SINTERING SIMULATION OF STAINLESS STEEL POWDER COMPACTS

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Summary Die compaction of powder metals is a classic discrete component fabrication process that relies on the rearrangement, distortion, and flow of metal particles in a die cavity, where the powders are compressed into a preform that is subsequently sintered. The sintered material has competitive properties, but without the cost associated with additional machining. One of the technological challenges when fabricating parts via powder processing methods is the ability to achieve undistorted, full density parts. For example, density gradients induced from the press motions lead to nonuniform shrinkage during the thermal processing. This research presents a model that predicts the shrinkage during high temperature sintering for powder compacts that have density gradients. The one-dimensional diffusional flow model for pressureless sintering includes an Arrhenius-type viscosity model and allows for the inclusion of grain growth and thermal expansion as functions of temperature.

OVERVIEW OF PAPER

The sintering simulation of metal powder compacts has been a popular topic in powder metallurgy processing for decades. This paper presents a phenomenological model of sintering which has been established to achieve the accurate prediction of sintering shrinkage throughout the sintering cycles. The sintering simulation results are compared and verified using the shrinkage data collected throughout a typical sintering cycle for a stainless steel 316 L cylindrical compact.

SINTERING MODEL DESCRIPTION

Because of the temperature and density variation during sintering, a thermal-visco-elasticity constitutive law has been employed in this model. The strain is comprised of the elastic strain $\boldsymbol{\varepsilon}^e$, thermal strain $\boldsymbol{\varepsilon}^t$, and creep strain $\boldsymbol{\varepsilon}^{cr}$. The portion of elastic strain is assumed to be linear and isotropic. The thermal strain is caused by thermal expansion or shrinkage. The incremental creep strain obeys a linear-viscous law as shown in Riedel (1990) and has the following form,

$$\Delta\boldsymbol{\varepsilon}^{cr} = \left(\frac{\boldsymbol{\sigma}'}{2G} + \frac{tr(\boldsymbol{\sigma}) - 3\sigma_s}{9K}\mathbf{I} \right)\Delta t \tag{1}$$

where $\boldsymbol{\sigma}'$ is the deviatoric stress, G is the shear viscosity modulus, K is the bulk viscosity modulus, $\mathrm{tr}(\boldsymbol{\sigma})$ is the trace of the stress tensor, and σ_s is the sintering stress (the equivalent hydrostatic pressure caused by local capillary stresses in porous structures). It has been shown in Olevsky (1998) that the sintering stress can be written as

$$\sigma_s = \frac{3\omega}{r_0}(1-\theta)^2 \tag{2}$$

where r_0 is assumed to be the mean radius of powder grains and ω is the surface tension energy of the material. The porosity θ is defined as the ratio of the volume of pores V_{pores}, to the total volume V_{total}.

Determining the parameters in equations (1) and (2) requires additional models and assumption. For example, the elastic deformation during sintering is relatively small. Thus an elastic modulus has been calculated (German 1994) and held constant throughout the sintering cycle. For the simulations shown in this work, an average relative density of 82% stainless steel 316L was used to determine the appropriate constant elastic modulus. Observations from initial experiments indicate that below 900°C increases in dimensions due to thermal expansion dominates the response. Therefore, since no sintering densification occurs below that temperature, a linear equation of thermal expansion coefficient was obtained and used to determine the first stage of the sintering shrinkage curve. Olevsky (1998) shows that the viscosity moduli are functions of porosity and apparent viscosity. For this work, the apparent viscosity for 316L type stainless steel powders was calculated with an exponential equation in Brandes (1983). Finally, the sintering driving force is proportional to the reciprocal of grain size, as can be seen in (2). Thus grain growth plays an important role during the sintering of 316L stainless steel. For example, large grain sizes tend to prohibit densification. A widely used empirical grain growth equation (Ashby and Easterling, 1982) for stainless steel 316L has been employed in this research:

$$\frac{dG}{dt} = \frac{A\exp(-Q_G/RT)}{G} \tag{3}$$

where A is a pre-exponent factor, Q_G is the activation energy for grain growth, R is the gas constant, T is the absolute temperature and G is the instantaneous grain size.

SINTERING MODEL VERIFICATION

Figure 1 illustrates a typical temperature cycle and the associated axial shrinkage of a cylindrical stainless steel 316L specimen as measured using a dilatometer and predicted using the finite element (FEM) simulation using the model presented in this paper. Significant features of the model include the description of grain growth by using information from metallographic photos taken of the compacts throughout the sintering cycle. Figure 1 shows two typical metallographs—one at the beginning and another at the end of the sintering cycle. Those images confirm the significant changes in grain size. Analysis of these photos gives material parameters necessary to establish the grain growth equation. For most metals, it is true that no significant shrinkage happens below certain transition temperature; therefore, based on experimental observations, a transition temperature trigger has been set in this model to enforce zero sintering driving force below that temperature. That transition temperature is a function of material and powder size distribution.

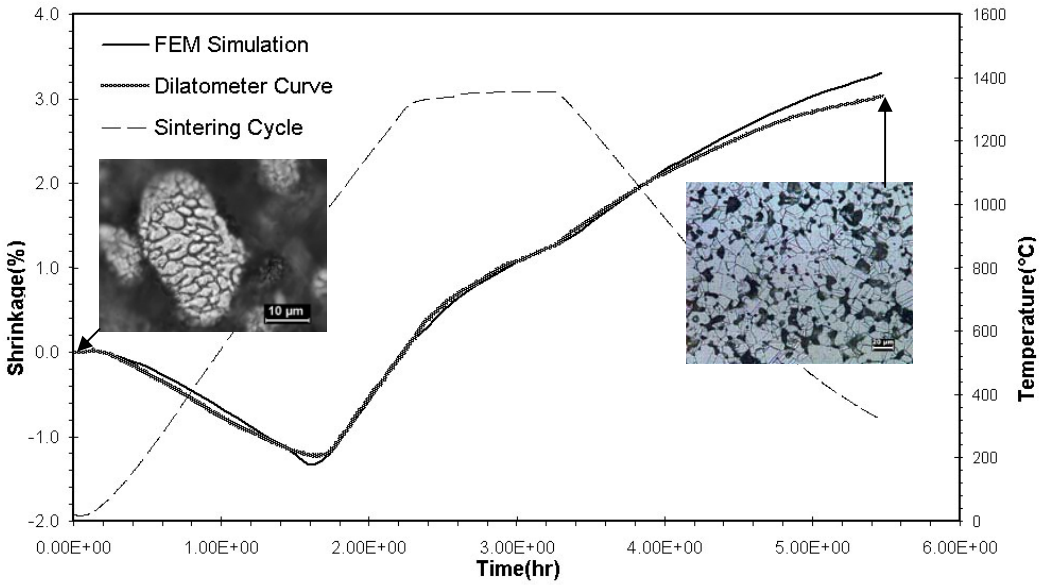

Figure 1. Comparison of the FEM simulation and dilatometry plots on axial shrinkage versus temperature for a stainless steel 316L presintered compact heated at a rate of 10°C/min to 1350°C in hydrogen (powder mean size 52.5µm).

CONCLUSIONS

Density variation in the green compact has been used as the initial condition in the sintering simulation. The distortion is driven by the creep strain which is dependent on the instantaneous grain size. The model presented here incorporates grain size as a function of temperature and knowledge about when particular driving forces dominate, e.g., thermal expansion is critical in the initial stage, whereas grain growth is critical at high temperatures. Axial measurements via a dilatometer throughout the sintering cycle demonstrate that the simulation results accurately describe the shrinkage throughout the cycle, even though the final value of the predicted shrinkage is slightly smaller than the shrinkage recorded experimentally.

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