FINITE-ELEMENT SIMULATION OF THE UNIAXIAL DIE PRESSING OF CERAMIC POWDER

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I. Background and Motivation
Modern engineering ceramics such as alumina and zirconia are widely used in aerospace, automotive and electronics industries, but are often difficult and costly to process. We are currently developing novel fabrication techniques to manufacture a meso-scale ceramic heat exchanger [1,2,3]. This device made of Functionally Gradient Materials (FGMs) contains a complex internal network of channels to circulate cooling fluids. Two different approaches have been attempted. In the first approach, ceramic powder is poured into a steel mold, and internal meso-scale channels introduced into the powder bed by embedding a fugitive phase such as a graphite piece. The powder bed with the embedded fugitive phase is then uniaxially die-pressed to form the green compact, which is sintered to yield the final product. The fugitive phase burns away during sintering, leaving behind channels in the shape of fugitive phase in the bulk of ceramics. One particular concern in this approach is the limited powder flow around the fugitive phase. In the second approach, green compact without fugitive phase is partially sintered and subsequently machined to achieve complex surface channels.

The success of these fabrication techniques is dependent on the relative density of the compact achieved upon compaction and partial sintering especially meso-scale devices. Inhomogeneity in relative density distribution will result in sintering rate differences, which may lead to crack formation. In addition, density gradients in pressed-powder compact may result in severe shape distortion and unpredictable shrinkage that deleteriously affect the accuracy and reliability. Researchers like Aydin et al [4], Zipse [5], Bouvard et al [6], Kim et al [7,8] and Kim et al [9] have approached the compaction and sintering problems using the finite element method. In this paper, various specimens are manufactured and machined to aid in understanding the proper implementation of a finite element model. Ceramic powder bed with and without embedded fugitive phase, both subjected to uniaxial die pressing and ejection, are simulated using commercial software ABAQUS. The simulation results are then analyzed for a) the effects of orientation and locations of embedded phase on the relative density distribution and b) the plausibility of machining on a compacted without an embedded phase based on the simulated density distribution.

II. Specimens and Machining
In the current effort, the fugitive phase is the graphite piece EDMed to a cross-section of 2mmx2mm and then CNC-machined to produce controlled groove features of 0.8 mm wide and 0.67 mm deep as shown in Fig. 1(a). These groove features are repeated on all 4 sides along the graphite piece. The graphite piece is then embedded in the powder bed before compacting, shown in Fig. 1(b). Subsequent processing details such as die pressing and sintering can be found [1-3]. The sintered products, and the features imprinted, are shown in Fig. 1(c). The channel final dimensions have shrunk to 1.5mmx1.5mm. It is clear from Fig. 1(c) that the groove features successfully implant their negatives, or fins along the channels. It is our hope that these fins can
be manufactured in controlled dimensions and orientations so that meso-surface-texture engineering on the channels are possible for optimum heat transfer.

![Figure 1: (a) EDMed and machined Graphite; (b) Graphite embedded in powder bed and compacted and (c) Final sintered product fractured to reveal the details.](image)

### III. Finite Element Simulations and Constitutive Model
A hyperbolic-cap elastoplastic model with a shear failure line (or critical state line) originally proposed by Kim et al. [7, 8] to model the zirconia compact behavior is employed in the compaction simulation. This model predicts hardening (as the cap yield curve expands, for example, from dash-dot to solid curve) under triaxial loadings by associative flow rule and non-dilational perfectly plastic deformation of the powder compact under shear loadings with a non-associative flow rule as shown in Fig. 2 where $F_s$ is the shear failure line; $F_c$ is the cap yield curve; $p$ is the hydrostatic stress; $q$ is the equivalent stress; $d$ is the material cohesion, and $\beta$ is the material friction angle. The stress state within the envelope assumes elastic deformation.

The model is implemented through a FORTRAN code UMAT in ABAQUS 6.3 with the algorithms proposed by Aravas [10] and Govindarajan [11]. The constitutive model, and the material properties of zirconia powder are detailed elsewhere [7-8]. This model is compared to simulation results using a similar model in ABAQUS internal library, namely the modified Drucker-Prager/cap model for verifications [4-6]. Due to the space constraint, the results from the hyperbolic-cap model only are presented as the simulated density distribution both models exhibit similar trend and magnitude, except for some local differences, which has to be further investigated through experiments. Based on literature resources [4-9], an arbitrary value of 0.17 for the Coulombic friction coefficient between the compact and powder wall in the 3D models, whereas in the axisymmetric and plain strain models a value of 0.2 are used. The graphite piece is assumed to behave elastically throughout the compaction process.

![Figure 2: The hyperbolic cap model](image)

### IV. Simulation Results and Discussions
In particular, the following models were developed and simulated to understand the processing techniques described in Section II. These models are:

a) Two axisymmetric models with different aspect ratios \((h/D)\) as in Fig. 3(a) and Fig. 3(b).

b) A 3D finite element model of the cylindrical powder compact with a rectangular graphite piece, as shown in Fig. 4; and

c) A plain strain finite element model with graphite piece located in different position and orientations, as depicted in Fig. 5(a) (b) and (c).

Figure 3. Relative density distribution after ejection for compact with different aspect ratio. (The contour bands in all results presented as follows are equally-spaced.)

Figure 4: Relative density distribution after ejection for the 3D model, subjected to 23 MPa. The empty spot is where the graphite resides.

Figure 5: Relative density distribution after ejection with embedded graphite piece in different orientation and location. All compacts are subjected to 23MPa.

Inhomogeneity in density distribution is simulated in the presence of the graphite. Regions of high density gradients should be avoided to reduce possible defects on the final products. Figs. 3
show that a cylindrical compact with a low aspect ratio yields more uniform density distribution and thus allowing PSC machining on the most region of the sample. Fig 3(b) shows the regions of higher density at the top corners as compared to that at the bottom corners are very consistent with the findings of various researchers [4-9]. In Fig. 4, the region around the graphite piece has high-density gradients, and is thus a possible crack initiation location. Fig. 5(a), (b) and (c) seem to suggest that a diagonal graphite piece orientation and midsection location are preferable, since they tend to reduce density gradients.

V. Conclusions
The compaction simulation provides a valuable tool to understand the processes used in this study, mainly micro-machining and compaction with fugitive phase. Machining PSCs with a low aspect ratio was successful due to the uniformity in density distribution. Engineering the micro-surface-texture of meso-scale mixing channels was also introduced within a ceramic bulk by using a graphite fugitive phase. The geometry and positioning of the fugitive phase can be designed with the aid of FEM. The effects of powder bed dimension, fugitive phase dimension, its orientation and location on density distribution during powder compaction had been simulated. These results can help in designing the optimum geometry without introducing defects in the final sintered products.

1 Shin, H., Kok, C., Case, E., Kwon, P., 2003, “Meso-Scale Channels On Ceramics By Machining,” ASPE Winter Topical Meeting, Machines and Processes for Micro-Scale And Meso-Scale Fabrication, Metrology and Assembly, Gainesville, Florida