Stresses State and Mechanical Behaviors of the Green Body During Die Compaction and Ejection Process

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Abstract

Finite element simulations for metal powder compaction of a clutch plate were performed to examine the stresses during compaction, unloading, and ejection. To describe the mechanical behavior of compacted green body, a modified density-dependent Drucker–Prager Cap model was utilized to predict the stress and density distribution of the compacted clutch plate during loading and ejection stages. The results indicate that maximum tensile principal stress was a main driving force for the tensile crack initiation during ejection stage, and shear stress may be another driving force in both compaction and ejection stages for shear crack initiation. There were peak value of the stresses during ejection stage, and the stresses are in compressive state only during compaction stage. Therefore, the tensile crack initiation is not possible during compaction except shear crack. Hoop stress in the clutch plate is of less contribution to the crack initiation during compaction, unloading and ejection. Study of criteria of the crack initiation and fracture is necessary in order to obtain uniform density and crack-free components in the manufacturing of metal powder compaction.

Keywords Powder compaction · Finite element simulation · Stress history · Cap model · Green body

1 Introduction

Manufacturing of near-net-shape product through metal powder compaction has become a very important technique in automotive industry. Today, the products with complicated geometry such as automotive powertrain components can be produced through this technology [1, 2]. Among the powder metallurgy (PM) manufacturing processes, the cold (i.e., at room temperature) uniaxial pressing of powder into a green body is one of the most common processes in PM industry. The process involves the stage of compaction, unloading, and ejection. After compaction, the loading force is removed, and the green body will be ejected from the held die. Because of the elastic constraint on the compact body,

the friction force between die and green body is extremely higher, and a forced ejection must be applied carefully in order to get crack-free green component [3]. Excellent green body properties such as high and uniform density with reasonable residual stress distribution are very important for obtaining the final product with a good quality. Analyses of green density distribution after compaction by employing finite element simulation have been done in the past decades and a great deal of research results have been achieved [4, 5].

However, stresses during compaction especially in the unloading and ejection process are not well understood with respect to complex geometry compaction. For pressing of a complex component, multiple punches are commonly used. Incorrect unloading and ejection of the complex component might result in cracks and high residual stresses. The residual stresses can cause problems during handling, machining and sintering of the green body. Crack-like defects most often arise after compaction before sintering. Prevention of cracking requires good understanding of development of the stresses during loading, unloading and especially the ejection stage. If the strength of the compact green body is low and stress during ejection is high, cracks may form inside or on the surface of the green body, which will affect the quality of the final component [6–9]. Therefore, the stresses

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during pressing and ejection are a main factor of affecting on the cracking of initiation and propagation. Understanding of the development of stresses during pressing process is a crucial step for elimination of cracks, optimization of compact kinematics of tooling, and improving product design [10–13].

Residual stress measurements of green bodies are unusual and require expensive equipment and specialist knowledge [14]. Therefore, numerical simulation of stresses development during pressing by finite element analysis can be aid to understanding of inside stresses picture of the green body without pay the extremely cost [15, 16]. The potential for cracks has been recognized as a significant concern and often limits its application of powder metallurgy technology for the product of complex part geometries [17]. Following investigations are carried out: What is driving force for crack initiation, primarily axial, radial or hoop tensile stress components in the green body or maximum principal stress? At what stage does cracking occur, compaction, unloading or ejection? How to control the compaction process to get crack-free components from the entire die compaction process? Those issues are still not clear, and it is necessary to establish the criteria for crack initiation during die compaction process. Therefore, knowing the state of stresses developed inside the compacted components is a crucial step for further establishing the criteria for crack initiation and fracture pattern.

The aim of this work is to explore all stresses state in the green body of clutch plate during die compaction process by finite element simulation during entire die compaction process including loading and unloading and ejection stages, to analysis the effect of each kind of stress on compaction process, and to establish a knowledge of relationship among stresses, green density, and kinematic of the tooling. To do this, a modified density-dependent Drucker–Prager/Cap (DPC) model was employed to simulate the entire die compaction process [15–18]. Because the development of stresses was highly related to material properties, such as elastic and plastic properties, material model parameters involved in the simulation were experimentally calibrated

using instrumental rigid cubic die tooling sets to ensure accurately reflecting the stresses level.

2 Density-Dependent Constitute Model

Metal powder is pressure-sensitive and density-dependent which induces a complex material behavior. In order to reproduce this complex behavior of the metal powder, density-dependent material model is needed to simulate the die compaction, unloading, and ejection process.

Here, phenomenological physical scale compaction model of modified density-dependent DPC in which treats the powder mass as a continuum was used to simulate the die compaction process. Figure 1a shows the yield surface of DPC model with constant material parameter described in the $p - q$ (hydrostatic pressure p – deviatoric stress q) plane [17–19]. Figure 1b shows the modified density-dependent DPC model, where the yield surfaces are not only the function of hydrostatic pressure p and deviatoric stress q but also the function of green density used in this study. The movement of both surfaces is controlled by green density of compacted green body.

The yield surface is described using two parts, a shear failure surface F_s and a cap surface F_c . The shear failure surface is represented by a straight line, while the cap surface is represented by an elliptical shape. In addition, a transition surface F_t is included in order to ensure a smooth transition between the shear failure and cap surface. The cap yield surface is expressed as:

$$F_c = \sqrt{(p - p_a)^2 + \left[\frac{Rq}{1 + \alpha - \frac{\alpha}{\cos \beta}} \right]^2} - R(d + p_a \tan \beta) = 0 \quad (1)$$

where β is friction angle, d is cohesion, R and α are the eccentricities of large and small ellipses respectively, α is generally taken as 0.01–0.05, p_a is the hardening/softening evolution parameter used to define the volume inelastic

Fig. 1 **a** Schematic illustration of DPC model with constant material parameter, **b** modified density-dependent DPC model showing the shear failure and cap surface as well as associated material parameters

strain, p_b is hydrostatic pressure which can be written as function of green density as follows:

$$d = d(\rho); \beta = \beta(\rho); R = R(\rho); p_b = p_b(\rho). \quad (2)$$

The parameter p_a in Eq. (1) can be calculated based on the following equation:

$$p_a = \frac{p_b - Rd}{(1 + R \tan \beta)} \quad (3)$$

The flow potential equation φ_c in the cap region is assumed to be associated, identical to the cap yield surface equation:

$$\varphi_c = \sqrt{(p - p_a)^2 + \left[\frac{Rq}{(1 + \alpha - \alpha/\cos \beta)} \right]^2} \quad (4)$$

where parameter α is used to define a smooth transition surface between the shear failure surface and the cap.

And the transition surface F_t is given as:

$$F_t = \sqrt{(p - p_a)^2 + \left[q - \left(1 - \frac{\alpha}{\cos \beta} \right) (d + p_a \tan \beta) \right]^2} - \alpha (d + p_a \tan \beta) = 0 \quad (5)$$

In the shear surface region,

$$F_s = q - p \tan \beta - d = 0 \quad (6)$$

where β and d are functions of green density same as shown in Eq. (2), and the flow potential equation is non-associated F_s and F_t , which are defined by [17]:

$$p = -\frac{1}{3} \text{trace}(\sigma) = -\frac{1}{3} (\sigma_1 + \sigma_2 + \sigma_3) \quad (7)$$

Using the conservation of mass, the density ρ is computed from the plastic volumetric strain by:

$$\varepsilon_v^{\text{pl}} = \ln \left(\frac{\rho}{\rho_0} \right) \quad (8)$$

where ρ_0 is initial filling density and $\varepsilon_v^{\text{pl}}$ is total plastic volumetric strain.

The general evolution equation for the plastic part of the deformation gradient ("flow rule") is given by:

$$\Delta \varepsilon_{ij}^{\text{p}} = \Delta \lambda \times (\partial \varphi / \partial \sigma_{ij}) \quad (9)$$

$$\varphi_s = \sqrt{[(p_a - p) \tan \beta]^2 + \left[\frac{q}{(1 + \alpha - \alpha/\cos \beta)} \right]^2} \quad (10)$$

where $\Delta \varepsilon_{ij}^{\text{p}}$ is plastic strain increment, λ is the plastic consistency parameter, φ_s is the plastic flow potential of the powder material.

The stress increment $\Delta \sigma$ can be written as:

$$\Delta \sigma = \left(K + \frac{4}{3} G \right) \Delta \varepsilon \quad (11)$$

where $\Delta \varepsilon$ is total strain increment, G and K are shear and bulk modulus expressed as function of density of green body.

The plastic strain increment for shear failure zone ($p < P_a$) is given by:

$$d\varepsilon_{ij}^{\text{p}} = d\lambda \frac{\partial \varphi_s}{\partial \sigma_{ij}} \quad (12)$$

The plastic strain increment for cap zone ($p > P_a$) is given by:

$$d\varepsilon_{ij}^{\text{p}} = d\lambda \frac{\partial \varphi_c}{\partial \sigma_{ij}} \quad (13)$$

where λ is the plastic multiplier and $\frac{\partial \varphi}{\partial \sigma_{ij}}$ gives the direction

of the plastic flow.

The initial of plastic yielding occurs when $\varphi = 0$. Using consistency condition, the explicit expression of consistent parameter λ in above equations can be deduced for both shear failure surface and cap surface. Thus, the stresses in the compacted components can be calculated by employing explicit algorithm [22–24].

3 Calibration of the Constitutive Model Parameters

The material of interested in this work is an ATOMET metal powder which contains 99.4% of iron, 0.2% of Mn, and 0.7% kenolube. The apparent density is between 2.95–3.10 g/cm³ with 26 s/50 g of flowability. The average particles size is 10 μm . The following modified density-dependent DPC model parameters of d , R , P_b , E , and ν , which are expressed as functions of green density were required to calibrate by a series of experimental test.

Parameters d and β for failure surface were obtained by using diametrical and axial compression tests [25]; the parameters R and P_b for cap surface are obtained by using an instrumented cubic die with measurements of vertical and horizontal stress, the details calibration can be found in another paper [18, 19]. The dependence of elastic parameter of Young's modulus E and Poisson ratio ν for elastic zone can be neglected in the modeling of die compaction because

Fig. 2 Elastic properties as function of green density: **a** Young's modulus E as function of green density, **b** Poisson ratio ν

Table 1 Material model parameter as function of relative density

DPC model parameters	Function
Cap surface parameters	P_b (MPa) = $2.8[(\rho/\rho_0)^{3.2} - 1]$
Eccentricity R ; isostatic pressure P_b	$R = 0.038[(\rho/\rho_0)^{5.6} - 1 + 0.50]$
Failure parameters	d (MPa) = $0.058[(\rho/\rho_0)^{10.3} - 1]$
Cohesion d ; angle β	$\beta = 71^\circ$
Elastic parameters	$E = 2523.2\rho/1189$
Young's modulus E ; Poisson's ratio	$\nu = 0.1379\rho - 0.7354$

the plastic strain overwhelms the elastic strain [14]. However, when unloading and ejection of the compact specimen from the die are considered, the elastic material parameters are very important in order to accurately calculate the stress during unloading and ejection from the die, the measurements of elastic parameters of the green specimen have to be carried out.

The elastic parameters were obtained using loading and unloading die compaction test with instrumental rigid cubic die tooling [20]. Figure 2 shows the measured Young's modulus of E and Poisson's ν of the ATOMET metal powder. The Young's modulus and Poisson ratio can be expressed as function of green density by fitting to the experimental data.

The calibrated material model parameters expressed as functions of the relative green density are summarized in Table 1. These functions were implemented into ABAQUS/Explicit codes by writing user subroutine through the interface provided by ABAQUS/Explicit. The green density was treated as a solution-dependent state variable in ABAQUS/Explicit code. The implementation details of user subroutine are in reference [26].

4 Simulation Methods

Using the implemented constitutive model in ABAQUS/Explicit, the simulation of a clutch plate as shown in Fig. 3a during compaction and ejection was carried out. The clutch plate has external and internal diameters of 162 mm and 121 mm, respectively, and it has a height of 9.85 mm and 7 teeth on the external surface. In order to reduce computational cost, the part geometry was simplified to an axially symmetric geometry and meshed with quadrilateral axisymmetric reduced integration elements as shown in Fig. 3b.

Figure 4 shows a schematic illustration of the assembled tooling consisting of the die, punches, core rod, and compact powder in the die cavity for two cases. The left side is

Fig. 3 Part geometry and model setup in the simulation: **a** geometry of the clutch plate part, **b** mesh for evaluation of stress and density state

Fig. 4 Schematic illustration of the assembled tooling and its kinematics

showing a position of tooling after compaction, while right side is showing the position of the tooling after ejection. In the compaction, the clutch plate powder was pressed by four punches, with a float die and core rod. The top surface was formed by top punch, and the bottom surface was formed by inner, middle, and outer punches

Loading was carried by remove the top punch, and following the ejection was performed by moving up all the lower punched to eject the compact green body after compaction.

The compressive ration of the punch tooling is set to 2.0 to set up the initial fill high of the metal powder in the die.

The die and punches were treated as analysis rigid body. In order to evaluate the stress state during the pressing process, three locations in the meshed green body model were selected to invest the stress history as shown in Fig. 3b.

The friction coefficient between die wall and powder will affect the density distribution and stress distribution, and here the value of friction coefficient is experimentally obtained by using instrumental cubic die compaction test [16, 17] and it was set to 0.2.

5 Results and Discussion

5.1 Density Distribution

The density distributions in the clutch plate both after compaction and ejection are shown in Fig. 5. It is shown that after ejection the density is slightly decreased because of the elastic spring back of compacted clutch plate.

In order to verification of the compaction model, the density distribution of the clutch plate was measured using immersion density technique based on the Archimedes principle. The clutch plate was cut into four parts (Fig. 6a), and each part was cut to seven regions along circumferential direction using wire electric discharge machining (WEDM) as shown in Fig. 6b. The measured green density of four parts within each region is shown in Fig. 7 and compared with the simulation. It is shown that the results of simulation agree rather well with the experimental measurement. The experimental measurement of average density for the four parts show the same trend in the seven regions, and the minimum average green density always occurred in the region 2 of the part.

5.2 Stress State

The stress state in the loading (compaction) and unloading and ejection process are main interested in this study. The potential for cracks has been recognized as a significant concern and often limits its application of powder metallurgy technology for the product of complex part geometries [1]. During the compaction, the areas of particles contact together and form a mechanical bond, and the bonds are quite weak, and hence, the brittle fracture during ejection is likely to occur depending on the maximum principle stress

Fig. 5 Green density distribution of compaction and ejection

Fig. 6 Seven regions of the measured average green density

Fig. 7 Density comparison between simulation and experimental measurement

[11]. However, other stresses such as direction stress may be also a driving force for crack initiation and propagation. Thus, this study not only concentrated the maximum stress but also the direction stresses. Figure 8 shows a history of maximum principle stress during the three stages of compaction, unloading, and ejection.

The maximum principle stress was of compressive state during compaction in the clutch plate. However, with starting of unloading, the maximum compressive principle stress was released and becomes tensile state throughout

the ejection process. The peak value of maximum tensile principal stress for the three locations was reached when the ejection was about halfway out of the die. Comparing the three locations, the maximum tensile residual stress was located insider after ejection. The oscillations correspond to a node losing contact with the die wall. In order to have a whole picture of maximum principle distribution at the three stages, after compaction, unloading and ejection, the contour plot of the maximum stress is shown in Fig. 9.

Fig. 8 History of maximum principal stress in the clutch plate during compaction, unloading and ejection

As one can see that there was a region where the tensile maximum principle stress occurred during ejection. This region was mainly formed between the inner punch and outer punch in angle of 45° with vertical direction. This region was moved toward to the bottom in the clutch plate during the ejection process. If the density in this region was too lower, the strength of the region is too weak to stand the tensile stress, a crack would happen.

Similar to the maximum principle stress, the history of direction stress in axial, radial, hoop and shear are shown in Figs. 10, 11, 12, and 13, respectively. For the radial

stress of s_{11} and axial stress of s_{22} , the evolution histories were same as maximum tensile principal stress with less value. A compressive stress was developed during die compaction stage. With starting of unloading, the states of both stresses were gradually decreasing and becoming a tensile state. There were peak values for both stresses during the ejection stage. The residual hoop stress had a maximum stress in tensile or compressive depend the locations after ejection. The shear stress during compaction and ejection had a peak value, which means that the shear crack may occur during compaction or ejection stages depending on the shear strength of the compacted plate.

Distribution of the direction stress states in the compacted clutch plate, during compaction and ejection are shown in Figs. 14, 15, 16, and 17. The axial stress has a similar trend to maximum principal stress; the axial tensile stress s_{22} is located between inner punch and outer punch and moved toward down to the contact surface of middle punch, because of the effect of friction between the punch and powder. The radial stress is lower than the axial stress, and it seems that the tensile zone is big than axial stress, but have a lower tensile stress value. The locations of maximum shear stress in compaction and ejection have different. During compaction, the maximum stresses were occurred at a location of both inside and outside of corners, while the maximum shear stress during ejection was only located at the outside of the corner (shown in Fig. 17).

Fig. 9 Maximum principal stress in the clutch plate during compaction and ejection

Fig. 10 History of radial stress in the clutch plate during compaction, unloading and ejection

The value of these maximum direction stresses was compared with maximum tensile principle stress as shown in Fig. 18. It is also shown that the maximum tensile stress be a main driving force for the tensile crack initiation during ejection stage; the hoop stress has a little contribution to the crack initiation, while the shear stress may be a driving force in both compaction and ejection stages for shear crack initiation.

This work was mainly employed the density-dependent DPC model to investigate the all the stresses state during entire compaction process. As we have seen that, the green density distribution in compacted clutch plate is not uniform, and there always remains a density gradient inside; the minimum density region is located at the region 2 as shown in Fig. 6, where the average green density was about 6.12 g/cm^3 . Because the strength of the compacted clutch plate was mechanical weak bonds and depend on the density, if large tensile stress above a certain level, brittle

Fig. 11 History of axial stress in the clutch plate during compaction, unloading and ejection

Fig. 12 History of hoop stress in the clutch plate during compaction, unloading and ejection

Fig. 13 History of shear stress in the clutch plate during compaction, unloading and ejection

fracture could be occurred in this region. During compaction, all the stress states (axial, radial, and hoop principle) were compressive except shear stress, and the crack initiation was driven only by shear force, because the die compaction is a confined uniaxial pressure process, and the crack caused by the shear stress may be healed during further compaction. During the unloading and ejection, the direction stress changes its sign from compressive to tensile state, the possibility of both tensile crack and shear crack may be developed if the stresses is above a strength limit. To precisely predict the crack initiation, considering the density-dependent fracture criterion is necessary to model the crack initiation and propagation during the compaction and ejection. The optimization of die compaction process with aim of minimum of density gradient and minimum of tensile and shear stress in the entire compact component is a final goal for obtaining a density uniform and crack-free product in the PM industries.

Fig. 14 Distribution of radial direction stresses in the clutch plate during compaction and ejection

Fig. 15 Distribution of axial direction stresses in the clutch plate during compaction and ejection

Fig. 16 Distribution of hoop direction stresses in the clutch plate during compaction and ejection

Fig. 17 Distribution of shear direction stresses in the clutch plate during compaction and ejection

Fig. 18 Peak value of five direction stresses in the clutch plate during compaction, unloading, and ejection

6 Conclusion

Finite element simulations for metal powder compaction of a clutch plate were carried out to examine the stresses inside during compaction, unloading, and ejection. This numerical analysis can give us a good understanding of the evolution of the stresses inside the compact plate for further development of modeling of crack initiation and fracture entire die compaction process. For the clutch plate compaction, the conclusion can be summarized here as follows: All the stresses (except for shear stress) are in compression during compaction stage. Therefore, the crack initiation caused by tensile stresses is not possible during this stage; the crack was only caused by shear stress. Tensile cracks develop during the ejection stage; the driving force for crack initiation comes from maximum tensile principal compared with other direction stresses. Shear stress can be a driving force for shear crack initiation both in compaction and ejection stages. Ideally, a modeling of criterion for cracks or fracture initiations should be utilized in the simulations in order to obtain optimized process parameters for crack-free parts in the die compaction of PM parts.

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