THE VORONOI CELL FINITE ELEMENT METHOD FOR MECHANICAL CHARACTERIZATION OF GRADED CERAMIC COATINGS ON ARTIFICIAL JOINTS

Pasquale Vena, Dario Gastaldi and Roberto Contro

Department of Structural Engineering
Laboratory of Biological Structure Mechanics
Politecnico di Milano
Milano
Italy

INTRODUCTION

The wear of articulating surfaces of biomedical devices can be considered one of the main issues in evaluating reliability of joint prostheses. For example, in hip joint prostheses, several material couplings are currently used: metal on metal bearing surfaces (cobalt based alloys), metal femoral heads on UHMWPE acetabular cups and ceramic femoral heads on UHMWPE acetabular cups.

Metal and ceramic materials exhibit different wear behaviour [1]: the first is characterized by groove formation due to plastic deformation of the metal beneath the abrading particle (ductile); the ceramic wear behaviour is characterized by a brittle process in which the material is removed mainly as a result of crack formation (Fig. 1). In this work we focused our attention on the ceramic surfaces that have optimal surface characteristic (low roughness), but their brittleness is a crucial point in the design of such devices. A current trend in this field is the study of new articulating surfaces made of graded composites. These are designed to increase the intrinsic toughness of the material which is directly related to the wear resistance [2]. The aim of the present study is to use a suited numerical technique for mechanical characterization of graded composites for surface coatings. The formulation of the numerical model allows to take into account the microstructure of ceramic based composites. Firstly the elastic behaviour of the zirconia-alumina composites at different compositions has been investigated and secondly the behaviour of a graded structure has been studied. The model can be considered as a useful tool for designing the optimal grading of the surface coatings so to maximize its wear resistance and also to provide useful indications for the manufacturing process.

MATERIALS AND METHODS

The use of composite materials represents a possible approach to improve the fracture toughness and mechanical strength of pure alumina (Al_2O_3) femoral heads. In this study an Alumina matrix reinforced with Tetragonal Yttria stabilized Zirconia (Y-TZP) has been studied.

The mechanical behaviour of the composite has been numerically investigated by means of the finite element method.

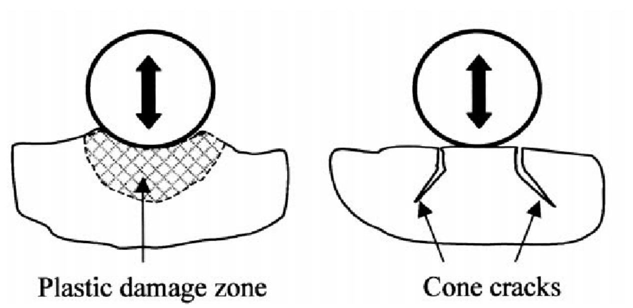

Fig 1. Damage modes for ductile (left) and brittle (right) materials [4]

A purposely formulated Voronoi Cell Finite Element [3] has been implemented into a commercial finite element code (ABAQUS). The finite element grid is made of polygonal elements which represent the real grained microstructure of the ceramic phases (Fig. 2).

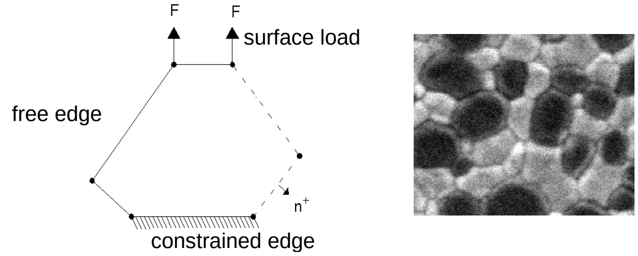

Fig 2. Polygonal finite element used in the numerical model and SEM image of 50% Al_2O_3-YTZP

The specific formulation is based on the polynomial interpolation of the stress field within each finite element (hybrid finite element). This approach allows for an accurate stress evaluation and significantly reduces degrees of freedom compared to the displacements based FEM.

An isotropic linear elastic constitutive law has been used for the Al_2O_3 and Y-TZP phases. The thermal expansion has also been included in the model in order to investigate the residual stresses due to manufacturing process. The constitutive parameters obtained from experimental tests on bulk materials are reported in the following table.

	E [GPa]	ν	α [°C^{-1}]
Al_2O_3	415	0.23	$7.75 \cdot 10^{-6}$
Y-TZP	220	0.29	$10.7 \cdot 10^{-6}$

RESULTS AND DISCUSSIONS

Preliminary analyses were performed in order to evaluate the elastic moduli (E), the Poisson ratios (ν) and the thermal expansion coefficients (α) of the composites for different values of Y-TZP volume fraction (Fig. 3). A roughly linear relationship between the elastic modulus of the composite and the Y-TZP content is found. This is due to the relatively low mismatch between the Young moduli of the two components. Similar results have been obtained for the Poisson ratio and the thermal expansion coefficient.

The mechanical behaviour of a graded coating subjected to a punching load was also studied. The model of the coating was made of five layers having 20 µm thickness each and a Y-TZP content of 10%, 20%, 30%, 40% and 50% respectively (Fig. 4). The finite element discretization has been obtained by means of a Voronoi tessellation of the model domain. The Voronoi cell mean size was chosen to fit the size of Alumina and Zirconia grains. The finite element analysis provided the stress distribution reported in Fig. 5, where color contour of the maximum principal stresses are represented. A region of high stress gradients at the edge of the indentation zone is clearly visible. The refined finite element discretization is such that the values of stresses within each of the two phases, in all the model domain, can be accurately estimated. This stress estimation can be used in the material specific fracture criterion to predict the onset of the material cracking and the propagation of the cracks within the composite. The position and the extent of these cracks can give direct information on the wear volume debris.

Currently ongoing combined experimental and numerical works, to be carried out on graded ceramic composites, are aimed at validating the computational model.

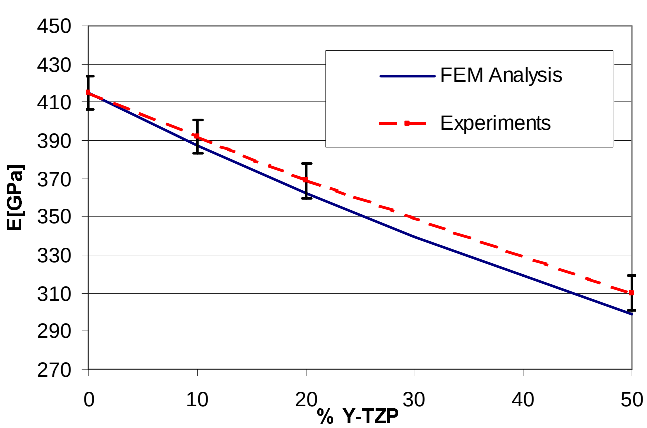

Fig 3. Young Modulus of the composite for different Zirconia contents

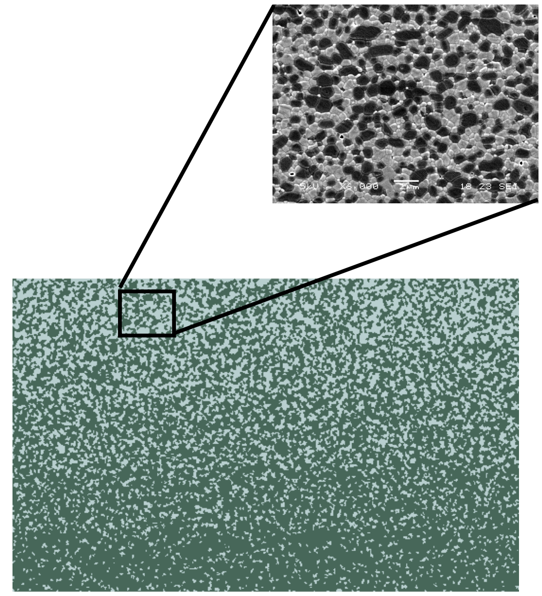

Fig 4. FEM model of the graded coating (darker: Al_2O_3, lighter: YTZP) and a SEM image in a 50% Al_2O_3-YTZP zone

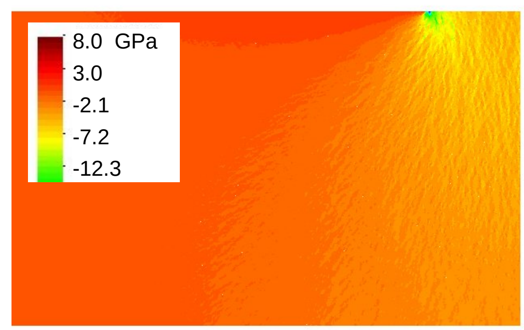

Fig 5. Contour plot of the maximum principal stress in the graded coating subjected to a punching load

ACKNOWLEDGEMENTS

The Authors are grateful to Prof. V. Sglavo and Ing. M. Bertoldi for providing the experimental results; and to master students A. Broggini and M. Galli.

REFERENCES

1. Aquaro, D., and Fontani, E., 2001, "Erosion of Ductile and Brittle Materials", Meccanica, Vol. 36, pp. 651-661
2. De Aza, A. H., Chevalier, J., Fantozzi, G., Schehl, M., and Torrecillas, R., 2002, "Crack growth resistance of alumina, zirconia and zirconia toughened alumina ceramics for joint prostheses", Biomaterials, Vol. 23, pp. 937-945
3. Ghosh, S., and Moorthy, S., 1995, "Elastic-plastic analysis of arbitrary heterogeneous material with the Voronoi Cell Finite Element Method", Computer Methods in Applied Mechanics and Engineering, Vol. 121, pp. 373-409
4. Teoh, S. H., 2000, "Fatigue of biomaterials: a review", International Journal of Fatigue, Vol. 22, pp. 825-837