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Investigations into the mechanical reliability of ceramic femoral heads for hip joints

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This paper reports the findings of a finite element analysis applied to the study of ceramic femoral ball heads. The objective of carrying out these analyses was to assess the shape design and loading conditions applied to specific femoral heads and to capture the stress fields developed when they are subjected to idealized test conditions. Two designs were considered, these being the existing Biolox keyhole shape, manufactured by Cerasiv, Medical Products Division and an alternative design with a flat top internal hole. For each of these designs, three load cases and two types of frictional contact were considered. It is shown that the key hole shape with full taper contact conditions together with the higher value of surface friction produce the lowest tensile stress fields in the ball head hence increasing mechanical reliability.

1. Introduction

Biolox femoral heads are manufactured from ceramic material and have an internal taper which accepts a wide variety of different hip stems supplied by other companies. To comply with various regulations and to ensure their integrity the femoral heads are subject to a test in which a stem is pushed into the taper in the ball head. This condition has been used in this paper to develop the numerical models used for the assessment and mechanical behaviour of the femoral heads subject to vertical loading.

The current Biolox design is axisymmetric in section with a keyhole shaped internal geometry which accepts the hip stem and this will be compared with an alternative design with an internal flat top. Finite element analyses of the two designs have been carried out to evaluate the mechanical behaviour from the consideration of stress concentrations and subsequent susceptibility to failure. The taper hole in the femoral head is designed such that the tolerance fields of the internal taper and the hip stem taper do not overlap and also different length stems can be utilized which cause conditions of different contact lengths. The finite element studies presented here have been carried out to indicate the differences which occur in the stress field when the contact area is spread over various lengths of the taper. Furthermore, the stress fields developed due to a perfectly smooth and a frictional contact between the stem and the walls of the taper hole have been studied.

2. The finite element model

An axisymmetric finite element model has been set up using six-noded triangular elements. It is well known that the finite element method gives approximate results and the accuracy of the results is related to the number of elements into which the body is discretized [1, 2]. After a number of preliminary studies, a refined mesh consisting of 3688 six-noded triangles having 15 180 degrees of freedom was adopted for the Biolox design of the femoral head and the mesh is shown in Fig. 1. The geometry of the alternative design of femoral head with the flat internal head is shown in Fig. 2. In this case, the mesh consists of 3676 six-noded elements having 15 098 degrees of freedom. The model is supported externally by a copper ring according to the ISO 7206-5 standard test, for which the position and boundary conditions are shown in Figs 5 and 8. Loading was applied vertically along the internal taper, the load for all cases being 1 kN.

3. Material properties and loads

The following parameters were used to describe the material properties of the ceramic head with the analysis being linear elastic.

Elastic modulus	: 380 GPa
Poisson's ratio	: 0.23
Coefficient of friction between the stem and taper hole walls	: 0.0 and 0.2

Since the analyses are linear elastic, the stresses have been computed for a unit load of 1 kN; the results for any other load can, therefore, be obtained by multiplying the given stresses by the applied load in kilo newtons. Two cases of friction between the stem and the taper hole have been considered. In the first case the taper hole has been assumed as perfectly smooth

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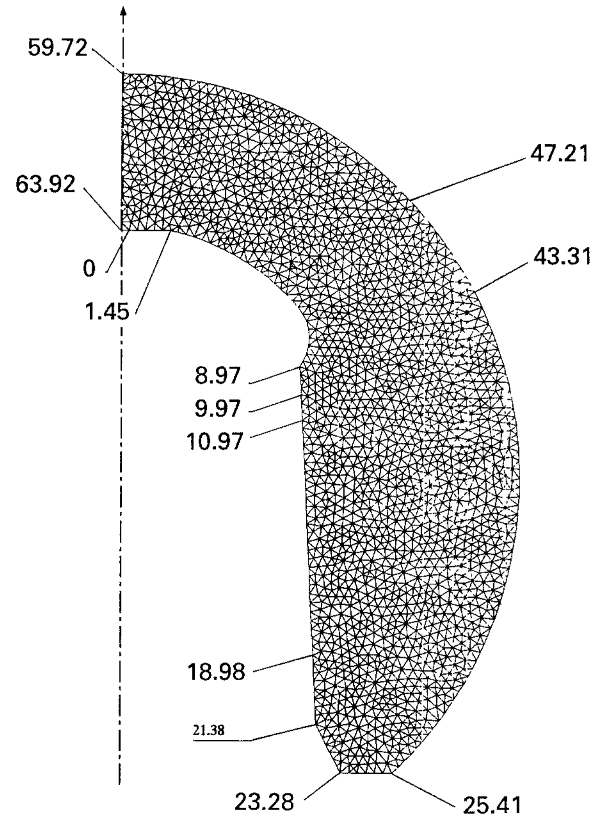

Figure 1 Mesh of Biolox head.

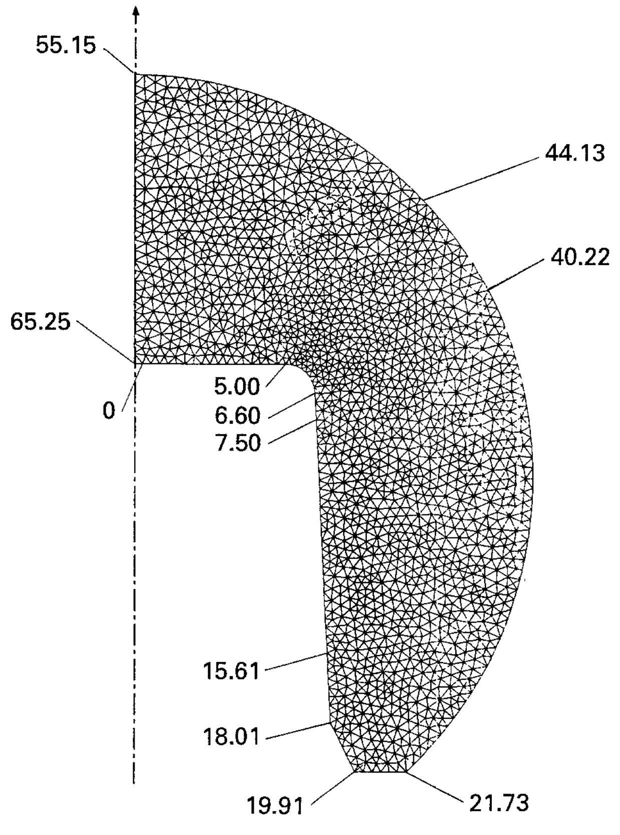

Figure 2 Mesh of flat top head.

so that the load on the taper boundary can be obtained by resolving the force normal to the taper, i.e. zero friction. In the second case the coefficient of friction between the stem and the taper hole has been assumed to be 0.2. Here, a uniform shear stress equal to 0.2 times the uniform normal stress is assumed to act at the taper hole walls. Three load cases were considered for each femoral head with the full load assumed to be spread over the taper length as follows: (a) 100% taper length (b) 50% taper length from top and (c) 10% taper length from top. Load case (a) is shown schematically in Fig. 5 together with the copper ring contact support condition.

4. Results

The results of the analyses are presented in graphical as well as in filled contour plot form. For the graphical form stresses are plotted along the running coordinates at the periphery of the models shown in Figs 1 and 2. To understand this one should imagine a piece of string wrapped around the perimeter of the head with the starting point at the position marked ‘0’ in Fig. 1 and ending at the same point. This determines the total length of the perimeter. Now imagine the string as being stretched into a straight line. The various stress outputs are then plotted against this as a ‘running coordinate’.

4.1. The Biolox femoral head

In Fig. 3 the three principal stresses, PS1 and PS2 (major and minor in-plane stresses) and PS3 the hoop stress, as defined in [1], are plotted against the running coordinate for load case (a) and Fig. 4 presents the results for load case (c). Figure 5 shows filled contour plots of the hoop stress for the load case (a) which is 100% taper contact.

4.2. The alternative design without key

Fig. 2 shows the finite element mesh and running coordinate for the flat top design without the key. The mesh density is similar to that of Fig. 1 so that a direct comparison can be made. In Fig. 6, the principal stresses are plotted against the running coordinate for

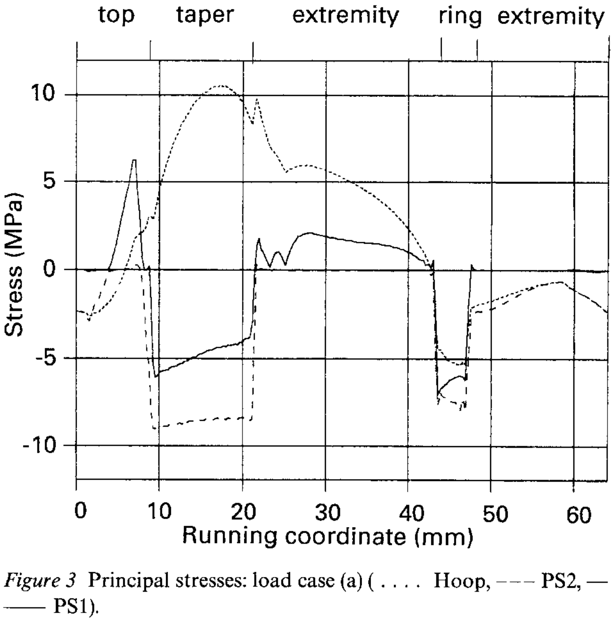

Figure 3 Principal stresses: load case (a) (. . . . Hoop, – – – PS2, —— PS1).

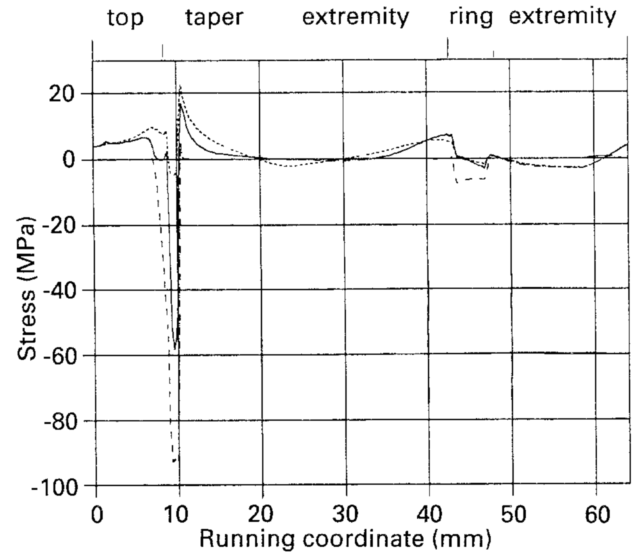

Figure 4 Principal stresses: load case (c) (. . . . Hoop, - - - PS2, —— PS1).

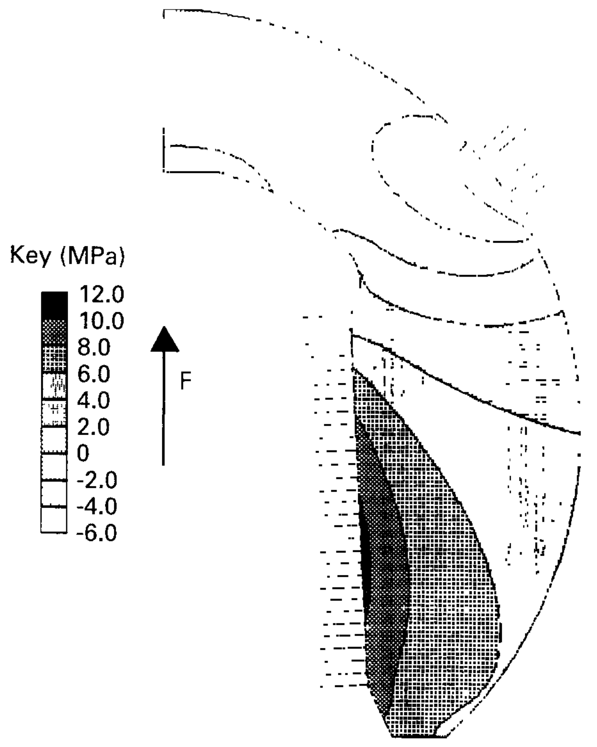

Figure 5 Hoop stress plot in Biolox head.

load case (a) and Fig. 7 gives the output for load case (c). Fig. 8 shows the filled contour plots of hoop stresses for load case (a).

5. Discussion

5.1. Full contact area versus reduced contact area

Comparison of Figs 3 and 4 indicates that hoop stress value in the case of 10% contact (load case (c)) is almost double the value when 100% stem contact is made (load case (a)). The maximum stress value for load case (b) falls in between the values for load cases (a) and (c). A similar conclusion can be drawn for the alternative design without the keyhole from the study of Figs 6 and 7.

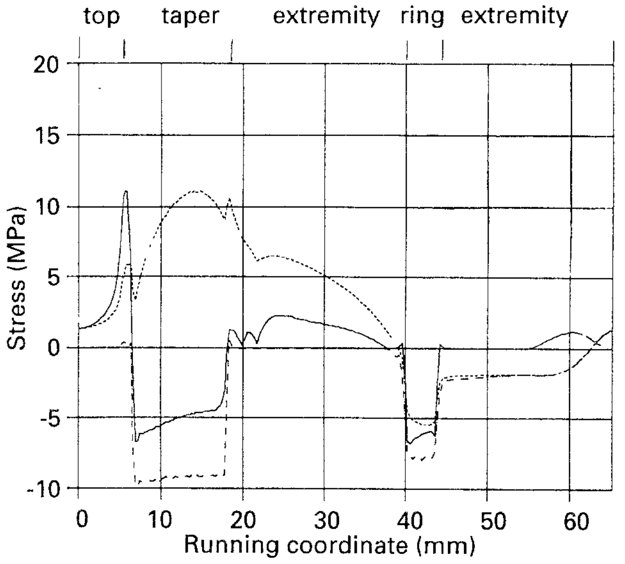

Figure 6 Principal stresses: flat top load case (a).

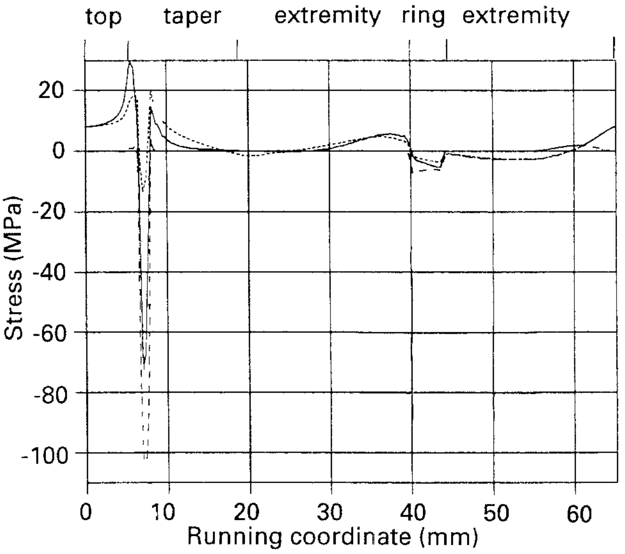

Figure 7 Principal stresses: flat top load case (c).

5.2. The Biolox design versus alternative design without keyhole

A careful study of Figs 3 and 6 indicates that higher tensile stresses occur in the alternative design with flat top taper hole. The maximum hoop stress is marginally higher by 5.4%, however it is seen that the maximum principal stress PS1 for the flat top head is 90% higher than the Biolox design. From these observations it is shown that for the loading conditions considered, the existing design with the key is more advantageous from considerations of reduced tensile stresses than the alternative design with the flat top profile.

5.3. Perfectly smooth versus frictional contact

The results for the two cases of surface friction (0.0 and 0.2) between the stem and internal taper show con-

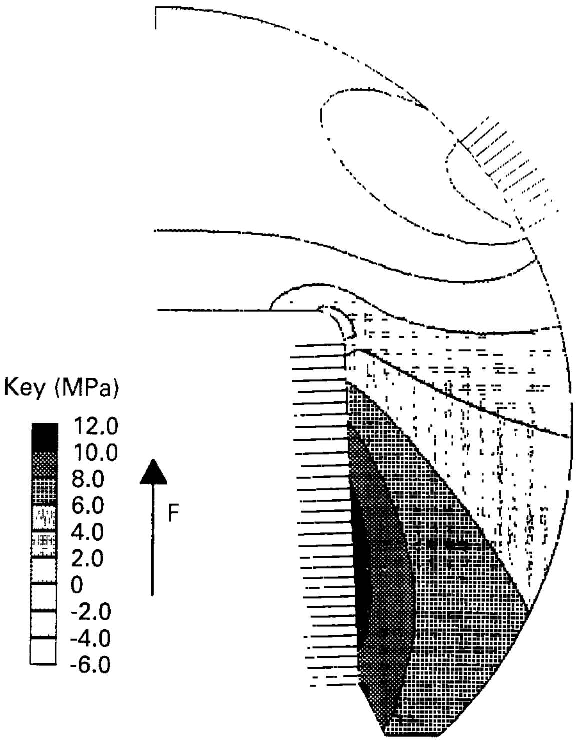

Figure 8 Hoop stress plot, flat top head.

siderable differences. Using a frictional constant of 0.0 at the stem–taper surface it was noted that the maximum hoop stresses (tensile) increased by a factor of five. The accurate determination of the coefficient of friction and contact behaviour at the stem–taper interface is therefore imperative.

6. Conclusions

The finite element analyses indicate that under the given test loading, the existing design with the key produces lower tensile stresses when compared to the flat-top taper design, therefore reducing stress concentrations and subsequent susceptibility to failure. It is also shown that the full contact condition along the taper length is preferable to a reduced contact along the taper length, since this condition gives lower tensile stresses. Furthermore it is shown that frictional conditions at the stem–taper contact surface plays a crucial role in determining the magnitude of the stresses in the femoral head.

References

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