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Original Research Paper

An investigation of densification behavior of nickel alloy powder during hot isostatic pressing

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ABSTRACT

Hot isostatic pressing process is used to consolidate powders to manufacture a near net shape parts of complex shapes for many applications including aeronautics. The optimal container design is very expensive to get by trial and error manufacturing method of prototypes. Numerical simulations are the solution to save these costs.

The densification behavior of nickel–chromium–cobalt alloy powder was studied by implementing the densification model of Abouaf et al. in the user defined subroutine CREEP of ABAQUS. The rheological functions of Abouaf et al. model were employed for nickel–chromium–cobalt alloy powder to describe the powder behavior under high temperature and pressure.

Experimental data were obtained for nickel–chromium–cobalt alloy powder after applying high pressure and temperature during hot isostatic pressing process. Experimental data were compared with finite element calculations. Good agreements were shown between finite element calculations and experimental data for the sample shape change after hot isostatic pressing.

1. Introduction

Nickel–chromium alloys exhibits excellent mechanical strength, resistance to creep, good corrosion resistance and oxidation resistance at high operating temperatures and under long exposures. Thus, nickel–chromium alloys can be used in aircraft engine parts, industrial gas turbines and industrial furnaces [1–3]. Nickel-base alloys parts can be manufactured by different process types. Nickel-based alloys are known as one of the most difficult to machine super alloys in order to satisfy production and quality requirement [4]. Powder metallurgy processes provide near net shape of products and thus offer important advantages in terms of material yield and number of productions stages [5].

Generally, cold isostatic pressing, hot pressing and hot isostatic pressing (hipping) are being used in powder metallurgy [6]. Hipping can be used for upgrading castings, densifying presintered components and consolidating powders. Also hipping provides better mechanical properties of parts than those produced by different manufacturing processes [6,7].

The driving force for densification and pores closure is reducing the surface area energy associated with pores. Grain boundaries and dislocations areas are zones of high energy relative to the bulk perfect crystal. Eliminating the pores is the first step toward system energy reduction, as pores specific surface energy is greater than that of grain boundary energy. Grain boundary diffusion, lattice diffusion and surface diffusion are different mechanisms of matter transport to fill the pores. In hot isostatic pressing a combination of pressure and temperature are used to densify the porous powders. The applied hipping pressure is always greater than the yield strength of the material at hipping temperature. Plastic flow then occur and creep processes such as Nabarro–Herring creep, Coble creep and dislocation creep start to operate to complete the densification process of porous powder. In metal powder usually the dislocation creep (power law creep) is dominant mechanism in the densification process [7].

Mainly studies regarding hipping of nickel alloys powder are concentrated on studying the mechanical properties and microstructure of hipped parts [8,9]. Recently, Chang et al. [8] studied the effect of hipping temperature on the microstructure and tensile properties of Inconel 718 powder compact. Chang et al. [9] showed the effect of heat treatment on microstructure and mechanical properties of hipped Inconel 718 powder compact. While studying the densification behavior of powder compacts

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Nomenclature

List of symbols

Ω	creep potential
$\dot{\varepsilon}_{ij}$	components of strain rate
$\dot{\varepsilon}_0$	reference strain rate
$\dot{\varepsilon}_{eq}$	equivalent strain rate
σ_{ij}	components of stress
σ_{eq}	equivalent stress
σ_0	reference stress
σ_m	hydrostatic stress
δ_{ij}	Kronecker's delta
n	stress sensitivity index for secondary creep rate
A	temperature dependent constant in power law creep relation
D	relative density

require to apply a densification constitutive model for powder compacts.

The densification model of Abouaf et al. [10] is the most popular one. It was used to describe the densification behavior of many powder alloys. Jeon and Kim [11] reported the densification behavior of 316L stainless steel powder under hip process by using Abouaf et al.'s model [10]. Kim and Yang [6] investigated the densification behavior of titanium alloy powder under hipping, they compared experimental data with finite element results by using the constitutive model of Abouaf et al. [10]. Other micromechanical models of Cocks [12], Castañeda [13], Duva and Crow [14] and McMeeking [15,16] were proposed to predict the densification behavior of powder compacts. These models do not have a good prediction as Abouaf et al.'s [10] model one. Wolff et al. [17] suggested modifications to micromechanical constitutive models of Cocks [12], Castañeda [13], Duva and Crow [14] and McMeeking [15,16], they compared experimental data from the literature for boron and lead powders with theoretical calculations from proposed modifications and also with the constitutive model of Abouaf et al. [10].

Studies for the densification behavior of nickel alloy powders and the effect of hipping conditions on their densification behavior are very rare in the literature.

In the present paper, nickel–chromium–cobalt alloy was hipped at high temperature and pressure. By implementing the constitutive model of Abouaf et al. [10] in a finite element analysis software ABAQUS [18], finite element calculations for shape distortion are compared with experimental data.

2. Experimental

Nickel–chromium–cobalt alloy powder with theoretical density of 8.22 g/cm^3 was used in this work. The chemical composition of the nickel–chromium–cobalt alloy powder used in this work is Ni–15Cr–10Co–15(Al.Mo.Nb.W.Ti). The particle size of nickel–chromium–cobalt alloy powder is −140 mesh. Fig. 1 shows a scanning electron micrograph of the nickel–chromium–cobalt alloy powder.

A full dense sample was produced by hipping nickel alloy powder at 1145 °C under 103 MPa. A container made of 304 stainless steel with 2 mm thickness was used to encapsulate nickel alloy powder with initial relative density of 0.63. The hip cycle started by heating up sample to 1145 °C in 5 h and holding for 4 h at 1145 °C and 103 MPa then finally cooling down to room temperature. Fig. 2 shows the hipping schedule for temperature and pressure.

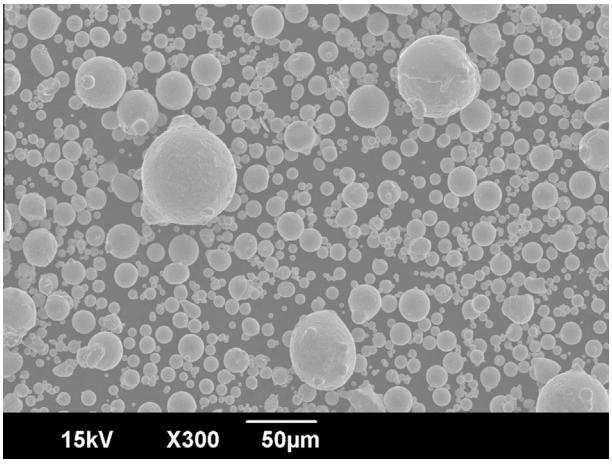

Fig. 1. Scanning electron micrograph of nickel–chromium–cobalt powder.

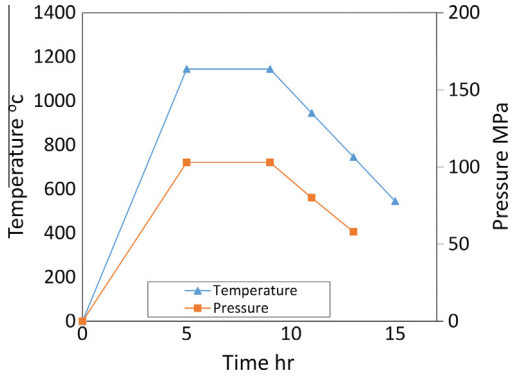

Fig. 2. Hipping schedule for temperature and pressure.

3. Analysis

3.1. Constitutive equations

Considering the creep potential Ω, the creep strain rate can be written [6,10].

$$\dot{\varepsilon}_{ij} = \frac{\partial \Omega}{\partial \sigma_{eq}} \frac{\partial \sigma_{eq}}{\partial \sigma_{ij}} \tag{1}$$

$$\Omega = \frac{\dot{\varepsilon}_0 \sigma_0}{n+1} \left(\frac{\sigma_{eq}}{\sigma_0} \right)^{n+1} = \frac{A}{n+1} \sigma_{eq}^{n+1} \tag{2}$$

Since the creep deformation of a porous materials is affected by both deviatoric and hydrostatic components of stress state, thus the constitutive relation for the equivalent stress of a porous body can be written as [6]

$$\sigma_{eq}^2 = fI_1^2 + 3cJ_2 \tag{3}$$

where $I_1 = \sigma_{kk}$, $J_2 = \frac{1}{2} S_{ij} S_{ij}$ and $S_{ij} = \sigma_{ij} - \frac{\sigma_{kk}}{3}$.