Mechanics of Materials 92 (2016) 248–260

Contents lists available at ScienceDirect

Mechanics of Materials

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

A Binghamian model for the constrained sintering simulation

Benjamin Desplanques*, Sébastien Saunier, François Valdivieso, Christophe Desrayaud

Ecole Nationale Supérieure des Mines de Saint-Etienne 158, Cours Fauriel, 42100 Saint-Etienne, France

ARTICLE INFO

Article history:
Received 24 February 2015
Revised 23 September 2015
Available online 19 October 2015

Keywords:
Ceramic material
Elasto-viscoplastic material
Creep
Finite element
Electron microscopy

ABSTRACT

The empirical "feed back" method is traditionally used in powder metallurgy to optimize the thermal cycle and therefore, to obtain a dense material or a piece with specific dimensions. However, the modeling method has a key role to play in the control of the sintering process and thus in the reduction of the cost of time, energy and raw materials. Usually, a classical model based on a Newtonian viscous law is used to perform the sintering simulation. But, this model showed some limitations when used for the simulation of constrained sintering with difficulties in representing the deviatoric strain. For these reasons, a new model based on a Binghamian law with the introduction of a yield stress in the shear strain part is proposed in this paper. Two test cases of constrained sintering were simulated using the Finite Element Method. The numerical results of the simulation of constrained sintering under thermal gradient of alumina (case 1) was compared to experimental results and allowed to validate our Binghamian model. The simulation of the constrained co-sintering of a multilayer ceramic (case 2) showed the influence of the threshold stress value on the relative density, strain and internal stresses.

© 2015 Elsevier Ltd. All rights reserved.

1. Introduction

Powder metallurgy (PM) is a low cost and an effective technology used in the manufacture of near net shape metallic or ceramic products. Therefore, PM is used for many applications in which the requirements are high such as medical, aeronautical and energy. More specifically, the sintering is a major step of the powder processing route because of the shrinkage phenomena, which induces material densification. Traditionally, the empirical "feed back" method is used to optimize the thermal cycle to obtain a fully dense material or a sample with specific dimensions. This method is quite expensive in terms of delay and raw material costs. Thus computational modeling has a key role to play to increase the understanding and the control of the sintering process. The first sintering modeling was developed at the grain scale with only one diffusion mechanism (Frenkel, 1945; Pines, 1946; Kuczynski, 1949; Herring, 1950; Coble, 1958). Then, models have been improved by coupling several mechanisms and by modifying the geometry of the systems (Riedel et al., 1994; Svoboda and Riedel, 1995; Bouvard and McMeeking, 1996; Pino-Munoz, 2013; Tossoukpe et al., 2013). However, sintering simulation at this scale is not suitable for studying the shrinkage of a macroscopic piece, due to the grain number in a sample of only 1 cm^3. A solution is to consider the material as a continuum (Olevsky, 1998) and to study the evolution of strain defined as the sum of various components (Kim et al., 2003). This approach allows estimating the deformation and the internal stresses in a sample. The problem can be solved analytically for simple geometries with a thermoelastic model (Cai et al., 1997b; Green et al., 1999; Ravi and Green, 2006; Ollagnier et al., 2009). However, Finite Element Analysis (FEA) is an effective tool when considering samples with complex geometries and complex boundary conditions (Zhang and Gasik, 2002; Shabana et al., 2006), or to account

* Corresponding author. Tel.: +33 477426625; fax: +33 47742662566.
E-mail addresses: desplanques@emse.fr (B. Desplanques), saunier@emse.fr (S. Saunier), valdivieso@emse.fr (F. Valdivieso), cdesray@emse.fr (C. Desrayaud).

http://dx.doi.org/10.1016/j.mechmat.2015.10.003
0167-6636/© 2015 Elsevier Ltd. All rights reserved.

for other phenomena (Schoenberg et al., 2006) such as gravity effects or thermal gradient, which induce constrained sintering.

The multilayer sintering is a good example of constrained sintering. Indeed, the differential deformation (shrinkage and thermal expansion) between layers induces stresses, which can create cracks or even debonding in the sample (Bordia and Jagota, 1993; Desplanques et al., 2014). Thus, the knowledge of the internal stress field is paramount in order to avoid these defects or to predict the deformation of a multilayer sample. Usually, the deformation of the material during the thermal cycle is expressed with a classical phenomenological constitutive model based on a Newtonian viscous law (Blaine et al., 2005; Schoenberg et al., 2006; Largiller et al., 2011).

Blaine et al. (2005) tried to simulate, with a Newtonian viscous law, the deflection of a stainless steel 316L beam during the thermal cycle, and compared the experimental and simulation results: the simulated deflection of the beam was excessive. The simulation results were first improved by multiplying the apparent viscosity by a factor 2, and were almost perfect in terms of density and strain values when the deviatoric viscosity value was multiplied by a factor 5. However, there is no physical reason for such a change in the material rheology. This means that the irreversible strain component expression requires to be reformulated, especially the deviatoric part (shear). In this context, the introduction of a yield stress threshold in the shear viscosity could be a solution.

Therefore, a new model based on a Binghamian law with the introduction of a yield stress in the shear part of the irreversible deformation expression was developed in our laboratory. Thus, the purpose of this paper is first to discuss this model accuracy with a comparison experimental/simulation, and second to study the effect of the yield stress value. For this, in the first section of this paper, the Binghamian model is described and justified. It is then validated with the experimental/numerical comparison (with the Finite Element Method) of the test case of a sintering stage under a thermal gradient of an alumina sample. Finally, a parametric study of the flow stress model including the effect of the yield stress threshold value is carried out on the test case of the co-sintering of a thick bilayer material.

2. Constitutive modeling

At the macroscopic scale, the total strain rate of the material during the thermal treatment can be decomposed in four different strain rates (Eq. (1)):

$$\underline{\dot{\varepsilon}} = \underline{\dot{\varepsilon}}^{el} + \underline{\dot{\varepsilon}}^{th} + \underline{\dot{\varepsilon}}^{s} + \underline{\dot{\varepsilon}}^{vp} \tag{1}$$

Where $\underline{\dot{\varepsilon}}^{el}$, $\underline{\dot{\varepsilon}}^{th}$, $\underline{\dot{\varepsilon}}^{s}$, $\underline{\dot{\varepsilon}}^{vp}$ are the elastic, thermal, sintering and viscoplastic strain rates, respectively.

Deformation mechanisms can be broken down into two categories:

- Reversible strains: elastic and thermal components.
- Irreversible: sintering mechanism and viscoplastic flow.

For the Newtonian and the Binghamian law, the reversible deformations are expressed in the same way:

The elastic strain rate $\underline{\dot{\varepsilon}}^{el}$ is described by the Hooke's law (Eq. (2)):

$$\underline{\dot{\varepsilon}}^{el} = \frac{1+\nu}{E}\underline{\dot{\sigma}} - \frac{\nu}{E}tr(\underline{\dot{\sigma}})\underline{I} \tag{2}$$

with E, ν, $\underline{I}$, the Young's modulus, the Poisson's ratio and the unit tensor, respectively.

The thermal strain rate is expressed as (Eq. (3)):

$$\underline{\dot{\varepsilon}}^{th} = \alpha\dot{T}\underline{I} \tag{3}$$

with α and $\dot{T}$ the thermal expansion coefficient and the heating/cooling rate, respectively.

However, the difference between the two models stands in the expression of the irreversible strain evolution, which involves two parts: $\dot{\bar{\varepsilon}}^{vp}$ and $\dot{\bar{\varepsilon}}^{s}$. The first one represents the strain rate due to the densification induced by the reduction of the free energy of the material grains surface. The second one corresponds to the plastic strain rate of the sample at high temperature.

2.1. Newtonian model

The irreversible strain rate ($\dot{\varepsilon}^{ij}$) is traditionally assimilated to a linear viscous strain with a Newtonian law written as follows (Eq. (4)):

$$\dot{\varepsilon}_{ij} = \frac{\sigma'_{ij}}{2G} + \frac{(\sigma_m - \sigma_s)}{3K}\delta_{ij} \tag{4}$$

with σ'_{ij}, σ_m, σ_s, G, K and δ_{ij} the deviatoric stress, the volumic stress (average stress or hydrostatic pressure), the sintering stress, the shear viscosity, the bulk viscosity and the Kronecker symbol, respectively. G (Eq. (5)) and K (Eq. (6)) are expressed with the uniaxial viscosity (η_z) and the viscous Poisson's ratio (υ^{vp}) as follows:

$$G = \frac{\eta_z}{2(1+\upsilon^{vp})} \tag{5}$$

$$K = \frac{\eta_z}{3(1-2\upsilon^{vp})} \tag{6}$$

Two distinct components can be seen in the Eq. (4). The sintering is acting only in the volumic part, whereas the viscoplasticity has an influence in the volumic and the deviatoric part.

2.2. Model discussion

During the sintering of alumina (for example), the time-constant of any material (defined as the ratio: viscosity/Young's modulus) is supposed to be small (Saunier, 2006), implying a short elastic strain stage up to the viscosity threshold. The elastic deformation rate can therefore, under this assumption, be neglected so that the total deformation rate is expressed in the following form (Eq. (7)):

$$\dot{\bar{\varepsilon}}^{tot} = \dot{\bar{\varepsilon}}^{th} + \dot{\bar{\varepsilon}}^{ij} \quad with \quad \dot{\bar{\varepsilon}}^{ij} = \dot{\bar{\varepsilon}}^{vp} + \dot{\bar{\varepsilon}}^{s} \tag{7}$$

Let us now analyze the physical significance of this model. A stacking of several grains is considered, and a load is applied on the top surface. In this case (Fig. 1 a), the granulate boundaries are directed only parallel or perpendicular to the

Download English Version:

https://daneshyari.com/en/article/797495

Download Persian Version:

https://daneshyari.com/article/797495

Daneshyari.com