the β-phase Ti based cementless THR.

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