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Journal of the European Ceramic Society 26 (2006) 2265–2272
www.elsevier.com/locate/jeurceramsoc

Visualizing isostatic pressing of ceramic powders using finite element analysis

Y. Gu, R.J. Henderson *, H.W. Chandler

Department of Engineering, University of Aberdeen, Aberdeen AB24 3UE, UK

Received 29 June 2004; received in revised form 17 March 2005; accepted 26 March 2005
Available online 21 February 2006

Abstract

Cold isostatic pressing, where a rubber bag is filled with ceramic powder, sealed and subjected to hydrostatic pressure, is a method of forming ceramic components with near-net shape. Cracking of the ceramic compact after pressing is one problem associated with the pressing of complex shapes. One mechanism responsible for the cracking of components is the interaction of the rubber bag with the component during the final stages of decompression where the elastomer can deform significantly and impose non-uniform loadings on the compact. Visualization of the detachment process and the stresses induced in the ceramic compact offer the opportunity for the design of press tooling which minimizes the potential for cracking of the components. In this paper, both 2D and 3D finite element models are developed to investigate this problem. The effect of different contact conditions between the compact and the rubber bag is discussed, and the distribution of stresses resulting from the interaction of the compact and the rubber tooling presented. These indicate methods for alleviating the stresses within the compact through suitable tool design.

Keywords: Pressing; Finite element analysis; Plasticity; Mechanical properties

1. Introduction

Ceramics have become increasingly important in modern industry because of their good mechanical and physical properties.[1] The products are produced by many different routes according to the shape and size of the product and the material out of which it is made. One common method of forming ceramic components is by powder pressing, where a ceramic powder is compacted to form an object that can be handled and fired.[2] The compaction can be achieved either by die pressing or by cold isostatic pressing. Die pressing, where a suitably shaped die is filled with powder and subjected to a uniaxial pressure, to produce a compacted green component, can be used to produce simple shaped compacts. This process, however has the inherent problems of producing a compact with inhomogeneous density distributions. Cold isostatic pressing, where a shaped rubber bag is filled with powder, sealed and then subjected to high all-round pressure to produce a compacted green component, can be used to produce complex shapes with a more uniform density distribution. In the latter case a number of problems can exist:

a. *Predicting the final shape and size of the pressed compact*: The method of cold isostatic pressing with near net shape can produce accurate shapes and size of compact compared with the desired component, but the elastomeric bag is different in both size and shape from the final component. This can result in difficulties in tool design and the wastage of material through green machining, although this problem has been alleviated by the use of process modelling tools[3,4] that usually make use of the finite element method. The majority of these models assume that there is no sliding at the powder-elastomeric bag interface as this increases significantly the complexity of the modelling.
b. *Cracking of the ceramic component*: Cracking of the ceramic component often occurs in die pressing and iso-

* Corresponding author.
E-mail address: Robin.Henderson@abdn.ac.uk (R.J. Henderson).

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doi:10.1016/j.jeurceramsoc.2005.03.256

static pressing. Some of these cracks may be visible, leading to rejection of the component; however, cracks that are not detected may affect the integrity of the final component. As the peak compaction pressures are sufficient to close any fissures any cracks must occur during decompression and bag detachment.

A number of mechanisms may be responsible for the cracking of components during isostatic pressing:

a. *The effect of the powder elastic properties*: If a component consists of more than one type of ceramic powders, and the powders have different compaction and elastic recovery characteristics, stresses will be induced at the interface between the powders, leading to cracking of component at the interface between them.
b. *The effect of entrapped air*: During the compaction process the level of porosity within the compact decreases and the air within the pores is pressurized. At the same time the permeability of the compact is much reduced. If insufficient time is allowed for air transport, the air pressure within the pores will remain high, even when there is no applied external pressure. In die pressing, effusion of air may be solved by the use of a slow pressing rate and control of the gap between the punch and the die,[5–7] but in isostatic pressing, the system is closed and there is no opportunity to remove air after the tooling is sealed. After bag detachment the air will begin to effuse through the compact into the space between powder and bag. If insufficient time is allowed for air effusion, the bulk of the ceramic compact can as a result of the internal pore pressure be in tension which can lead to cracking.[6]
c. *The effect of bag detachment*: The elastomeric bag will slide at the interface between with the powder. Whilst this might not be significant in the compaction stages significant sliding can occur during the decompression process. Whilst the effects of friction have been investigated in the case of die pressing by a number of authors[8,9] the effect of the interfacial properties between the elastomer and compact has received little attention for isostatic pressing. If the geometry of the compact is very simple in isostatic pressing, for example, a cylinder, it would be expected that the detachment of the elastomeric bag from the compact would be almost instantaneous. However, for complex components it is different because there is always one part of bag which detaches first.[10] Once the elastomeric bag is partially detached the elastomeric bag can deform independently, the deformation in part being controlled by the interfacial conditions, and this can result in non-uniform loading on the compact. In addition, there will be stresses induced by the air pressure in the pores. If the total tensile stress exceeds the tensile strength cracking will occur. The magnitude of the tensile stresses required to produce cracking does not have to be large as the green strength measured in laboratory experiments can be as low as 2% of the compaction pressure.

In this paper, the finite element method is used to simulate the pressing process of two ceramic components. Firstly an axisymmetric component is presented and the work is then extended to include full three-dimensional modelling where the effects of imperfections in the rubber bag are investigated by perturbing the geometry of the press tooling. The role of friction at the interface between the powder and the press tooling is also investigated. In order to simplify the problem the role of air in the process is ignored.

2. Material behaviour

To simulate the pressing process accurately, the behavior of the powder material and elastomeric bag must be modeled appropriately.

2.1. Powder material

Granular materials exhibit many interesting features when deformed under a combination of shear and hydrostatic loading. In ideal isostatic compaction the stress regime would be solely hydrostatic, however, the presence of tooling (the elastomeric bag and often rigid metal closures) means that in reality isostatic pressing occurs under high hydrostatic and low shear conditions. The powder can deform by the particulates rolling relative to each other, plastic deformation occurring at the interfaces between the powder particles and through fracturing of individual particles. A key feature of the powder deformation is that the volume changes under both pressure and shear loading, unlike standard elastic and metal plasticity models where volume change only occurs under hydrostatic conditions.

The powders used in this study are composed of carbon-resin-alumina aggregates, which are relatively soft and deformable and therefore the powder deformation mainly occurs through contact point plasticity. If it is assumed that the loading within the system is proportional (that is the ratio of the stress components remains constant throughout the compaction) a shear-coupled plasticity model with an elliptical isodensity surface is adequate.[11] This is illustrated in Fig. 1 where the volume obtained from loading to pressure p with no shear, can also be obtained by loading to pressure p' with a shear of τ' (shown in Fig. 1). As compaction occurs the isodensity surface expands but retains its elliptical shape.

In order to simulate the decompression process it is necessary to develop a model to describe the behaviour of the green compact subsequent to compaction. Diametral compression tests were performed on sections of cylindrical compacts, subsequent to compaction, and these tests indicate that the green compact displays a predominately linear response prior to the development of microcracks within the compact. Therefore, during decompression the compact was assumed to be linear elastic with the stiffness throughout the compact depending upon the density achieved during compaction. Whilst this behaviour will not account for any

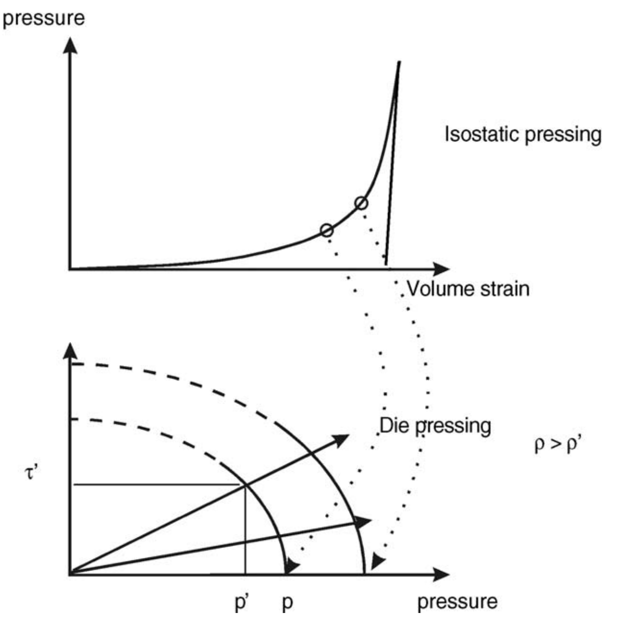

Fig. 1. Behaviour of the ceramic powder under a range of loading conditions: (A) shows the deformation of the powder under pure hydrostatic loading whilst and (B) illustrartes isodensity curves which would be obtained under combinations of shear and pressure loading.

plasticity induced within the detachment process (for example, through the development of alternative pressure–shear stress states on the compact) the simulations performed using this approach do provide useful information for the designer of isostatically pressed components. The diametral compression tests also indicated the strength of the compact prior to the initial onset of microcraking. For a compact pressed to the maximum pressing pressure the stress at the initial onset of microcracks was of the order of 3.5% of the compaction pressure. Specific material parameters regarding the powder compaction properties are not included within this paper as they are commercially sensitive, and therefore, all stresses within the paper have been normalized relative to the maximum applied compaction pressure.

A number of models similar to that described above are available and have been used to simulate isostatic compression. In this paper, a constitutive model with an elliptical cap was implemented as a user defined subroutine in ABAQUS. This model gives increased robustness and computational speed when compared to more complex powder models (for example, those which include shear failure surfaces) that are available.

2.2. Rubber bag

The elastomeric rubber bag not only prevents contact between the pressuring fluid and the powder but also play an important role in the compaction and decompression process. During the initial stages of compaction, the loose powder is much less stiff than the elastomeric bag, even if the elastomeric bag is relatively thin. Therefore, the deformation is controlled in the initial stages of compaction by the elastomeric bag.[4] If the elastomeric bag is of a complex geometry, it will deform leading to distortion and a change in shape of the powder compact.

During decompression, the elastomeric bag will try to recover to its initial shape. As the powder has been compacted the green compact is now significantly stiffer than the elastomer and therefore, the elastomeric bag can deform significantly after it has partially detached. This deformation adds extra loading to the compact and therefore, accurately simulating the behaviour of the elastomer is important in accurately predicting the stresses induced in the compact.

In this paper, the two different strategies have been utilized to model the behaviour of the elastomeric bag. In the two-dimensional simulations, a hyper-elastic model as discussed in[4,5,12] was used. Parameters for this model were obtained by uniaxial tension–compression tests as described in.[10] However, for the three-dimensional simulations, due to difficulties in obtaining a converged numerical solution, a simple linear elastic model was utilized. Whilst this may reduce the accuracy of the stresses predicted it still allows qualitative results to be obtained, which provide insights into the bag detachment process.

3. Finite element modelling

The finite element method, has been successfully utilized in many areas of powder compaction, including prediction of the shape and size of components formed by the isostatic pressing,[3,4] prediction of density distributions of compacts,[8,9,13] and evaluation of the effect of friction between the powder and pressing tools in die compaction.[9] The finite element simulation of the decompression process, should allow the tooling designer the opportunity to understand the detachment process and where applicable alleviate the stresses which may be induced by the detachment process.

In this work, the commercial implicit finite element code ABAQUS standard[14] has been used to model the compression and decompression process in isostatic compaction.

3.1. Axisymmetric model

Many components that are formed by isostatic compaction exhibit some elements of symmetry, which allow the simplification of the modelling process. Whilst this may not accurately reflect the detachment process, due to initial detachment occurring as a truly three-dimensional problem, the results presented in Section 3.2 highlight that this issue is not as significant as might first be imagined. Secondly the ease of obtaining converged numerical solutions is significantly aided by modelling in two dimensions allowing more parameters to be investigated without limitations being imposed on the parameter space by convergence difficulties such as overclosure of contact surfaces (where the simulation algorithm cannot resolve the contact problem) and distinct non-linear

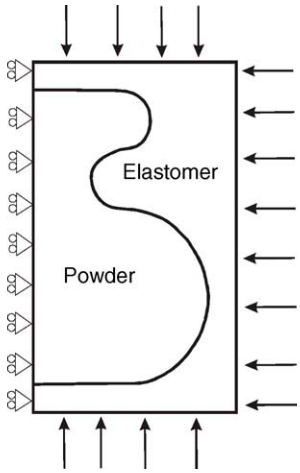

Fig. 2. The boundary conditions and loading for the axisymmetric model.

events resulting form the surfaces coming in and out of contact. The geometry chosen for investigation in this paper is shown in Fig. 2. This geometry includes a number of features such as variable bag thickness, an obvious stress concentration location and significant variations in the thickness of the compact.

The model was developed using linear quadrilateral elements within ABAQUS and the contact was simulated using a master-slave algorithm (where the master surface can penetrate the slave surface but the slave surface cannot penetrate the master). The interface was also modeled as a hard contact, where there is instantaneous rise in stiffness at the interface when the contact occurs. The friction coefficients utilized ranges from 0.25 to 0.6 and were assumed to be constant as the contact pressure varied. In order to achieve improved numerical convergence it was necessary to ensure that the meshes were initially matched—that is a node on one contacting surface directly corresponds to a node on the other contacting surface. This ensures that during the initial stages of compaction, where the powder is significantly less stiff than the elastomer that the contact algorithm operates efficiently. During the later stages of compression this is less of a problem as the powder is significantly stiffer at this stage.

The boundary conditions and loads applied to the system are also shown in Fig. 2. A symmetric boundary condition is applied along the axis of rotation and the pressure was applied to the outer surface of the powder. It is important to note that the geometric non-linearity introduced by the change is shape of the elastomeric bag was included within the simulations. In order to prevent rigid body motions of the press tooling and powder compact, whilst not over-constraining the system soft springs were utilized to prevent movement of both the powder and the tooling in the along the vertical axis.

The results obtained from the simulations are shown in Figs. 3–7. Each one of these results will be discussed in turn. The deformation of the press-tooling during the detachment process is shown in Fig. 3. This highlights the significant distortion that occurs within the press tooling during the compaction process and also the distortion of the compact resulting from the variations in thickness of the press tooling and powder fill. The deformation patterns also highlight the initial and secondary detachment points of the elastomeric bag from the compact. The primary detachment occurs at the upper section where the strains are highest within the elastomeric bag. Similarly, the second detachment point relates to a second region of high strain within the elastomeric bag. After the elastomeric bag has detached initially it is clear that significant deformation occurs and in this instance the relaxation of the elastomeric bag in the region of the narrow portion of the elastomeric bag results in a direct loading from the elastomer to the compact. This therefore, results in a region, which has significantly greater stresses than the rest of the compact as shown in Fig. 4.

A number of methods are available to reduce the stresses experienced within the compact. Similar to the results presented in[10] significant differences were noted in the stresses obtained as the stiffness of the elastomeric bag was varied. When the elastomeric bag had an initial modulus of 50 MPa the peak stresses were of the order of 6% of the compaction pressure, which is significantly greater than the green strength

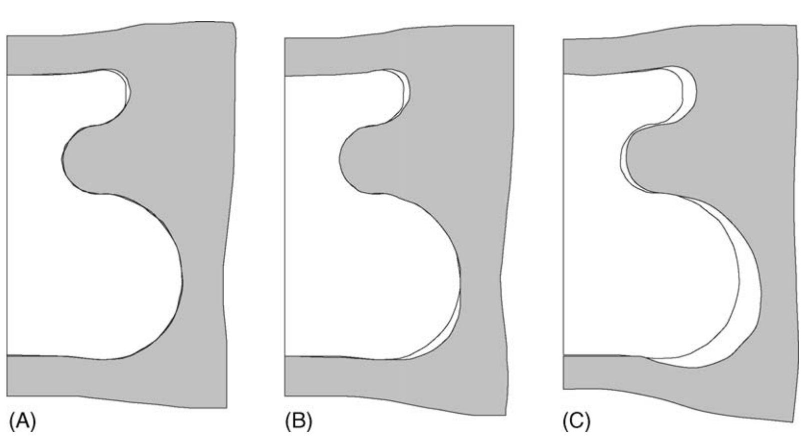

Fig. 3. The deforamations observed during the detachment process, as the detachment progresses. The initial detachment occurs in (A) followed by a second detachment location in (B) followed by more general detachment in (C).

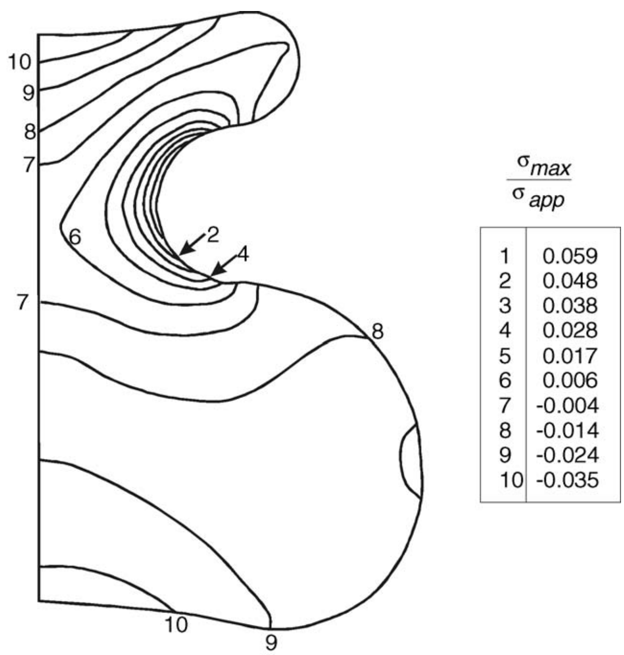

Fig. 4. Contours of the maximum principle stresses simulated during the detachment process at the point when the peak stresses are observed.

of the compacts. As the stiffness of the elastomer decreases the stresses induced within the compact also reduce to the point where the stresses are of the order of 3% of the compaction pressure with an elastomer of stiffness 10 MPa. This is shown in Fig. 5 for a wide range of bag stiffness where the stress levels (both the applied and induced) have been normalized relative to the maximum applied pressure. The maximum stress within the compact occurs when the bag initially detaches from the compact. When initial detachment occurs, tensile stresses induced within the compact as a result of bag distortion, are no longer alleviated by a compressive stress resulting from the contact with the elastomeric bag.

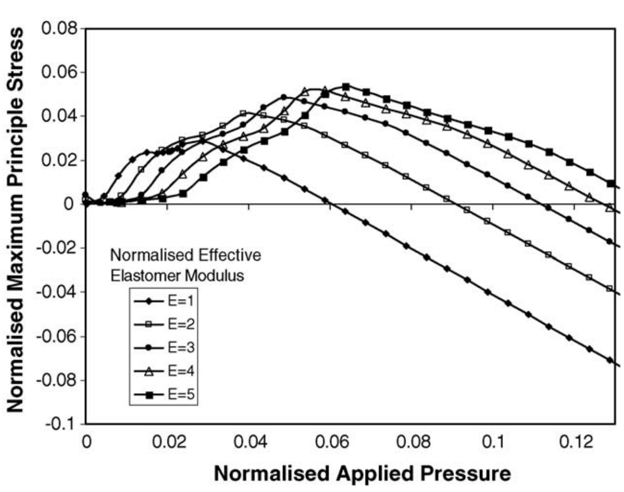

Fig. 5. The maximum principal stress predicted during detachment for the axisymmetric model. The simulations have been performed with a range of elastomer effective stiffnesses from 10 to 50 MPa and illustrate the sensitivity of the detachment stresses on the stiffness of the elastomeric bag.

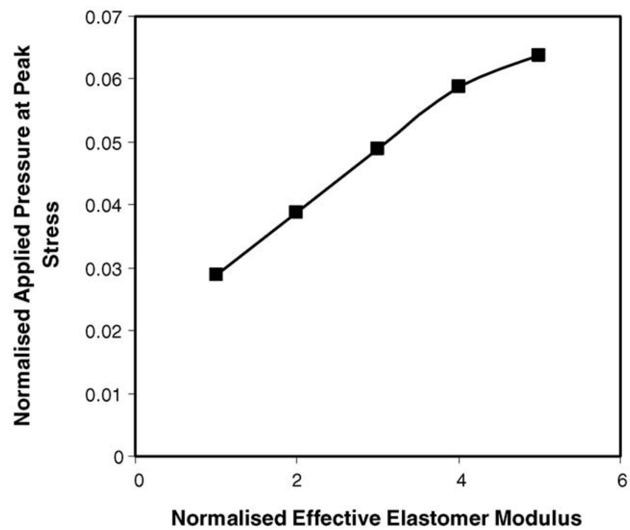

Fig. 6. The applied pressure at, which initial detachment occurs. This demonstrates that the loading transmitted by the compact increases as the stiffness of the elastomer increases.

The reduction in stress when a soft elastomer is utilized can be explained by examining the applied pressure at which detachment occurs (Fig. 6). As the stiffness of the elastomer reduces, the external pressure at which the bag detaches reduces (as a result of the reduction in stored elastic energy in the elastomer) and therefore when a soft elastomer is utilized the external stresses transmitted to the compact at the point of detaching are lower when a soft elastomer is utilized. It should be noted that non-linearities within the system, such as distortion of the elastomer and powder during the compaction process do not result in a linear scaling and thus the stresses induced by an elastomer which is five times stiffer will not necessarily be five times greater.

An alternative approach to reducing the stresses observed within the compact is through modifying the contact conditions at the interface. As already stated the simulations were performed with a range of contact conditions and the peak stresses obtained from the simulations are shown in Fig. 7. These results indicate that reducing the friction at the interface can reduce the stresses observed during the decompression process. Whilst not as marked as the reduction obtained by reducing the elastic modulus of the elastomeric bag the reduction in interfacial friction could play a vital role in reducing the instances of cracked components. In order to understand why reducing the friction coefficient reduces the stresses experienced during detachment it is necessary to consider the whole of the compaction process. As the friction coefficient increases the distortion observed during the compaction process will reduced as the elastomeric bag is unable to slide at the interface. However, as decompression progresses if there is reduced friction at the interface the elastomer is better able to deform and return to its original shape as the external pressure is reduced. This increased recovery of

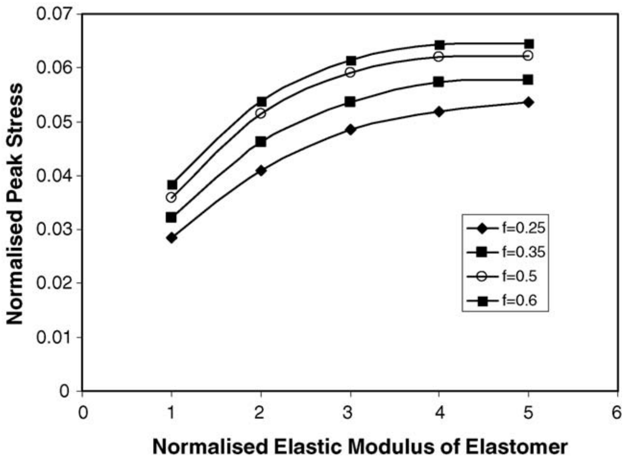

Fig. 7. The effects of frictional forces on the peak stress observed during detachment. It is clear that as the friction coefficient increases the stresses within the compact increase.

the elastomer, which is permitted by sliding at the interface, has the effect of delaying the detachment of the bag from the compact as more of the elastic recovery of the elastomeric bag can be achieved by sliding. Therefore, at initial detachment, where the stresses induced within the compact have been found to be consistently highest, the applied external pressure is lower and therefore the stresses induced within the compaction are reduced when the friction coefficient is reduced.

3.2. Three-dimension simulations

Modelling the compaction process in two dimensions, either for plane strain conditions as reported in[10] or axisymmetric conditions as reported above presents some problems in obtaining numerical convergence. However, these problems are multiplied when attempts are made to simulate fully three-dimensional components with sliding contact at the interface. In particular obtaining fully converged solutions for the contacting surfaces is problematic. This is exacerbated by difficulties in obtaining a suitably refined, matched mesh at the interface at the same time as obtaining solutions in a sensible length of computation time. For this reason the geometry modeled in this paper is simple (Fig. 8) but allows the discussion of the effects of perturbations in the geometry in three dimensions.

The mesh consisted of linear hexahedral elements with initially matched meshes at the interface. Similar to the axisymmetric model, sliding contact was introduced at the interface between the elastomer and the rubber bag. However, in this model, a tied contact condition was also utilized in some of the simulations to observe the effect of not allowing sliding during the compaction process in order to test the assumptions made in previous papers[4,5] where compaction has been modeled without recourse to sliding contact. The boundary conditions and loadings are shown in Fig. 8. Similar to the axisymmetric model non-linear geometric effects were taken into account throughout the simulation.

The results presented in Fig. 9 illustrate that the prevention of sliding does indeed modify the final compacted shape with significantly more distortion of the elastomeric bag being observed when sliding is allowed. This results in the final pressed shape being more distorted than would be simulated by preventing sliding at the interface. Whilst this has practical implications for the simulation of isostatic pressing in that increased accuracy will be obtained by allowing sliding the penalty to paid in simulation times and the difficulty of developing suitable meshes for three-dimensional components may be such that making the assumption of no sliding at the interface is the more pragmatic choice with the subsequent compromise on quality.

The bag detachment process is undoubtedly a three-dimensional problem and as such the effects of non-

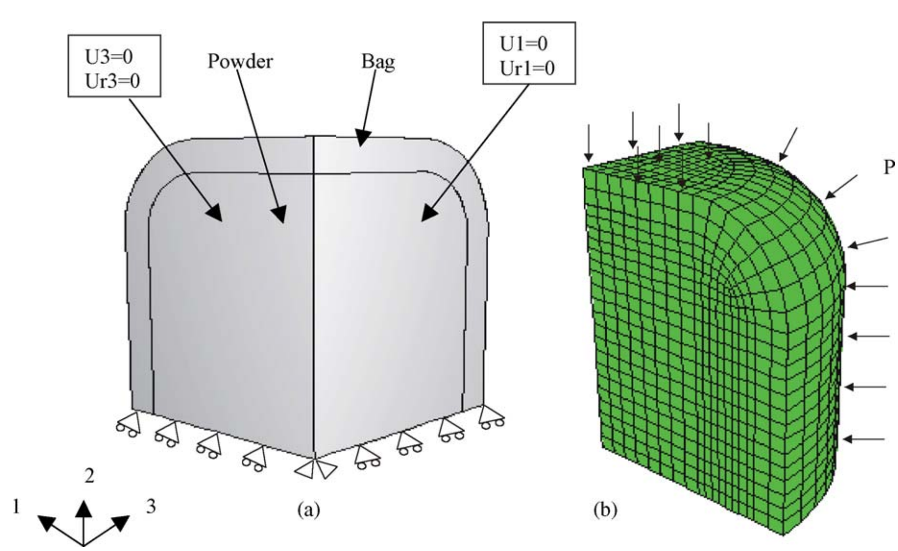

Fig. 8. The boundary conditions, loading and mesh utilized for the three-dimensional model.

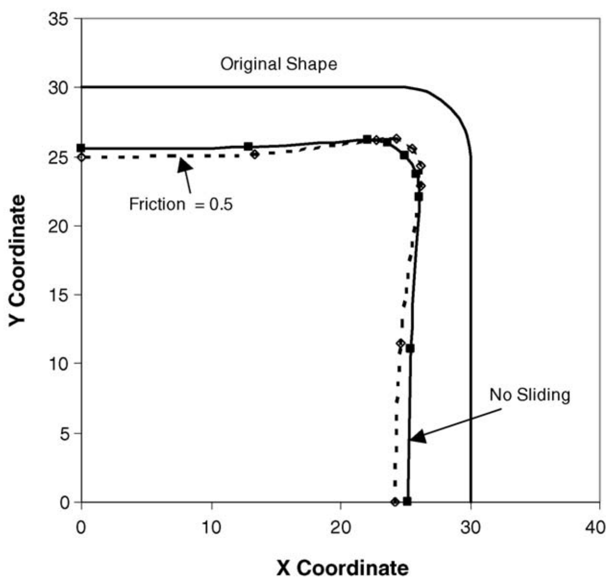

Fig. 9. The effects of modifying the contact conditions on the simulated compact shape.

symmetric features may play an important role in the detachment process. For example, it would be expected that small distortions resulting from the sagging of the elastomeric bag prior to filling with powder may result in nominally axisymmetric components being slightly non-symmetric. In order to investigate this the three-dimensional mesh was perturbed by modifying the some nodal coordinates to introduce a non-axisymmetric feature into this model as shown in Fig. 10. The simulations were performed with sliding contact and the detachment profiles (shown in Fig. 11) and detachment pressures observed. This indicated that the initial detachment did indeed occur within the perturbed location (as would have been expected as the result of the perturbation was to increase the strain locally within this region) but it did so at a pressure not noticeably different to that observed in the unperturbed simulation. Following the initial detachment at the perturbed location, the elastomeric bag then detached fully at the top component and mimicked the detachment profile of the unperturbed geometry. This occurred at the next incremental pressure (0.5%) calculation. It can therefore be concluded that slight non-symmetric effects do not have a significant effect on the detachment process. However, more significant non-symmetric effects may have more profound effects on the detachment process although these are very

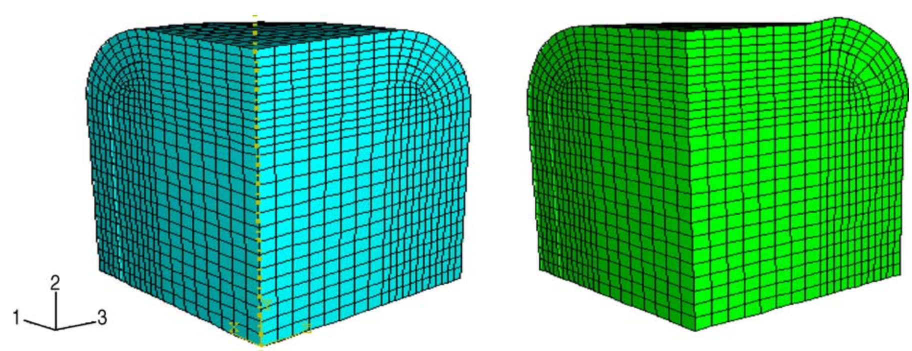

Fig. 10. The original three-dimensional model and the perturbed model. The mesh has been perturbed at the top right hand side of the component by modifying the nodal positions.

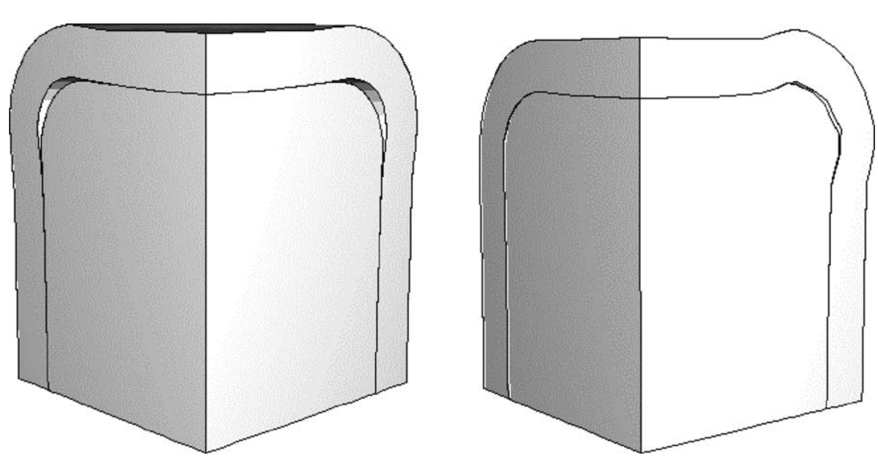

Fig. 11. The detachment profiles observed within the three-dimensional simulations. The perturbed geometry (shown on the right) initially detaches at the perturbed location followed by a detachment process that closely resembles that of the unperturbed geometry (shown on the left).

difficult to simulate due to meshing and convergence issues as described previously.

4. Conclusions

Bag detachment plays an important role in the development of tensile stresses in the powder compact during the decompression process. The magnitude of the stresses developed can be influenced by modifying the stiffness of the elastomeric bag or by modifying the interfacial conditions between the compact and elastomeric bag. If simulating the compaction process, regard must be paid to the interfacial conditions as these can modify the predicted shape and size of the pressed compact. Whilst the detachment process is undoubtedly a three-dimensional process, perturbing the geometry of a simple component does not make a significant difference in the detachment process and therefore useful information can be gained from plane-strain and axisymmetric simulations.

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