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Analysis of Materials for Tibia Tray component of Artificial Knee Joint

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Abstract— This paper presents basic stress analysis at the bone-implant interface in total knee replacement using finite element modeling. The tibial component of the joint consisting of an insert, base, bone cement and cortical bone is modeled as a two-dimensional skeleton. Various material combinations of the tibial base component are considered to test the bone-cement interface stresses. In addition to conventional Ti alloy and Co-Cr-Mo, the material of tibial base is considered as a functionally graded material (FGM) made-up of Ti metal-ceramic combination with varying volume fractions. By treating all the materials as isotropic and linearly elastic, the von-Mises and shear stresses are obtained using two-dimensional finite element analysis. Results reveal that the FGM base material provides uniform stress distribution characteristics.

Index Terms— **Biomaterials, Finite element analysis, Interfacial stresses, Tibial insert.**

I. INTRODUCTION

Knee joint is one of the most complex synovial joints. It supports the whole weight of the body. Also, it is the joint most vulnerable to both injury and development of osteoarthritis. Since 1950s, knee-implantations were designed to replace the damaged cartilage and bone of the tibiofemoral and patellofemoral joints. Fig.1 shows the anatomical view of the knee joint.

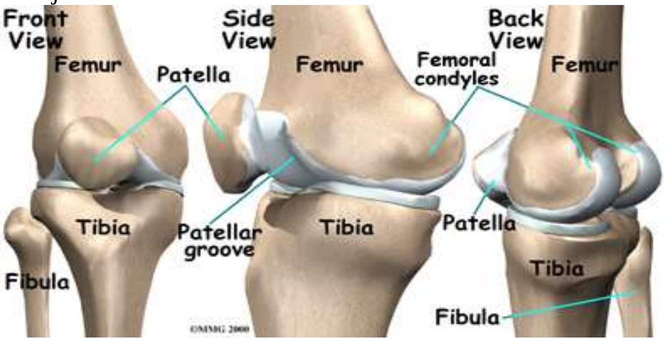


Fig.1. Configuration of knee joint

The total knee replacement involves removing the articulating surfaces of the affected knee joint and replaces them with artificial components made of biomaterials. Usually, the tibial articulating surface and the patellar components are made of ultra-high molecular weight polyethylene. The femoral component and tibial tray are usually made of metals such as titanium-based alloys, stainless steels and cobalt chromium molybdenum (Co-Cr-Mo) alloys or sometimes they are fabricated from ceramics such as alumina, zirconia and their composites. Fig.2 shows different components of knee implant. All the components are either fixed by cement or uncemented. Cemented components usually use polymethyl methacrylate cement. On the other hand, uncemented components rely on bone in growth into the implant.

Knee prosthesis minimizes the stresses on the tibial bone due to difference in Young's modulus between implant material and bone. The artificial joints eventually fail due to either loosening at the points where metal/cement meets the bone or by the wear of polyethylene layer.

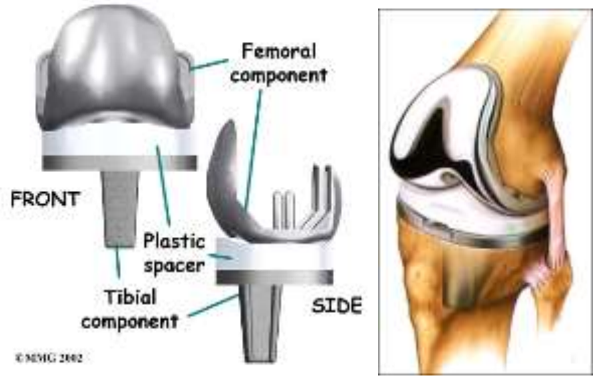


Fig. 2. Components of knee implant

A number of works in literature reported the effects of material properties, loading conditions and geometry of implants on the stress distribution at tibial component of implants. Au et al.[1] reported that it would be beneficial for zone beneath the tibial tray by using implant with elastic modulus of same order of magnitudes as the surrounding cancellous bone. The mechanical behavior of bone around tibial tray and stem has recently changed by stem design, geometry and material. It was found that long stem design with a polyethylene tip reduces the stresses at tip region due to its better mechanical bone effect [2]. Bahraminasab and Jahan [3] presented a strategy to select suitable materials for femoral components of knee prosthesis based on sensitivity analysis. Development of new biomaterials for medical application is one of the challenging tasks in material science. Long lasting ability and better functioning is a desirable requirement in implants of human body. New biomaterials which have multifunctional properties improve the knee plants by minimizing the stress-shielding effect, relative micro-motion and wear debris. Now-a-days, finite element models are increasingly used for analysis of effective functioning of artificial implants. Hedia et al.[4] developed a finite element model using ANSYS software for optimizing the implant material. It was found that replacing homogeneous titanium stem in cement less hip prosthesis by functional graded materials (FGM) reduces stress-shielding at stem-bone interface. Similarly, Hedia and Nemat-Alla [5] predicted the efficiency of hydroxyapatite-titanium FGM in dental implants compared to conventional titanium and stainless steel implants in reducing stress-concentration in cortical bone. Enab and Bondok [6,7] investigated the performance of cemented tibia tray component of total knee replacement through FGM and employed a two-dimensional finite element model to investigate the bone-interface stresses for tibial prosthesis with different FGMs. Cawley et al. [8] analyzed the effect of cementing techniques for tibial component in total knee replacement using clinical and experimental techniques. In a more recent work [9], the performance of cement less osseointegrated tibial tray was investigated using finite element analysis that employs the shape and elastic modulus of tibia and tibiofemoral joint loads.

Present work deals with the finite element modeling of bone and interface stresses for tibial prosthesis with base materials of titanium, Co-Cr-Mo and functional graded material. Optimum materials with favorable stress distribution are predicted. Section 2 presents the approach followed in this work along with one dimensional FGM formulation to find the distance dependent elastic modulus. Section 3 gives results and discussion along with the computational approach employed.

II. MATERIALS FOR TIBIAL COMPONENT

In biological systems, natural bones change from a dense, stiff external structure (cortical bone) to a porous internal core (cancellous bone), which demonstrates its functional gradation and material's response to external loading. A similar gradation is required for an artificial implant material. Such functional graded material has at least two components characterized by a compositional gradient from one component to the other, resulting in corresponding changes in properties of the material. In FGM, the continuous gradation of the material properties can be represented by two different models: (i) analytical solution and (ii) volume fraction and rule of mixtures. Analytical solutions mean a consideration of exponential functions for continuous gradation of material properties. Often, these functions do not give real representation of material properties except for the upper and lower surfaces of the FGM. Alternatively, volume fraction and rule of mixture models are most realistic way of representing the continuous gradation of the FGM properties. Due to the complexity of using volume fraction and rule of mixtures, several authors employed finite element method (FEM) for analysis of FGM problems. Using FEM, biomechanical performance of various joint implant designs as well as the effect of various factors on implant success can be predicted. Finite element method can be used to study the developed stresses and contact conditions at the bone-implant interface. This will help in understanding the biological response of the bone around implant. Different designs of tibial, femoral and patellar components are available, such as the design of tibial component with straight central stem, stems and pegs etc. All the designs have the tibial insert fabricated by poly ethylene.

In general, a tibial component has central stem and its tibial insert is anchored in the respected proximal tibia using a bone-cement made of poly-methyl methacrylate. The model should include (i) tibial bone, (ii) bone cement, (iii) tibial base component and (iv) tibial insert. The tibial base component was made of either titanium alloy or Co-Cr-Mo or functionally graded materials. The FGM model contains a structure composed of titanium and hydroxyapatite so as to satisfy both mechanical and biocompatible property requirements. The commercial finite element program ANSYS is used to predict the stresses at different locations of tibial base component.

A. Elastic modulus of FGM

When the tibial tray is considered as a plate of FGM with porosity p which is functionally graded from ceramic and metal, its elastic modulus is predicted as follows:

If V_m and V_c, are the volume fractions of metal and ceramic respectively, then these are distributed over the x-direction (horizontal distribution) and y-direction (vertical distribution), according to following equations [10,11]:

$$V_m=(x/l)^k \tag{1}$$

$$V_m=(y/t)^k \tag{2}$$

$$V_c=(1-V_m) \tag{3}$$

Where l and x are the total length of the tibial tray and the horizontal position of different points along it respectively. Similarly, t and y are the total thickness of the tibial tray and vertical positions along it, respectively as shown in Fig.3. The superscript called material gradient k is a parameter that controls the composition variation through the tibial tray. As shown in Fig.4, for metal rich composition k is less than 1, while for ceramic rich composition $k > 1$. When $k = 1$, it implies a linear variation of metal (Ti) and ceramics (hydroxypatite) compositions.

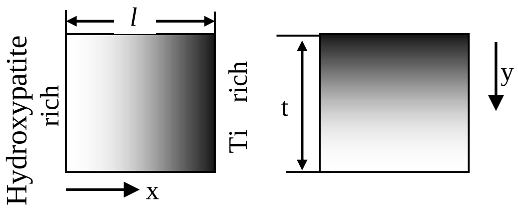


Fig.3. functionally graded material composition

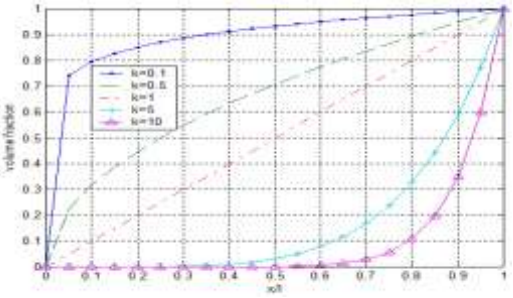


Fig.4. Variation of volume fraction with x/*l* ratio

Both elastic modulus and Poisson ratio will be affected by volume fraction. The porosity p of the FGM may be represented for horizontal distribution model by:

$$p= A\left(\frac{x}{\ell}\right)^n\left(1-\left(\frac{x}{\ell}\right)^z\right) \tag{4}$$

Likewise, for vertical distribution model, the porosity p is given by:

$$p= A\left(\frac{y}{t}\right)^n\left(1-\left(\frac{y}{t}\right)^z\right) \tag{5}$$

Where A, n and z are arbitrary parameters that control the porosity. As shown in Fig.5, porosity variation along the length depends on these values. For factor n, values other than 0 cause no porosity at the leftmost and rightmost surfaces of FGM while the maximum porosity exists within the FGM. Factors A and z can be varied to provide various amounts and gradients of porosity in the FGM implant. The changes in porosity alter the gradients of Young's modulus. On the other hand, the amount of porosity can influence the frictional characteristics of the surface, which subsequently might affect the micro-motion. The FGM effective properties, with porosity and continuously graded profile, are determined by employing the suspended spherical grain model.

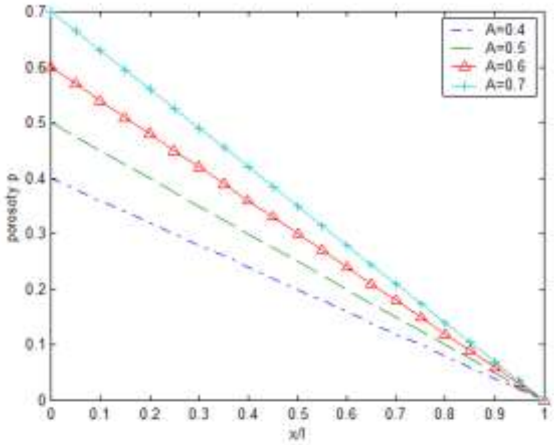


Fig.5. Effect of A on porosity (n=0, z=1)

It was derived on the assumption that the granular phase is in a matrix phase. The elastic modulus is obtained from the rule of mixtures as:

$$E=\frac{E_0(1-p)}{1+\dfrac{p(5+8\nu)(37-8\nu)}{8(1+\nu)(23+8\nu)}} \tag{6}$$

Where

$$E_0=E_c\left[\frac{E_c+(E_m-E_c)V_m^{2/3}}{E_c+(E_m-E_c)(V_m^{2/3}-V_m)}\right] \tag{7}$$

and

$$\nu=\nu_m V_m+\nu_c V_c \tag{8}$$

Here E_0 is the elastic modulus when the porosity equal to zero, E_m, ν_m and E_c, ν_c are the elastic moduli and Poisson's ratio of the metal and ceramic, respectively.

III. RESULTS AND DISCUSSIONS

Finite element analysis (FEA) can be used to predict the biomechanical performance of various designs and to evaluate the effect of material variables on implant stresses. Mechanical properties of bone, cement, tibial base component and tibial insert were taken from literature. All materials are assumed to be isotropic, homogeneous and linearly elastic. Table I shows the mechanical properties employed in the analysis.

Table I Mechanical properties used for FE analysis

Material	Young's Modulus (MPa)	Poisson's ratio
1.Tibial insert	2,300	0.25
2.Tibial Base		
(a) Ti-13Nb -13Zr	79,000	0.36
(b) Co-Cr-Mo	208,000	0.3
(c) FGM		
hydroxyapatite	40,000	0.3
Titanium	110,000	0.3
3. Cement	2,150	0.46
4. Cortical Bone	7,000	0.3

Standard dimensions of the simplified model of healthy knee are taken for analysis and the four material surfaces representing tibial insert (1), central stem (2), polymethyl methacrylate bone cement (3) and cortical bone (4) are considered as shown in Fig.6.

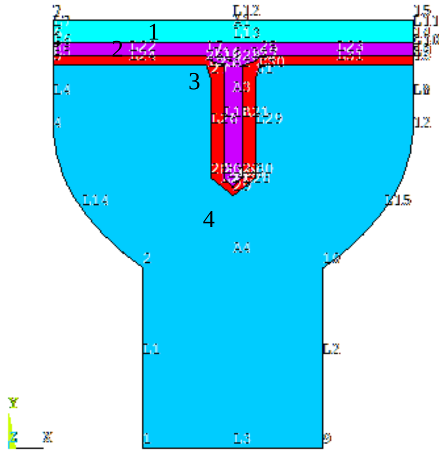


Fig.6. Proposed surface model of the tibial component

Separate simulations are carried out each for different tibial base component materials: (a) Ti-alloy, (b) Cr-Co-Mo and (c) FGM. General purpose FE program ANSYS-V13 is employed with parametric design language APDL. The lower part of the model is completely constrained in all directions. A total load of 1 kN is applied to the tibial insert. As this load components acting on proximal surfaces of tibia are asymmetrical, it is assumed that 80% of this load was acting on poster medial side of the tibial component, while remaining 20% was applied to the poster lateral side. These loads are normally distributed on tibial insert. It is also assumed that the bonded surface between implant and bone as rigid and all the stress-strain behavior is in elastic region. In order to study the loosening behavior of tibial component, the stiffness of the tibia tray and cement layer is to be properly controlled. It was observed from literature that reduction of tibia tray stresses and increasing bone stresses would reduce the stress shielding of the bone and prevent implant loosening. Fig.7 shows the von-Mises stresses (color plot) along the x-direction. It indicates high magnitudes of stresses in bone.

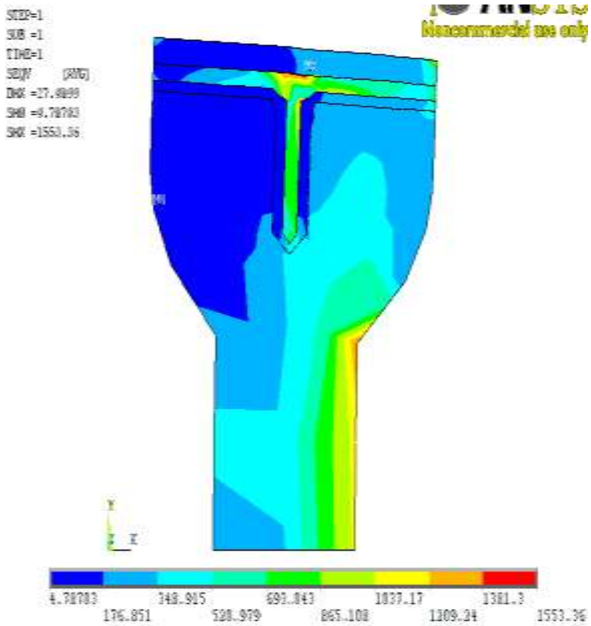


Fig.7. von-Mises stress distribution with Ti alloy base

Fig.8 shows the variation of these stresses along the poster medial side at bone-cement interface.

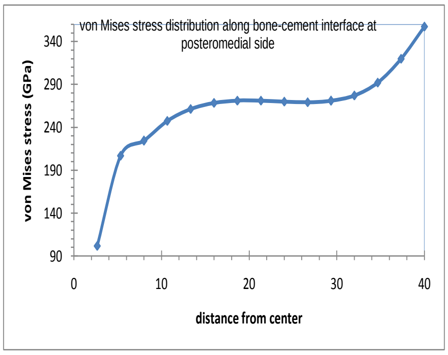


Fig.8. Stress distribution along bone-cement interface

There is a sudden change of von Mises stress distribution. Fig.9 shows the corresponding shear stress distribution also.

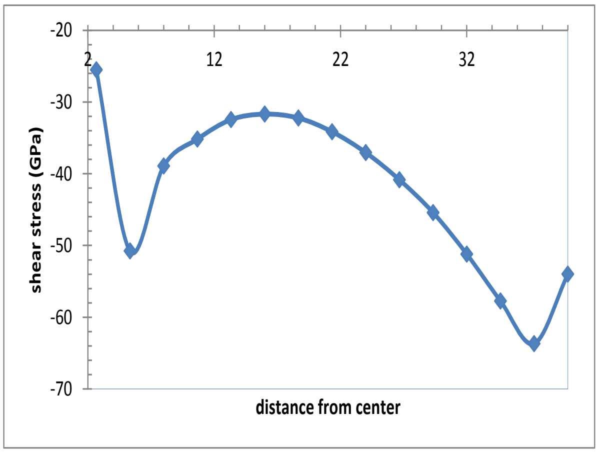


Fig.9. Shear stress distribution along bone-cement interface

By selecting Co-Cr-Mo material for tibial base, the corresponding von-Mises stress distribution is depicted in Fig.10. Obviously for same loading stress pattern is different.

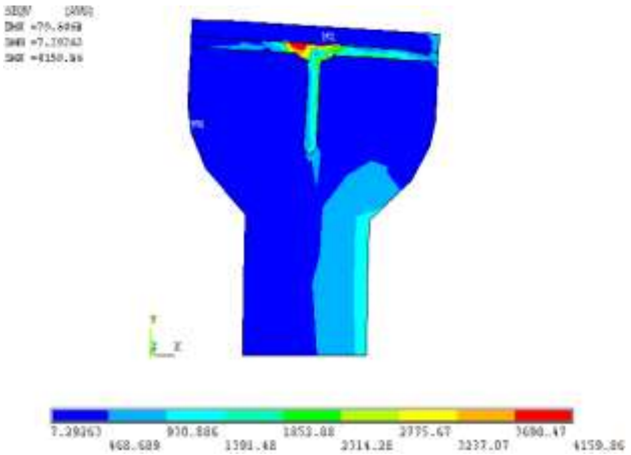
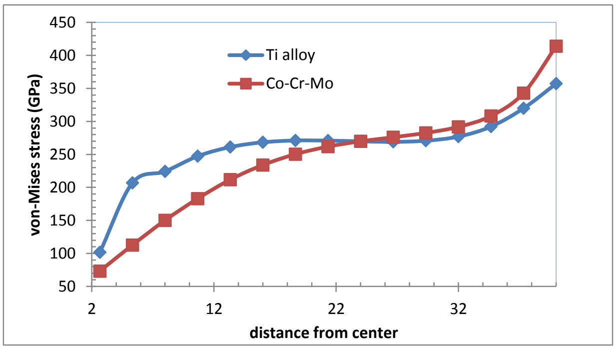
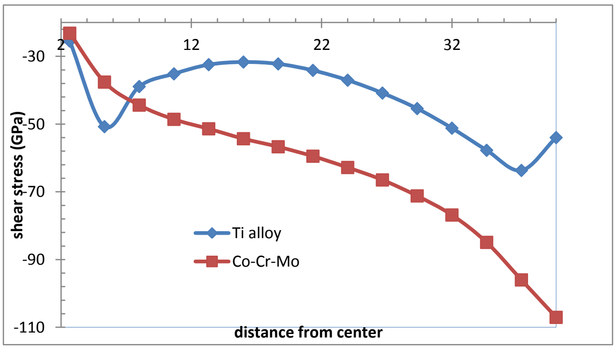


Fig.10. von-Mises stress distribution with Co-Cr-Mo alloy base

Fig.11 shows the comparative variation of von-Mises and shear stresses at the bone-cement interface for Co-Cr-Mo alloy and Ti-alloy tibial base materials. It is seen that the shear stress magnitudes are increasing as compared to von Mises stresses for Co-Cr-Mo alloy.



(a) Comparative Von-Mises stress distribution



(b) Comparative shear stress distribution

Fig.11. Stress distribution along bone-cement interface nodes

By considering A=0.4, n=0, z=1, the elastic modulus of the FGM varies from center line as shown in Fig.12. When *k*=0.5 comparatively the elastic modulus changes from ceramic (center) end to titanium rich end (edge).

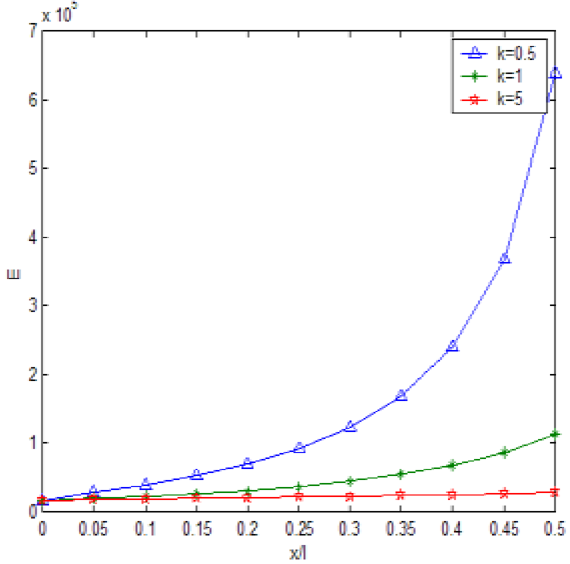


Fig.12. Variation of Elastic modulus of FGM

The elastic modulus and Poisson’s ratio at different locations (4 sub-regions are considered) of the tibial base component were provided for meshing them separately. Fig.13 shows the von-Mises stress distributions. It is seen that the variation is quite effective compared to the earlier two base materials.

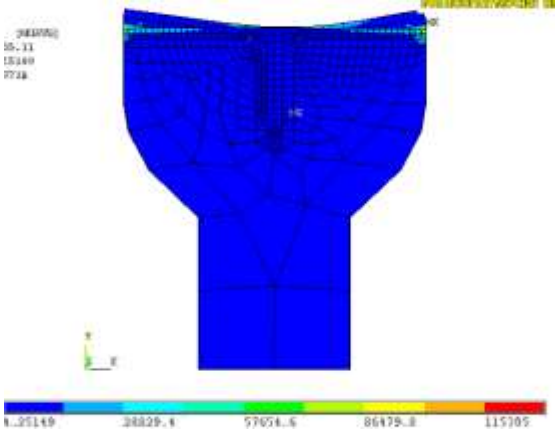


Fig.13. Von-Mises stress distribution with FGM base

A. Experimental frame work

In order to find the stress concentration effect, a model of the tibial bone and insert are fabricated. Epoxy resin is used for lower portion and tin metallic sheet is used for tibial base material. Asymmetrical uniformly varying compressive load is applied on the top base component and the photo elastic is chromatic fringes are obtained using circular polariscope. Fig.14 shows the colored fringe pattern obtained in dark field set-up with white light source. The fringe ordering is started from lowest dark fringe and at the interface. According to the theory of photoelasticity, the principal stress difference can be computed at each and every point.

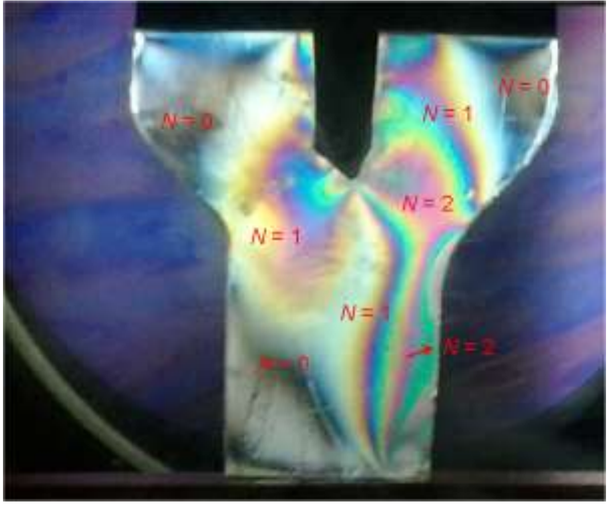


Fig.14. Estimation of interface stresses using photoelasticity

Thus, maximum shear stress at the interface can be computed accordingly. Using the principle of similitude between model and prototype, stresses in the prototype are obtained.

IV. CONCLUSIONS

In this work, three different tibia tray materials were considered to obtain optimal stress distributions in a total knee replacement operation. Using finite element analysis, the mechanical condition of bone-implant interface was determined. Based on the type of material (stiffness) for the base, stress-distributions were significantly influenced. With the increase of prosthesis stiffness (material), the maximum stresses on the poster medial side decreases. Changing the elastic modulus of tray gradually in horizontal direction will reduce the stresses developed in it and it will transfer more stresses to bone. Thus, it reduces bone stress shielding and the possibility of implant loosening. More insights of use of functionally graded material to achieve full integration in implant with living bone are still required.

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