Powder Technology 204 (2010) 27–41

Contents lists available at ScienceDirect

Powder Technology

journal homepage: www.elsevier.com/locate/powtec

Experimental calibration of density-dependent modified Drucker-Prager/Cap model using an instrumented cubic die for powder compact

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ARTICLE INFO

Article history:
Received 14 January 2010
Received in revised form 9 June 2010
Accepted 8 July 2010
Available online 18 July 2010

Keywords:
Metal powder compaction
Material model calibration
Cubic die compaction

ABSTRACT

Theory and experimental calibration of density dependent modified Drucker-Prager/Cap (DPC) model are presented by using a novel instrumented cubic die in powder compaction tests. The cubic die is designed for directly determining the loading and unloading forces and displacements of powder compact inside the die in compaction and transverse directions without any additional calibration. The cap surface parameters and elastic properties are characterized by fitting stress and strain curves recorded during loading and unloading at different green density values and the plastic material parameters for failure surface are obtained by additional radial and axial compressive tests. The experimental data is subsequently used in the simulation of cubic die compaction to verify the results from the density dependent modified DPC model.

1. Introduction

Manufacturing of near net shape metal powder products has become an important technique in the production of highly stressed components. An increasing number of products with complex geometry such as automotive powertrain components are being produced using this technology [1–3]. The manufacturing process for the powder metallurgy parts mainly consists of three stages, die filling, powder compaction and sintering [4]. Among these stages, die compaction of powder is the main step in the manufacturing of metal powder components, because many defects such as density gradient and cracks can occur during the die compaction. It is well known that any inhomogeneity in density which is generated at die compaction stages will persist throughout the sintering process. Therefore, the density distribution of the compact component will directly affect mechanical strength as well as dimensional accuracy of the final parts made from powder metallurgy (P/M) method. In order to fully understand the compaction stage and optimize the die compaction process, modeling and simulation of the die compaction using finite element method (FEM) is being increasingly studied. FEM can provide the distribution of green density, stresses and crack in the compacted parts [1–3,5–10]. Most importantly, it allows the visualization and optimization of compaction process including interaction of tools and powder body before investment in time and money is made in the tool design and try-outs. Two tasks must be performed prior to a reliable numerical simulation. The first task is to utilize an appropriate constitutive model for the powder. Secondly, well defined calibration experiments must be conducted for easy identification of the constitutive model parameters of powder material.

In the past decades, many constitutive models including micro-mechanical [11–13] and macro-mechanical models (see reference [1] for a review) have been studied. Specifically, phenomenological Drucker-Prager Cap (DPC) constitutive model [14] which was originally intended to model geological materials has been modified and adapted for metal powder compaction. It has been shown that the DPC model appropriately represents the behavior of powder rearrangement and consolidation during compaction processes. However, the representative numerical simulation of powder compaction not only requires a realistic constitutive law but also needs the experimental calibration facility that is easily conducted for accurate calibration of material model parameters.

The most commonly performed experiment to calibrate metal powder materials is the high pressure triaxial compression test [15–17]. With the triaxial equipment, the loading paths are controlled by introducing both the shear and compressive stresses in the compaction. Many mechanical parameters of the Cap model can be characterized. However, the cost of developing the tools for high pressure triaxial compression test system for metal powder compaction can be quite high. Therefore, a relatively cheaper alternative cylinder die test with instrumented sensor was developed in order to provide equally effective means of characterizing the material parameters of the model [18,19]. Most calibrations of material model parameters using the instrumental cylinder die have been carried out with pharmaceutical powders for tablet compaction in the past [19–24]. Only limited experimental studies on the calibration of metal powder have been published [1,15–18]. However, one of the

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doi:10.1016/j.powtec.2010.07.003

major difficulties for calibration of materials model parameters is the determination of the radial stress in the powder specimen inside of the die by using instrumented cylindrical die [1,25–27]. In these references, there are several methods for measuring the radial stress using the instrumented cylindrical die. The disadvantages to all these methods are additional calibration, and the need for finite element calculations to verify the accuracy of the measurement from the sensors. Particularly, the compaction of a metal powder under high pressure is needed to be verified. In reference [18], radial stress was measured using a circular or square section die where the square section was formed by four separate plates mounted inside an external housing. This may have caused considerable complexity during unloading and ejection stages. It is also to be noted that the analyses of unloading and ejection steps were considered for the circular die only. The above procedures make the measurement of radial stress inside powder rather complicated and error prone.

In this work, a novel instrumented cubic die with force transducers has been designed to calibrate the density dependent DPC model parameters for a metal powder. Using this equipment, there is no need for calibration and only average stresses in compaction and transverse directions inside cubic specimen are directly measured. The main objective of this work is to: (1) design novel instrumented cubic die for directly measuring stresses in compaction and transverse direction during the die compaction, (2) develop a new mathematical procedure for the characterization of the DPC model parameters from cubic die compaction data, (3) utilize the experimental data for the calibration of the modified DPC model parameters, and (4) validate and compare the experimental result of die compaction with FEM simulations.

2. Instrumented cubic die design

The first step is to design the instrumented cubic die with force transducers in order to measure the stresses both in compaction and transverse directions and strain in the compacted powder. The instrumented cubic die was made up of tool steel and fabricated by CNC machining. Fig. 1 (a) shows the schematic illustration of the system design of instrumented cubic die.

The 3D assembly drawing of a two-part cubic die tooling system with four force transducers is shown in Fig. 1(b). The force transducers are mounted through the screw hole to tightly hold the two die parts. The die was made of tool steel to keep the deformation of the die as minimum as possible. In order to accurately obtain the horizontal force component, all four force transducers (or load sensing bolts) were calibrated after clamping the die plate and prior to compaction. However, in order to observe the movement inside particles, one of the die walls is comprised of a high strength transparent glass in some of the experiments (not reported in this study). Fig. 2 shows photographs and drawings of the instrumented cubic die and associated test equipment. It is to be noted that the drawing in Fig. 2(d) shows a transparent wall section. The tests were conducted using a servo-hydraulic 100 KN MTS test machine (Fig 2 (a)).

The cubic die had a cross-section with a width of 8 mm and a length of 10 mm. The stress and displacement in compaction direction were deduced from the axially mounted load cell and the displacement sensor (LVDT). The transverse stress was deduced from the four average force-sensing bolts transducers that were positioned on the cubic die wall shown in Fig. 2 (b, d).The force sensing bolts had a load capability of 31,137 N (Fig. 2(c)). This design enabled a more accurate measurement of the average transverse force in the specimen during compaction without any additional calibration of the sensor. The evolution of the average green density was deduced by measuring the compact height. The forces in both the compaction and transverse directions were recorded using computer controlled data acquisition system.

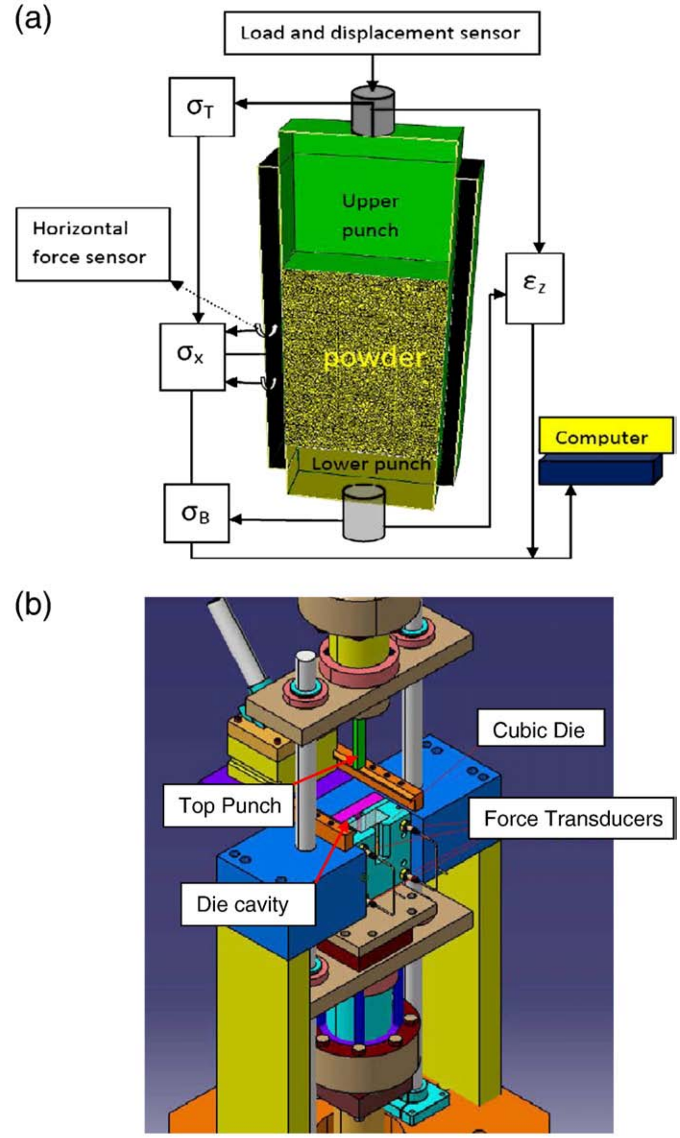

Fig. 1. (a) A schematic of cubic die pressing apparatus, and (b) 3D cubic die with four force transducers.

The green density of compacting cubic specimen was calculated using the following expression:

$$\rho = \frac{M_o}{H \times ab} \tag{1}$$

with

$$H = H_0 - D_{up} - D_{bot}$$

where ρ is the green density of compacting cubic specimen, M_0 is fill mass of metal powder in the cubic die cavity, H_0 is initial fill height of metal powder in the die cavity, and D_{up} and D_{bot} are displacement of the upper and bottom punches respectively, and (ab) is the area of cross section of the cubic specimen. The stress and strain in cubic specimen in the compaction direction can be easily calculated from:

$$\sigma_{up} = \frac{F_{up}}{ab}; \sigma_{bot} = \frac{F_{bot}}{ab} \tag{2}$$

$$\sigma_z = \frac{\sigma_{up} + \sigma_{bot}}{2} \tag{3}$$