Available online at www.sciencedirect.com

ScienceDirect

Procedia CIRP 55 (2016) 188 – 193

www.elsevier.com/locate/procedia

5th CIRP Global Web Conference Research and Innovation for Future Production

Influences of Powder Compaction Constitutive Models on the Finite Element Simulation of Hot Isostatic Pressing

A. M. Abdelhafeez[a,*] , K. E. A. Essa[a]

[a] *Department of Mechanical Engineering, School of Engineering, University of Birmingham, Birmingham B15 2TT, UK*
* Corresponding author. Tel.: +44(0)1214145159; fax: +44(0)1214147484. *E-mail address:* a.m.abdelhafeez@gmail.com; k.e.a.essa@bham.ac.uk

Abstract

Hot isostatic pressing (HIPing) is a promising near net-shape manufacturing technology that can be employed for fabrication of complex parts out of metal powders. Design of tooling/canister that allows net-shape HIPing is still based on expensive experimental try-outs and subsequent iterations to modify the initial canister geometry. An auspicious alternative approach is finite element (FE) simulation. However, the FE results are strongly dependant on the implemented powder metal constitutive model. The current research shed the light on finite element analysis of HIPing process, based on steel 316L powder, using three different constitutive models namely; CAM-Clay, modified Drucker-Prager and modified Drucker-Prager with creep. Comparison with experimentally deformed final geometry and densification history of the HIPed material were carried out. Discrepancies in predicted final geometry dimensions were ranging from 1% to 6.34% compared to experimental trials. Drucker-Prager with creep constitutive model showed the highest accuracy in final geometry predictions with relative error of 1.5~4.8%.

Peer-review under responsibility of the scientific committee of the 5th CIRP Global Web Conference Research and Innovation for Future Production

Keywords: Hot Isostatic pressing; Finite element; Powder compaction; Constitutive model.

1. Introduction

In the HIP process, high temperature (about 70% of the melting point) and high pressure (generally 100-200 MPa) are simultaneously applied to encapsulated powder particles resulting in fully dense components and almost isotropic material properties [1]. The ability to produce near net-shape workpieces (reducing costly machining) has been a major driving force for its commercial advancement. In order to obtain net-shape dimensions, the initial powder canister configuration i.e. tooling needs to be designed accurately which is a major obstacle against further development in the HIPing practice. Finite element simulation was proposed as a promising solution for the tooling design in HIPing.

Ability of finite element simulation to accurately predict the shape of HIPed component shape depends on the adopted powder compaction constitutive model. Mechanical behavior of powders in the normal HIPing cycle includes meshing micromechanical phenomena [2]. Particle re-arrangement initially by particles sliding at low pressure followed by plastic deformation of the particles and void closure at higher pressure levels. Lastly, upon holding the pressure and reaching higher temperature levels, the powder compact creeps which only account for small amount of the total deformation in the powder compact. A good constitutive model of the powder compaction should capture various behaviors of the compaction process to predict the final shape of the HIPed product accurately.

Models that are based on viscoplastic deformation or creep have been extensively used. Svoboda et al. [3] investigated the HIPing of APM2390 stainless steel powder utilizing a modified porous metal plasticity model which consider creep behavior. The results revealed very good agreement in terms of the final deformed shape compared to experimental work. Similar approach was used by Wikman et al. [4] who investigated the HIPing of APM2390 steel powder using a special model that uses either Cam – Clay model or Abouaf model based on a switching critical relative density value. The

Peer-review under responsibility of the scientific committee of the 5th CIRP Global Web Conference Research and Innovation for Future Production
doi:10.1016/j.procir.2016.07.025

results showed good agreement with experiments. Kim and Kim [5] investigated HIP of Tungsten – fiber – reinforced copper powder experimentally and numerically. Two models were compared against experimental data; namely McMeeking model [6,7] and Abouaf model [8,9]; using ABAQUS software. The comparison revealed that McMeeking model which based on micro-mechanical aspects underestimate the density distribution while Abouaf model overestimate the density distribution however both the models gave good agreement in terms of deformed shape prediction. Similar comparison had been done also before by Kim and Jeon [10] when simulating HIPing of steel 316L powder using the same two models implemented in ABAQUS subroutine called Creep and experimental data. Simulation results showed good agreement when using Abuoaf model however McMeeking model underestimated the final deformed shape and the density distribution. Baccino and Moret [11] studied HIP of 316LN steel powder using numerical modeling. Abouaf model was used to describe material viscoplastic behavior and good agreement with experimental data was achieved. Gillia et al. [12] examined simulation of HIPing of 316LN steel powder using Abouaf model to account for viscoplastic behavior. The model showed good agreement with experiments. Liu et al. [13] investigated effects of pressure on HIPing of 316L steel powder material experimentally and numerically using MSC Marc software. Perzyna viscoplastic model [14] was used and good agreement in terms of final shape was achieved. The study revealed that at high pressure of 120 MPa, the densification was the highest and most uniform compared to lower pressures. ElRakayby et al. [15] used Abouaf material model implemented through a subroutine in ABAQUS to simulate the HIPing of nickel-chromium-cobalt alloy powder. Good agreement was achieved with final deformed shape. The same material model was used by Nguyen et al. [16] to simulate Anisotropic shrinkage in HIPing of 316L steel powder using ABAQUS. A very good agreement was obtained between modeling and experiment, see figure 1. Simulation and experimental results have showed that an initially inhomogeneous relative density distribution and a temperature gradient contributes to non-uniform shrinkage of the components after HIP. Therefore, the initial relative density distribution and temperature distribution need to be implemented in the FE model for accurate results.

On the other hands, models that are based on pure plastic collapse are very attractive as they are good in shape prediction and don't need large computation time.

Lee and Kim [17] examined; the Shima–Oyane, the Fleck–Gurson, the Cam–Clay , and the modified Drucker–Prager/Cap model on Al powders cold die compaction using ABAQUS for simulation and they concluded that the Shima–Oyane model besides the proposed modified cap model agree well with experimental data of cold die compaction of AA6061 aluminum powder, see figure 2. Parteder et al. [18] studied hot forming experimentally and numerically using Abaqus/Explicit of molybdenum powder. Two constitutive models were used and compared to the experimental data namely; Gurson – Tvergard [19] model and Gologano model [20]. The latter model is a modification of Gurson model that accounts for pore shape evolution during powder compaction using an internal variable of pore shape aspect ratio. As depicted in figure 3, simulation that used Gurson – Tvergard model agreed well the experimental densification distribution when hot compressing of an already sintered (initial relative density of 95%) tapered disk at temperature of 1000 C.

Another comparison was focused on the Cam-Clay model and the modified Drucker-Prager cap model with an atomized iron-based powder [21]. The experimental data of density and tooling forces during die compaction were examined and it can be concluded that the numerical simulation with the modified Drucker-Prager cap model showed a better performance in the prediction of the density.

It have been shown that models based on pure plastic deformation as the only densification mechanism can predict the shape changes during HIPing with good accuracy [22–25] and this could be justified by the fact that 90% of the full density is gained by initially powder plastic yielding and that these models require few and easy to determine parameters. On the other hand, models that included viscoplasticity/ creep demonstrated better prediction of the densification history. However, these types of model require very large computation time and hard-to-determine parameters.

The current research focus on finite element analysis of HIPing process of steel 316L powder using three different constitutive models namely; CAM-Clay, modified Drucker-Prager and modified Drucker-Prager with creep. Comparison with experimentally deformed final geometry and densification history of the HIPed material were carried out

Nomenclature

b	Burger's vector of this material
d	Material cohesion
k	Boltzmann constant.
p	pressure
q	a measure of deviatoric stress
r	Third invariant of Cauchy stress tensor.
R	Universal gas constant.
t	time
α	A number that define transition between cap and failure surface in Drucker-Prager model
β	Angle of friction of the material
$\dot{\varepsilon}_{cr}$	The equivalent creep strain rate
σ_{eff}	Effective stress

2. Finite element model

2.1. Constitutive models

The CAM-clay plasticity model describes the inelastic behaviour of the granular material by a yield function that depends on the three stress invariants, an associated flow assumption to define the plastic strain rate, and a strain hardening theory that changes the size of the yield surface according to the inelastic volumetric strain. The model is based on the yield surface described in Equations (1-3).