VIII International Conference on Computational Plasticity
COMPLAS VIII
E. Oñate and D. R. J. Owen (Eds)

A NUMERICAL PROCEDURE FOR MODELING CRACK FORMATION IN POWDER COMPACTION BASED MANUFACTURING PROCESSES

J. Oliver[*], J C. Cante[†] and J A. Hernández[*]

[*] E.T.S. Enginyers de Camins, Canals i Ports de Barcelona
Technical University of Catalonia (UPC)
Campus Nord UPC, 08034 Barcelona, Spain
e-mail: xavier.oliver@upc.edu,

[†] E.T.S. de Enginyeria Industrial de Terrasa
Technical University of Catalonia (UPC)
Colom,11, 08022, Terrassa, Spain
email: juan.cante@upc.edu

Key words: Compaction, non-associated flow, crack formation

Summary. *A numerical model for modelling crack formation during the powder compaction stage of powder metallurgy manufacturing processes is presented. A numerical model, previously developed by the authors, to predict the densification of the powder material during the compaction, is extended to detect the cracks onset during the pressing stage. The main ingredients of the new model are: a) using a Drucker-Prager failure surface together with a parabolic plastic potential function (non-associated flow), b) inclusion of a softening law which reflects the loss of material cohesion associated with the crack formation, c) a fractional step type algorithm to solve the return mapping problem and d) an implicit-explicit integration scheme which improves robustness of the numerical model. Such a general approach is assessed via the numerical simulation of the compaction process of an L-shaped industrial part.*

1 INTRODUCTION

Compaction processes play a fundamental role in powder metallurgy and structural ceramic manufacturing. Besides, numerical simulation of die compaction is a keystone for reducing the time and cost associated with the designing process of new components. Most of the phenomenological models developed so far for this purpose are characterised by a double-surface yield criterion, consisting of a hardening cap surface and a failure envelope. We focus our attention on the last one, since it is involved in the formation of cracks. As our aim is to describe cracking as a process of strain localization, the evolution of the failure surface parameters are ruled by a softening law, which allows representing the loss of strength associated with cracking. As for the yield surface, the standard associated Drucker-Praguer model poses many computational difficulties, as the elasto-plastic tangent operator at the vertex is singular. In order to overcome this difficulty, we propose a modified Drucker-Prager yield-criterion, whose parameters depend on an internal variable, and a non-associated plastic flow determined by a parabolic (in the p-q plane) plastic potential function. The thermodynamic constraints are fulfilled by imposing the evolution of the internal softening variables, and by the definition of the fracture energy as a property of the material.

2 CONSTITUTIVE MODEL

The model is formulated in terms of the large plastic deformations and it is based on the results presented in [2]. The hardening cap surface is a centred ellipse in the p-q plane, defined by two parameters governed by density. The novel failure surface could be written as $\phi_F = q^a + \alpha(c)\, p - c^a$, where q is the norm of the deviatoric part of the Kirchhoff stresses, p is the mean stress and c and $\alpha(c)$ are the cohesion-like strength parameter and internal friction-like parameter, respectively. For $a=1$, $\phi_F = 0$ is a straight line in the p-q plane. We focus our attention in this case. Note that if $\alpha(c) = \alpha_0$, a standard Drucker-Praguer yield surface is recovered. An evolution for $\alpha(c)$ should be assigned in such a way that the elastic domain defined by $\phi_F = 0$ decreases its volume as c decreases and, also, the maximum mean stress $p_{cr} = \alpha / c$ tends to zero as $c \to 0$. For this purpose, it suffices to take an homogeneous function of c with a positive degree of homogeneity $s_h < 1$. For $s_h = 0.5$, we have $\alpha = \left(c / c_0\right)^{0.5} \alpha_0$, where c_0 and α_0 are the values of the cohesion-like and internal friction-like parameters for the undamaged material.

The direction of plastic flow is determined by a plastic potential function, which can be defined in the same terms as the yield function, that is: $\varphi_F = q^b + \beta p + K(c)$. Setting $b=2$ (parabolic surface), the plastic flow at the vertex is no longer singular. The positive dissipation constraint obliges to consider β a function of c, $\beta(c) = \gamma\, c\, \alpha(c)$, $0 \le \gamma < 8$, where the parameter γ controls plastic dilatancy [5].

Next constraint is that the total plastic energy dissipated in the failure zone (fracture energy) does not depend on the stress path (material property). Therefore, we fix the evolution of the strain-like internal variable ξ in order to fulfill this constraint:

$$\dot{\xi} = \lambda_F\, r_\xi(\boldsymbol{\tau}, c), \ \textit{if} \quad r_\xi = \frac{1}{c}\tau : \frac{\partial \varphi_F}{\partial \boldsymbol{\tau}} \ \Rightarrow \int_0^{t_\infty} \int_\Omega \boldsymbol{\tau} : \mathbf{d_p}\, d\Omega dt = E(c_0, G_f), \tag{1}$$

where λ_F is the corresponding consistency parameter and $\mathbf{d_p}$ is the plastic deformation rate [5].

3 INTEGRATION ALGORITHM

The use of non-associated flow rules and softening laws leads, generally, to problems of lack of robustness and computational efficiency, due to the non-symmetrical and non-positive definite character of the corresponding elasto-plastic tangent operators. In order to avoid this drawback, an explicit-implicit integration scheme is proposed [1]. First, the internal forces at time t_{n+1} are computed using *explicit stresses* $\tilde{\boldsymbol{\tau}}_{n+1} = \tilde{\boldsymbol{\tau}}(\boldsymbol{\tau}^{trial}_{n+1}, \Delta\lambda_n, c_n)$. Then, the internal variables and plastic strains updates are performed, as usually, solving a return mapping algorithm, which constitutes the implicit phase. Note that we deal with softening plasticity and, consequently, the well-established hardening uniqueness theorems [3] cannot be applied. Therefore, an iterative procedure, which converges conditionally to the solution for an a priori-known range of the softening modulus values H, has been developed. It is a recurrent

two-step algorithm based on the fractional step methods. In a first step, we freeze the cohesion-like variable and solve a perfect plasticity problem, whose solution is unique (since ϕ_F and φ_F are convex functions of $\boldsymbol{\tau}$) and is obtained in a close form. In a second step, the cohesion-like variable is updated.

4 NUMERICAL RESULTS

This section presents some numerical simulations of die compaction carried out with the finite element code POWCOM, using the previously described yield surface model. In order to investigate the effects of the press kinematics on the occurrence of cracks during the compaction, the axisymmetric L-shaped part, shown in figure 2, is pressed using two different kinematics: the first one with simultaneous movements of the upper and lower punches, and a second one with a delay in the onset of movement of the lower outer punch. The displayed results correspond to 85% of the compaction level for each case. Parameters c_0 and α_0 are taken $c_0 = 50$ Mpa and $\alpha_0 = 2.71$. Mesh size dependence of the smeared approach to localization is avoided by regularizing the softening modulus via a characteristic element length, l_e, as $H_0 = l_e c_0^2 / G_f$, where G_f is the fracture energy (G_f = 0.9 N/mm). For the dilatancy coefficient a value of $\gamma = 0.2$ is used. As can be seen in figure 1, a non-balanced punch kinematics leads to non-homogenous density distributions. This non-homogeneity can be also displayed via a mechanical variable as the cohesion-like parameter (figure 2). Loss of cohesion is concentrated at the inner corner, in a characteristic "comma" shape region. A radial cut through the bottom of the component body shows a discontinuity in the vertical displacement field at the region corner (figure 2), which is a clear sign of a crack.

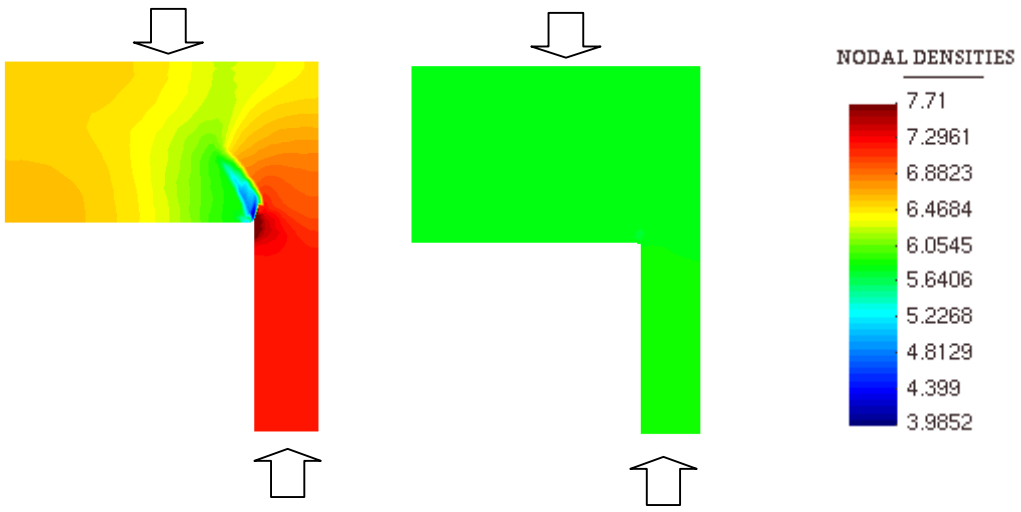

figure 1. Density distribution in the wrong-pressed (left) and the well-pressed (right) components at the 85 % of level compaction (initial density $\rho_0 = 3.34$ g/cm^3). In the well-pressed case, the upper and lower punches move simultaneously.

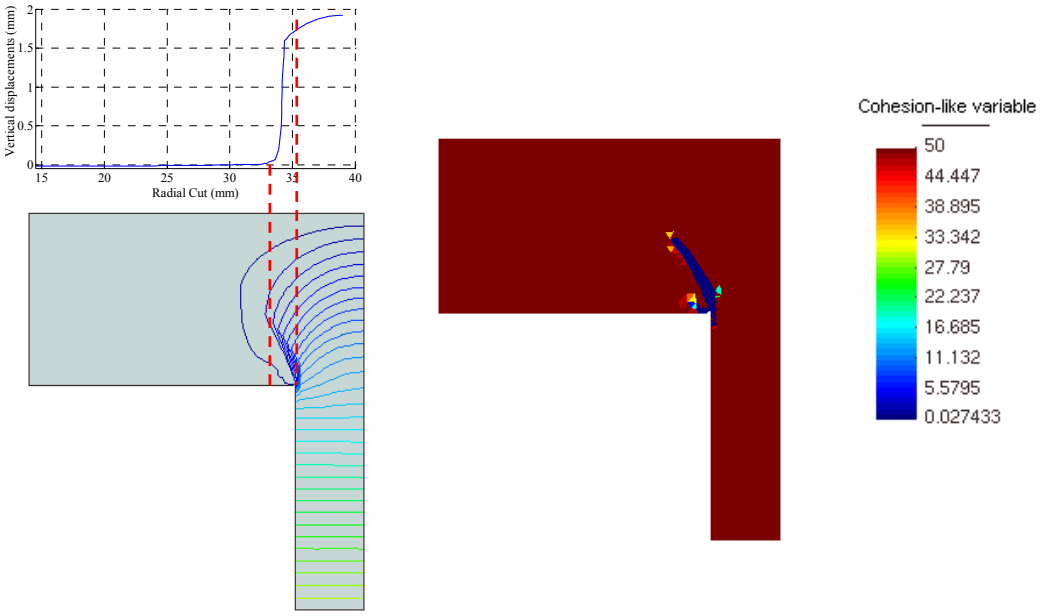

figure 2. Contour lines of the vertical displacement field showing the discontinuity at the corner (left) and the cohesion-like variable distribution in the wrong-pressed part (right).

The main achievement of the proposed methodology is the possibility of translating the non-homogeneities in the density field, arising from wrong-designed compaction processes, into a loss of cohesion and a subsequent detection of a crack. The locus of the region affected with this loss of cohesion is similar to the crack location observed experimentally [4], and, therefore, the results obtained are, at least qualitatively, satisfactory.

5 ACKNOWLEDGEMENT

The authors would like to thank the Spanish Ministry of Science and Technology for financial support (grant DPI2003-00629 and DPI2004-07666-C02-02).

REFERENCES

[1] J. Oliver, A.E. Huespe, S. Blanco, D.L. Linero, "Stability and robustness issues in numerical modeling of material failure in the strong discontinuity approach", *Computational Methods in Applied Mechanics and Engineering (in press)* (2005).

[2] R. Weyler, "Simulación numérica de procesos de compactación y extrusión de materiales pulverulentos", Tesis Doctoral, Universidad Politécnica de Cataluña, Barcelona, 2000.

[3] J.C. Simó and T.J.R. Hugues. *Computational Inelasticity*. Springer and Verlag, (1998).

[4] Federal Mogul, "Study of crack formation in an axisymmetric powder metal component" (Internal Report) , 1999.

[5] J.A. Hernández, J. Oliver, J.C. Cante, "Modelo numérico para la detección de grietas en el conformado de pulvimateriales", Congreso de Métodos Numéricos en Ingeniería, Granada, 2005.