A 3D MULTILAYERED MODEL FOR UHMWPE GAMMA STERILISED TIBIAL INSERT.

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UHMWPE is the bearing material the most commonly used in total knee joint replacement. It is known that γ-sterilisation in air causes oxidative changes in polymer that are correlated with mechanical property variations through the component thickness. A 3D elastic multilayered contact model is used here to account for the layered structure of irradiated UHMWPE component. The purpose is to analyse the effects of tibial insert thickness, thickness and mechanical properties of the constitutive layers, the clear, cloudy and center zones, on the contact stresses and the resulting internal stresses in relation to the occurrence of cracking. The current results indicate that sterilisation induces higher contact pressure, stress discontinuities at layer interfaces, possible bending effects at cloudy/center interface.

INTRODUCTION

Current Total Knee Joint Replacement (TKR) consists of a metallic femoral component articulating on a ultra high molecular weight polyethylene (UHMWPE) tibial insert, the latter usually resting on a metal tray. The cyclic nature of the contact stresses at the articulating surface can lead to loosening of the implant, pitting and delamination. It is believed that one of the cause for the fracture of UHMWPE in joints may lie in the sterilisation process that is an essential prerequisite before implantation. This sterilisation process in an ambient air environment and shelf ageing cause structural and morphological changes of the UHMWPE leading to oxidation and a decrease in its mechanical properties. Examination of retrieved prostheses has shown subsurface layers exhibiting different oxygen concentration from the surface to the core (Figure 1) that correlate well with changes in mechanical properties through the component thickness (Collier et al, 1). These layers are called the clear, the cloudy and the center zones.

A new TKR contact model has been developed to investigate the effects of sterilisation on the contact solution and the internal stresses including the UHMWPE finite thickness e_{tot}, its sterilised layered structure. This layered

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structure is modelled with a number of homogeneous, isotropic, elastic layers of thickness e_i and Young's modulus E_i. Layers are considered to be perfectly bonded to each other (Plumet and Dubourg, 2).

THEORY

The femoral component and sterilised tibial UHMWPE are respectively modelled as a rigid ellipsoid and a multilayered parallelepiped body of finite thickness (figure 2). The ellipsoid is defined by two radii of curvatures R_x and R_y. (Jin et al. (4)). The multilayered medium has a core mirror structure. Five layers are here considered as a first attempt. Up to 50 ones can be taken into account to model accurately the progressive change in mechanical properties with depth. No underlying tibial tray is considered. Boundary conditions corresponding to nil displacements are imposed at the bottom of layer 5. No residual stresses are present. Dry sliding and rolling contact, considering both normal and tangential loading are considered.

A Fourier Integral transform along x and y directions is applied to Lamé's equations and stress-displacement relations of each layer. The transformed equations are then solved analytically in each layer and presented in matrix form. A layer assembly yields a system of equations that links the transforms of the unknown displacements and stresses to the boundary condition transforms. A FFT algorithm is then used to obtain the space domain functions (2).

STERILISED UHMWPE TIBIAL COMPONENT

A tibial insert of finite thickness e_{tot} varying from 6 to 10 mm is considered. It is modelled as a monolayer of Young's modulus E=800 MPa and Poisson's ratio of $\nu=0.3$ in the unsterilised case. In the sterilised case it is modelled as a fivelayer

TABLE 1 – Peak contact pressure and maximum Von Mises (σ) stress and location (Z) for both unsterilised and the 5 sterilised configurations.

		Sterilised Component number $e_1=e_5$, $e_2=e_4$ (mm)				
	un-sterilised	1 $e_1=0.8$ $e_2=1.3$	2 $e_1=0.7$ $e_2=1.3$	3 $e_1=1$ $e_2=2.1$	4 $e_1=0.8$ $e_2=1.8$	5 $e_1=0.8$ $e_2=1.4$
Po(MPa)	21.83	22	22.14	22.15	22.35	22.07
e_2/e_1		1.625	1.857	2.1	2.25	1.75
Z (mm)	1.4	2	1.8	1.6	1.8	2
σ(MPa)	20.17	20.71	21	19.8	20.3	20.5

medium with a core mirror structure. The top layer (E_1=600 MPa) corresponds to the clear zone, the intermediate one (E_2=1000 MPa) to the cloudy zone and the core layer (E_3=800MPa) to the center zone (1). These layers range in thickness depending on the amount on ageing. Five configurations labelled from 1 to 5 corresponding to typical values of e_1 and e_2 are considered (1). e_3 is adjusted in such a way that $2e_1+ 2e_2 + e_3=e_{tot}$. Loading conditions corresponding to a typical walk cycle can be simulated. Here only one normal loading condition for P=500N and a semi-bended position R_x = 60 mm and R_y = 130 mm is considered. The contact solution and internal stresses obtained for the monolayered and multilayered cases are compared.

Contact solution

The peak contact pressure Po is shown in table 1 for e_{tot} = 8mm and in figure 3 for varying e_{tot}. The values obtained for the sterilised configurations are higher than those obtained for the unsterilised one. Two parameters affect the component stiffness :

- the ratio e_2/e_1 : Po increases with increasing e_2/e_1 for e_{tot} greater than 7 mm e_2/e_1 accounts for the relative influence of the constitutive cloudy (stiff) and clear (soft) zones. Therefore for a given e_{tot}, increase in e_1 induces a component softening whereas increase in e_2 results in a stiffening,
- e_{tot}: a thinning of e_{tot}, e_2/e_1 being fixed, causes a stiffening of the component due to thinning of e_3 together with an increased influence of the boundary conditions at the bottom of layer 5. This effect is predominant for e_{tot} up to 6.5 mm.

Stress field analysis :

Internal tibial insert stress field is analysed for a thickness e_{tot} equal to 8 mm. Particular attention is focused on interface layer stresses and Von Mises stresses. Recall that the assumption of perfect bonding between layers implies displacement and contact stress continuity, i.e σ_{zz}, σ_{xz}, and σ_{yz}, at an interface. The interfaces are labelled from the subscripts of adjoining layers. For instance ½ interface is the interface between layers 1 and 2. Stresses are analysed versus x, in the contact centre plane (y=0) where the severest state of stress occurs. Concerning σ_{xx} stresses, which could cause cracking, discontinuity at i/i+1 interface is dependant on contact loading, e_{tot}, the relative location of the interface with respect to the contact surface, the ratio E_i/E_{i+1}. These parameters interact to lead to a complex behaviour. Therefore general tendencies can be formulated as follows :

- increase in σ_{xx} stress discontinuity coincides with an increase in ratio E_i/E_{i+1},

- tensile and compressive σ_{xx} stresses may arise respectively at i and i+1 interface sides for ratio E_i/E_{i+1} greater than 1, resulting in a bending effect (figures 4-5). This occurrence is dependent on the interface location with respect to the contact patch dimensions: an interface location close to the contact surface is situated in a compressive zone and will not undergo tensile σ_{xx} stresses, as for instance configuration 2,
- increased e_{tot} results in an increase in tensile stresses, the medium being less compressed (3).

Thus significant discontinuities in σ_{xx} leading moreover to bending effects which could cause cracking are obtained at 2/3 interface. Further significant shear stresses are obtained at the interfaces, that may be responsible for delamination. It appears (3) that shear stress magnitude depends on the interface depth location with a peak value for a critical depth, the highest values are obtained at ½ and 2/3 interfaces, and that increased e_{tot} results in increased shear stresses. Von Mises peak value and the corresponding depth are reported in table 1 for the five configurations and contour plots are presented for configuration 2 in figure 6. Sterilisation induces a higher peak value and a deeper location than in the unsterilised case. The location is close to 2/3 interface where tensile stresses occur whereas stresses are compressive throughout.

CONCLUSION

A new TKR contact model has been developed to investigate the effects of sterilisation on the contact solution and the internal stresses. Clear, cloudy and center zones are here modelled as homogeneous, isotropic and elastic layers perfectly bonded to each other. These first results show that tensile/compressive stresses resulting in a bending effect, maximum shear stresses together with maximum Von Mises stress occur at cloudy/centre interface. These predictions correlate well with the degradation locations observed on retrieved prostheses.

REFERENCES

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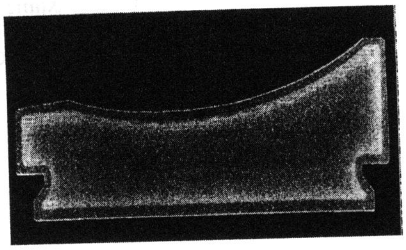


Figure 1 Sterilised tibial component (1)

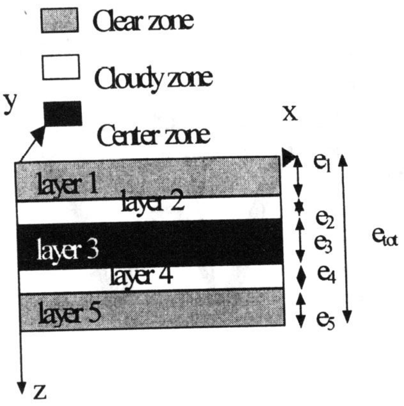


Figure 2 Multilayered model

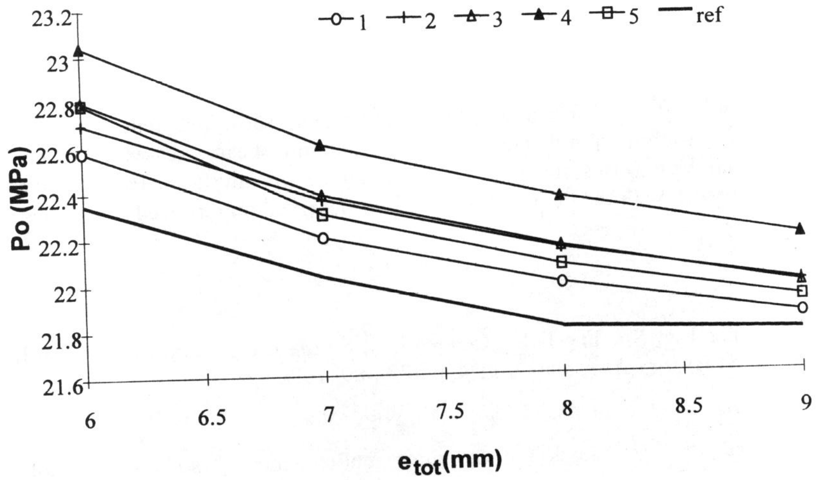
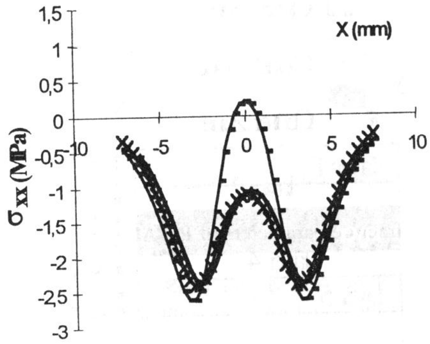


Figure 3 Po variations versus e_{tot} for each configuration



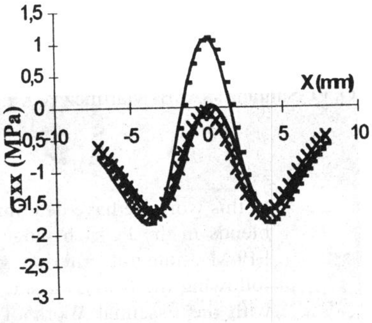


Figure 4 Configuration 1 σ_{xx} at 2/3 interface - side 2 x side 3

Figure 5 Configuration 3 σ_{xx} at 2/3 interface - side 2 x side 3

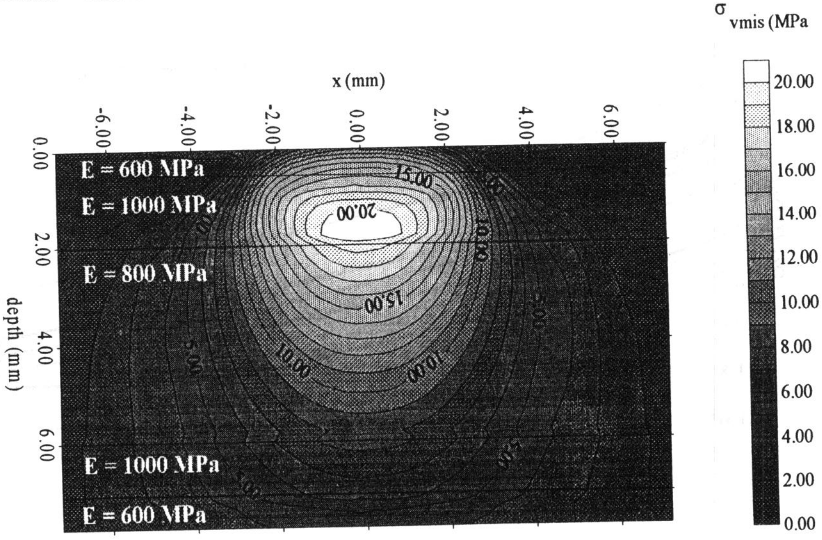


Figure 6 Von Mises contour plots for configuration 2. Horizontal black lines represent the interface locations.