Deformation of press-fitted metallic resurfacing cups. Part 2: finite element simulation

A Yew[1], **Z M Jin**[2*], **A Donn**[3], **M M Morlock**[4], and **G Isaac**[3]
[1] Division of Bioengineering, National University of Singapore, Singapore
[2] School of Mechanical Engineering, University of Leeds, Leeds, UK
[3] DePuy International Ltd, Leeds, UK
[4] Biomechanics Section, Technical University Hamburg-Harburg, Hamburg, Germany

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Abstract: The deformation of metallic acetabular cups employed for metal-on-metal hip resurfacing procedures was considered theoretically using the finite element method in the present study, following on the experimental investigation reported in Part 1. Three representative cups, characterized by the cup wall thickness as thin, intermediate, and thick, were considered. For the intermediate cup, the effects of both the size and the diametral interference on the cup deformation were investigated. Both two-dimensional axisymmetric and three-dimensional finite element models were developed to examine the important parameters during and after the press-fit procedure, and in particular the deformation of the metallic cup. The theoretical prediction of the cup deformation was in reasonable agreement with the corresponding experimental measurement reported in Part 1. The most significant factor influencing the cup deformation was the cup wall thickness. Both the size and the diametral interference were also shown to influence the cup deformation. It is important to ensure that the cup deformation does not significantly affect the clearance designed and optimized for tribological performances of metal-on-metal hip resurfacing prostheses. Furthermore the contact parameters at the cup and bone interface associated with the press fit were also discussed.

Keywords: metal-on-metal implants, resurfacing, finite element, cup deformation, press fit

1 INTRODUCTION

The importance of the deformation of press-fitted metallic acetabular cups used for metal-on-metal (MOM) hip resurfacing procedures was highlighted in Part 1 of this study [**1**]. It was shown that the cup deformation depended on the wall thickness and the diametral interference. Because of the cost and time required for the experimental tests, only one size of 60 mm (outside diameter of the cup) was considered. Furthermore, only the cup deformation was measured in the experimental study and it was difficult to examine other important parameters, particularly at the interface between cup and bone (foam) such as contact area and contact pressure. Theoretical modelling (in particular, that based on the finite element method) can provide an alternative approach to the experimental study of the press-fit mechanism of a metallic resurfacing cup. Once established and validated, the theoretical models are especially useful for providing parametric analyses on design, materials, and surgical variables, therefore providing guidelines for conducting further limited experimental tests. Compared with experimental measurements, it is often much easier to isolate a particular factor in the theoretical model in order to investigate its effect, and this helps to elucidate the press-fit mechanism involved. However, such a theoretical approach relies on the understanding of the physical mechanism involved, and it is only possible to build on extensive experimental studies and only useful when validated through experimental tests.

There have been a number of finite element studies on press-fitted metal-backed cups for total hip replacements reported in the literature [**2–4**]. Only a few studies have been reported in the literature

Corresponding author: School of Mechanical Engineering, University of Leeds, Leeds LS2 9JT, UK. email: Z.Jin@Leeds.ac.uk

where hip resurfacing prostheses were addressed. In all these studies, the primary focus has been on the stress transmission through bone and potential problems of stress shielding [**5**, **6**].

The purpose of the present study was to investigate the deformation of a metallic resurfacing cup during and after the press fitting. Finite element models were developed to simulate the experimental studies reported in Part 1 and to carry out parametric studies on different sizes and interferences.

2 MATERIALS AND METHODS

Three MOM hip resurfacing cup designs were chosen, two based on the prototypes specified in Part 1 and one current design available in the market. The main difference considered in these cups was the wall thickness, described as thick, thin, intermediate, and thick, as shown in Fig. 1 for a nominal size of 60 mm (outside diameter) and the principal dimensions. All cups are made from cast high-carbon cobalt–chromium alloy and differences in processing routes and compositions were not considered in the present study since these parameters are unlikely to influence the mechanical properties required for the finite element modelling.

The press-fit procedure was firstly simulated by means of a two-dimensional axisymmetric finite element model for the intermediate cup (Fig. 1). The simple bone model was assumed to consist of both cortical (with 1 mm thickness) and cancellous regions as shown in Fig. 2 [**2**]. The angular coordinate was defined as the angle measured from the pole of the cup. The cortical bone was removed in the acetabulum by the simulated reaming process before implantation. A simplified 'rigid' impactor was assumed to push the edge of the cup. All the solid models were created in I-DEAS 9 and exported to ABAQUS 6.2-7 for simulation and analysis. Four-noded bilinear axisymmetric elements were used to mesh the acetabular cup and the simple hip bone shown in Fig. 2. The total number of elements was about 650, and mesh sensitivity checks were performed to ensure the accuracy of the finite element model. Boundary conditions imposed on the axisymmetric model included constraining the acetabulum end as well as restricting nodes on the axis of symmetry to the vertical direction only. Contact was modelled at interfaces between the impactor and cup and between the cup and bone, using the contact pair option of master and slave surfaces available in ABAQUS. Such a technique has been validated against the classical Hertzian contact mechanics and subsequently used extensively for contact mechanics analyses of various types of hip implant [**7**]. For the impactor–cup interface, small sliding and frictionless contact was assumed. For the cup–bone interface, finite sliding and a relatively large coefficient of friction of 0.62 were employed to account for the porous coating on the outside of the cup [**8**]. However, the porous coating itself was not modelled as part of the acetabular cup, since a thin porous coating is unlikely to have any significant effect on the stiffness of the cup, and a similar assumption was made in the previous finite element study by Spears *et al.* [**2**]. The diameter of the cavity was adjusted accordingly to provide specified interferences.

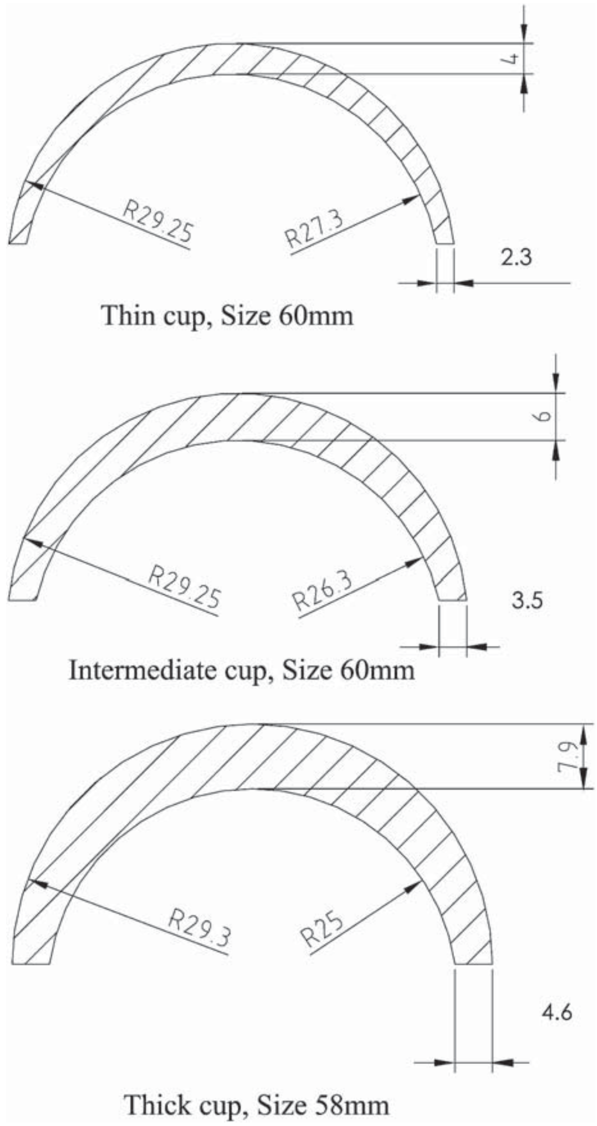

Fig. 1 Cross-sections of the three cup designs. The porous coating on the outside of the cup is not considered. Dimensions are in millimetres

The press-fit surgical procedure involves repeated hammering of an acetabular cup via an impactor

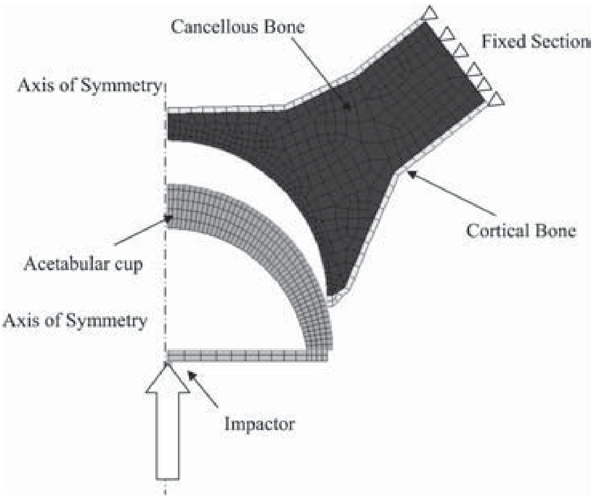

Fig. 2 An axisymmetric finite element model for a typical MOM hip resurfacing acetabular cup and a simple pelvic bone model with cortical and cancellous regions

with a mallet [**2**], and a similar procedure was adopted for the present resurfacing cup. Two different methods of simulating the press-fit procedure were examined. The reason for doing so was to determine which method was able to simulate the press-fit procedure as realistically as possible without drastically increasing the computational overheads, particularly when non-linear three-dimensional models involving contact surfaces were involved. Figure 3 shows the schematic representation of the two methods. The first method was involved with multiple-displacement control [Fig. 3(a)]; the initial gap between the cavity and the resurfacing cup at their polar points was determined, which was used as the initial displacement to be pushed for the press-fit simulation. The displacement was then removed by moving the impactor back to its original position to simulate load removal at the end of each mallet blow and preparing for the next impact. This completed one cycle of press fitting using the displacement control. Subsequent impaction simulation cycles were achieved in the same way with an increment of 1 mm in each new cycle. The simulation was terminated when any further impaction cycles had negligible effect on the residual cup seating. However, if the subsequent impaction cycle, following immediately that of a converged solution derived from the previous cycle, resulted in over-closure of the contact nodes (i.e. divergence of the solution), the displacement increment was reduced by 0.5 mm and the analysis was repeated. The total computational time required for multiple-displacement control was approximately 6 min on a desktop computer with a 1.7 GHz processor and 1.5 gigabytes of

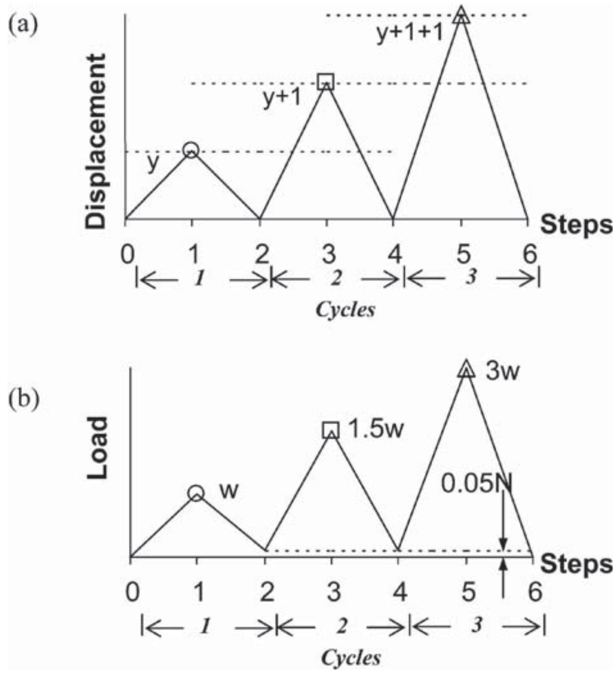

Fig. 3 Schematic representations of (a) multiple-displacement control with a step 1 displacement y and (b) multiple-load control for press fitting with a step 1 load w

random access memory. Similar procedures were also applied for multiple-load control [Fig. 3(b)], following the similar protocol used by Spears *et al.* [**2**], with an initial load corresponding to the initial displacement in the displacement control method. A small load of 0.05 N was maintained when the impact load was released for convergence purposes of the finite element model.

The detailed cup deformation was investigated using three-dimensional finite element models and the press-fit procedure developed from the two-dimensional axisymmetric model. As shown in Part 1, it was possible to simulate the non-uniform deformation behaviour of the cup in a human pelvis through a two-point pinching model with a modified spherical cavity of polyurethane foam [grade 30 (Fig. 4)]. The cup deformation was assessed in a Cartesian coordinate placed on the cup face along and perpendicular to the pinching direction

Three-dimensional brick and tetrahedral elements (first order) were employed to mesh all the components, and the total number of elements was between 8000 and 9000 for different cups. The press-fit procedure (in particular, multiple displacement control) was used to investigate the cup deformation for different cup sizes (diameter between 46 and 70 mm) and with various interferences between 0.25 and 1 mm as detailed in Table 1.

Table 1 Diametral interferences considered for the different cup models and diameters together with the applied finite element models

Cup model	Size (mm)	FE model	Diametral interference (mm)
Intermediate	60	Two-dimensional axisymmetric	1
Intermediate	60	Three-dimensional pinching	0.25, 0.5, 0.7
Intermediate	46	Three-dimensional pinching	0.5
Intermediate	70	Three-dimensional pinching	0.5
Thin	60	Three-dimensional pinching	0.5
Thick	58	Three-dimensional pinching	0.5

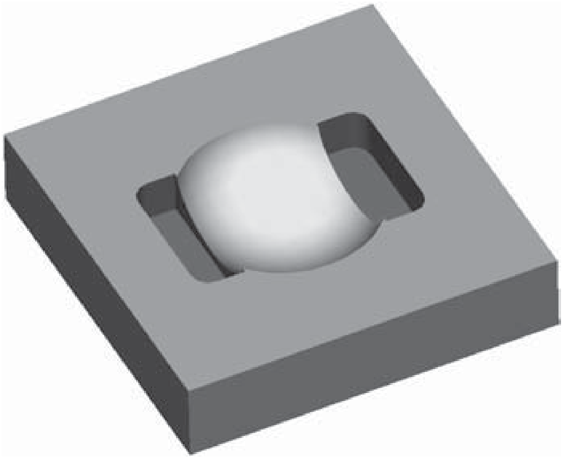

Fig. 4 Schematic two-point pinching cavity model for the study of press-fit of metallic resurfacing cups.

Table 2 Mechanical properties of resurfacing cup and relevant bone structures

Material	Young's modulus (MPa)	Poisson's ratio	Source
Cortical bone	17 000	0.3	[**9**]
Cancellous bone	800	0.3	[**9**]
Polyurethane form 30	553	0.3	[**10**]
Co–Cr	210 000	0.3	–

All the materials considered were assumed to be linear elastic. The mechanical properties in terms of elastic modulus and Poisson's ratio required for all the materials are shown in Table 2.

Important parameters to be examined during the press-fit simulation include the contact pressure and area at the interface between cup and bone, and the cup deformation at the end of the press fit. Only the intermediate cup with a size of 60 mm was considered for the two-dimensional axisymmetric press-fit simulation.

3 RESULTS

Figure 5(a) shows the contact pressure at the cup–bone interface at the end of different press-fit cycles using the multiple-displacement control approach for the 60 mm intermediate cup with a diametral interference of 1 mm. Contact pressure was noted on only part of the cup, mainly in the equatorial region and around the rim of the cup, while, in the polar region, the contact pressure was zero, and a gap was maintained.

Figure 5(b) shows the relative position of the cup with reference to step 1. At step 0, the cup was positioned just to touch the bone and was pushed into the bone cavity; contact was achieved between cup and bone at step 1. However, at step 2, when the impactor was moved back to its original position, the cup bounced back and a polar gap of approximately 0.3 mm was formed. Following the successive impacting cycles, the polar gap remaining at the end of the cycle was reduced to about 0.2 mm but never became zero even at the end of cycle 4 when steady state equilibrium was achieved, as shown in Fig. 5(c). The percentage of the contact area over the cup outer surface was 50 per cent at the end of step 1 and became over 90 per cent at the end of step 4, as shown in Fig. 5(d). The diametral deformation of the cup at the rim (compression) is shown in Fig. 5(e) at the end of different steps.

A more realistic press-fit procedure has been perceived with multiple-load control [**2**] and this was also considered in the present study [Fig. 3(b)]; this procedure usually took more computing time. The comparisons between the calculations, particularly regarding the cup deformation, between multiple-displacement and multiple-load controls showed only small differences in the predicted cup deformation and the remaining polar gap (Table 3). Therefore only multiple-displacement control was subsequently used to examine the cup deformation in the three-dimensional finite element models. However, it should be pointed out that an unrealistically high load of over 100 kN was predicted to achieve the required displacement at step 1 using the displacement-control approach.

Figure 6(a) shows a typical non-uniform deformation of the cup, resulting from a two-point pinching cavity loading model for the intermediate cup.

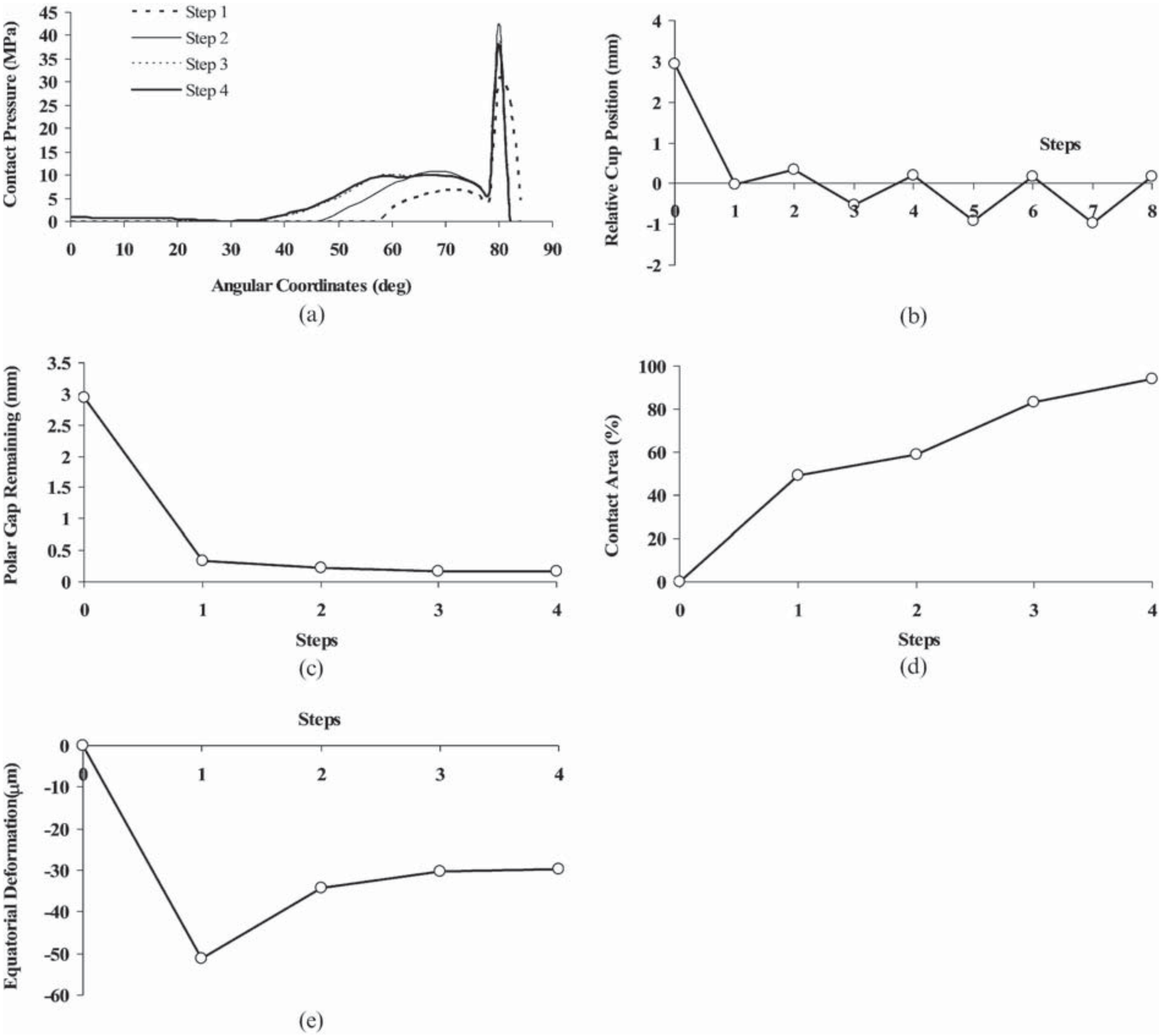

Fig. 5 Two-dimensional axisymmetric simulation of press-fit procedure based on multiple-displacement control for the intermediate cup (60 mm) with a diametral interference of 1 mm at different steps: (a) contact pressure distribution between the cup and bone; (b) relative cup position defined with reference to step 1; (c) polar gap remaining; (d) percentage of contact area; (e) equatorial diametral deformation of the cup

Table 3 Comparison of the predicted diametral cup deformation at the rim and the remaining polar gap at the final step of press-fit simulation between the load-control and displacement-control approaches (for the intermediate cup with a nominal cup size of 60 mm and a diametral interference of 1 mm)

Press-fit simulation method	Remaining polar gap (mm)	Maximum diametral cup compression (mm)
Multiple-displacement control	0.164	29.8
Multiple-load control	0.172	29.6

The contact pressure inside the foam cavity is shown in Fig. 6(b). The deformations of the cavity and the cup in different directions are shown in Fig. 6(c).

Figure 7 shows the maximum diametral cup deformation between the finite element prediction and the experimental measurement reported in Part 1 for the 60 mm intermediate cup. The maximum diametral cup compression and expansion are presented

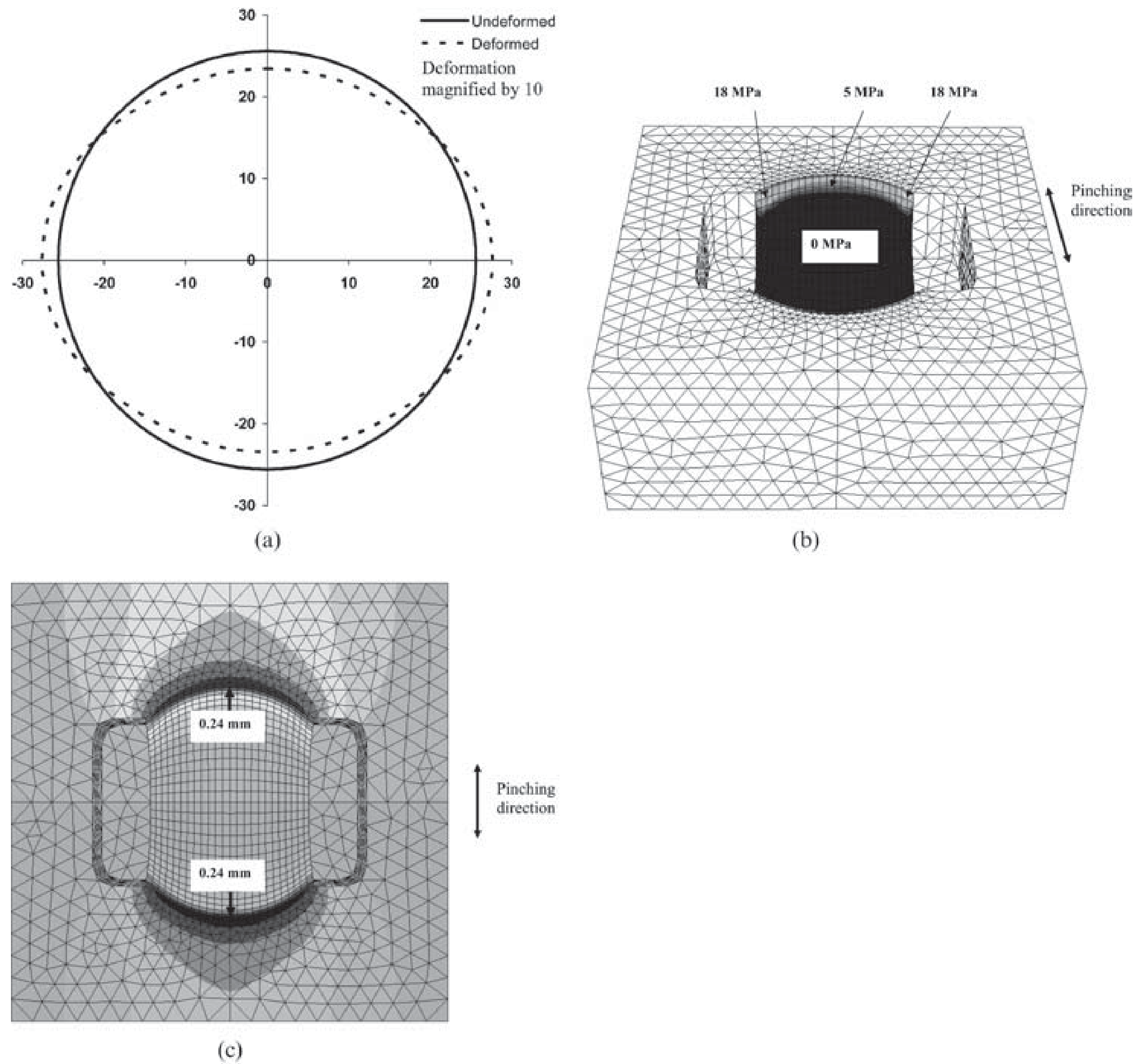

Fig. 6 (a) Original and deformed intermediate cup (in micrometres) with a size of 60 mm and a diametral interference of 0.5 mm under the pinching action caused by press fitting of the cup. (b) Contact pressure between the cup and the foam.The pinching direction is indicated. (c) Displacement (expansion) of the foam in pinching direction

in Table 4 for the three cups shown in Fig. 1 as well as for the intermediate cup with different sizes between 46 and 70 mm and different diametral interferences between 0.25 and 0.7 mm.

For a given size of 60 mm and a fixed diametral interference of 0.5 mm, the maximum diametral cup compression was 110 μm for the thin cup (Table 4). The corresponding maximum diametral compressions were reduced to 42 μm and 17 μm for the intermediate and the thick cups respectvely. This clearly shows the importance of the cup wall thickness on the resultant cup deformation. For a given diametral interference of 0.5 mm, the maximum diametral cup compression was 22 μm for the intermediate cup with a 46 mm size and increased to 69 μm with a 70 mm size. For the intermediate cup with a given size of 60 mm, an increase in the diametral interference from 0.25 to 0.70 mm results in an increase in the maximum diametral compression from 19 to 52 μm.

4 DISCUSSION

The press-fit procedure was successfully simulated with either displacement or load control. Displacement control was not as realistic as load control since the calculated press-fit force was considerably higher

Table 4 Maximum diametral periphery compressions and expansions at the inner bearing surface for various cup sizes and diametral interferences (three-dimensional finite element model based on two-point pinching loading model and grade 30 foam)

Cup size (mm)	Diametral interference (mm)	Maximum diametral periphery compression (μm)	Maximum diametral periphery expansion (μm)	Notes
60	0.50	110	120	Thin
60	0.50	43	40	Intermediate
58	0.50	17	17	Thick
46	0.50	21	16	Intermediate
70	0.50	69	67	Intermediate
60	0.25	19	17	Intermediate
60	0.70	52	48	Intermediate

than that used by Spears *et al.* [**2**]. There are a number of potential reasons for this discrepancy. A higher coefficient of friction of 0.62 was used in the present study, compared with those between 0.1 and 0.5 considered by Spears *et al.* [**2**]. In order to reduce the number of impacts, a relatively large displacement of 3 mm was applied at step 1 in the present displacement control method. Nevertheless, the predicted cup deformations were similar for the two methods (Table 3). Therefore, the press-fit simulation based on displacement control was subsequently used to examine the cup deformation.

Only partial contact between the cup and the bone occurred during the press-fit and the corresponding contact pressure mainly occurred around the periphery of the cup [Fig. 5(a)]. With consecutive impact cycles the contact area was further increased by gradually extending into the polar region and seating of the cup. The overall contact pressure was also increased [Fig. 5(a)]. The bounce-back of the cup at the end of the step when the impactor was moved back to its original position can be seen from Fig. 5(b). Such a prediction was consistent with the experimental observation reported in Part 1 [**1**]. Similar observations from the finite element modelling of the metal-backed cup for total hip replacements have been reported [**2**]. Although the cup was pushed into the cavity gradually, a polar gap (defined as the relative distance between the polar nodes of the cup and bone) remained at the end of the simulation, since any more impacting cycles did not result in any further cup seating, as shown in Fig. 5(c). Similar polar gaps have also been reported in finite element studies of metal-backed cups [**2**]. The predicted polar gap of 0.2 mm is less than the 0.35 mm limiting bone ingrowth [**11**]. Furthermore, the contact area was about 50 per cent of the available area at the beginning of the press-fit simulation and was increased to just over 90 per cent, as shown in Fig. 5(d). The importance of the gaps remaining between the cup and the bone may affect the bone ingrowth and the potential biological fluid within these gaps may contribute to debonding [**12**]. The final maximum diametral compression of the cup at the rim was around 30 μm as predicted from the two-dimensional axisymmetric model shown in Fig. 5(e) and is significantly smaller than the non-uniform compression of the cup from the experimental measurement based on the two-point loading model reported in Part 1. It should also be pointed out that only a fixed diametral interference of 1 mm was used for this case. An increase in the diametral interference to 2 mm would be expected to increase the contact pressure between the cup and the foam, but such an increase would be mainly around the rim of the cup and generally result in a larger polar gap [**2**].

Non-uniform deformation of the cup around the rim can be seen from the three-dimensional finite element model [Fig. 6(a)], similar to the experimental measurement reported in Part 1. It is also noted that the maximum diametral expansion is similar to the maximum diametral compression in magnitude, but in the perpendicular direction. The contact pressure mainly occurred around the cup periphery, corresponding to the two loading areas with the interference specified as shown in Fig. 6(b). The maximum diametral expansion of the cavity at the rim in the pinching direction was around 0.48 mm, as shown in Fig. 6(c), slightly smaller than the diametral interference of 0.5 mm specified. The maximum diametral cup compression in the pinching direction was approximately 43 μm, as shown in Fig. 6(a), which is similar to the maximum expansion of 40 μm in the perpendicular direction.

It is generally noted that the cup deformation was overestimated from the finite element model (Fig. 7). As pointed out, the porous coating was not considered in the finite element modelling, and a relatively large coefficient of friction of 0.62 was used instead. The main function of the porous coating is

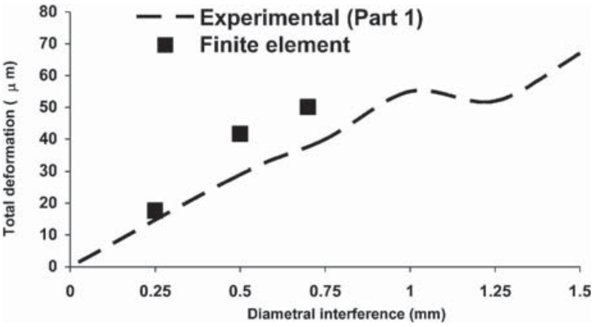

Fig. 7 Comparison of the maximum diametral cup deformation between the finite element prediction and the experimental measurement for the intermediate cup (size, 60 mm) for different diametral interferences

to enhance the surface property and bone ingrowth, rather than the structural support. The nominal diametral interference is generally specified with the reference to the outside diameter of the cup, including the porous coating. Therefore, the diametral interference specified from the consideration of the porous coating is effectively reduced. It is interesting to note that, if the thickness of the porous coating of approximately 0.08 mm plus the same amount to account for the polyurethane foam removed during the press fit, were subtracted from the nominal diametral interference [**1**], much better agreement as shown in Fig. 7 between the experimental measurement and the finite element prediction can be achieved. Furthermore, the reamed cavity is generally 0.5–1 mm larger than the specified diameter and the effective interference is reduced accordingly [**1**, **13–15**]. Consequently, relatively small effective diametral interferences of up to 0.7 mm were considered in the present study. Furthermore, the expansion of the foam cavity and the compression of the cup may all contribute to reducing the effectiveness of the interference fit. All these may have important implications on the effective interference required to achieve adequate contacts and initial stability between the cup and the bone, and the nominal recommendation of diametral interferences between 1 and 2 mm for metal-backed cups may not be appropriate for the metallic resurfacing cup.

It is important to consider the cup deformation in the context of the clearance required for the prosthesis from a lubrication point of view and the bone stock conservation. The normal diametral clearance designed and optimized for MOM hip resurfacing prostheses from tribological considerations with a size of 60 mm is generally between 80 and 120 μm [**16**]. Clearly, a thin cup as shown in Fig. 1(a) would experience significant deformation over 100 μm and cannot be used with the clearance specified to achieve correct articulation. On the other hand, the deformation of the thick cup is significantly reduced and can be used with a much smaller clearance. However, over-stiffening the cup not only results in more bone stock removed but also may increase problems such as stress shielding, increased contact pressure, and depleted lubrication at the bearing surfaces. For the intermediate cup with a larger size of 70 mm, the cup deformation is increased and it would become necessary to increase the diametral clearance. The lubrication associated with the increased diametral clearance for the larger-sized prosthesis would not be compromised because of the corresponding increase in lubrication film thickness produced by the increase in both the effective radius and the sliding velocity [**16**].

Only idealized conditions, represented by a two-dimensional axisymmetric hip model, a three-dimensional two-point pinching loading foam model, and the use of polyurethane foams, were considered in the present finite element modelling. The assumption of the linear elastic deformation for the foam and the metallic cup was justified since no significant plastic deformation was observed in the experimental study [**1**]. Future studies should include more realistic three-dimensional pelvic bone geometry with non-linear and viscoelastic material properties as well as focusing on reaming errors and the effective interference required to achieve adequate initial fixation.

Only metallic resurfacing cups were analysed in the present study, with the aim of minimizing the cup wall thickness and yet not compromising the clearance required from a tribological point of view owing to the cup deformation. The optimized cup wall thickness was found to be between 3.5 and 6 mm, with an average of 4 mm in the main loading direction. For other forms of MOM hip implant such as conventional total hip joint replacements, the cup deformation may also be important, in particular, if the cobalt–chromium insert is attached to a titanium shell or backed by a polyethylene inlay [**17**] and these should be considered in future studies.

5 SUMMARY AND CONCLUSIONS

The press-fit procedure and the corresponding deformation of metallic acetabular cups employed for metal-on-metal hip resurfacing procedures under laboratory conditions using polyurethane foams were successfully simulated by the finite element method. Important parameters at the interface between the cup and the foam have been examined during the press-fit procedure. Reasonably good agreement of the predicted cup deformation from the present finite element model was demonstrated with the previous experimental study reported in Part 1. The cup deformation was found to increase as the cup wall thickness decreased, the interference increased, and the size increased. The intermediate cup represented the best compromise between the cup deformation, tribological requirements, and bone stock conservation.

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