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Anisotropic shrinkage during hip of encapsulated powder

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ABSTRACT

In P/M HIP, the capsule volume is reduced to 25–30% depending on the initial relative density of the powder after pre-consolidation. Under isostatic pressing conditions the capsule should have a uniform shrinkage, but in practice this is often not the case. This phenomenon is driven through many factors including, but not limited to, the temperature gradient, inhomogeneity of powder inside the capsule and capsule thickness of which the influence will be further examined in this study. Experimental Image Analysis is used to investigate the initial powder distribution which is subsequently implemented in a FEM model as initial condition to simulate the shape changes of hot isostatically pressed products. To analyze the effect of a temperature gradient in the capsule, the temperature is assumed to be inhomogeneously distributed on the surfaces of the capsules. Different temperature fields are then applied to a FEM model. Additionally, capsule thickness will be varied to study its influence on the final shape. Finally the simulation results are compared with experimental findings. Based on that the conclusion about the influence of inhomogeneous powder distributions, temperature gradients and capsule thickness on the final shape of powder HIP-ed products can be given.

1. Introduction

Powder Hot Isostatic Pressing (HIP) is a modern manufacturing process for the production of complex and highly specified components made from a wide range of metals and/or ceramics. A wide range of component types can be manufactured by using HIP as summarized by Atkinson and Davies (2000). Its capabilities include large and massive near-net-shape metal components (Samarov et al., 2005), such as parts applied in the oil and gas industry weighing up to 30 tones (Mashl et al., 1999), or net-shape impellers up to one meter in diameter reported by Masi et al. (2014). Alternatively it can be used to make rods and profiles to produce small PM High Speed Steel cutting tools (Eisen, 1997), such as taps or drills (Bose and Eisen, 2003), which can weigh less than 100 g, or even very tiny parts such as dental brackets overviewed by Conway and Rizzo (1998). Major applications of HIP are the production of super alloy parts for aeronautical engines (Garibov and Grits, 2014), off-shore industry; medical industry as described in detail by Boris et al. (1996). In the studies of Widmer (1993) and Jakobsson et al. (2014), the advantages of HIP material compared with sintered and casted materials were shown. These results line up well with that of Hebeisen (2005) and Conway et al. (1996). The use of HIP has increased thanks to its advantages compared to other conventional manufacturing methods such as forging, casting etc. as described by Hellman (1988) and EPMA (2011). The principle of the powder HIP process can be described as: a steel capsule, with a thickness typically ranging from 2 to 4 mm, is filled with powder. Tapping and vibration are usually used in the pre-consolidation process in order to increase the initial relative density of the powder compact; after which the capsule is out-gassed, sealed, and placed into the HIP device where it is submitted to an inert gas pressure of about 100 MPa and temperatures higher than 70% of the absolute melting temperature of the metal powder for several hours. After HIP 100% material density is obtained. Near-net-shape Hot Isostatic Pressing (HIP) simulation has been used for a long time in order to reduce development costs and design time. Many different constitutive densification models and simulation tools have been reported, which relate to two different approaches to simulate the densification process of porous powder during HIP: microscopic and macroscopic approach as summarized by Jinka and Lewis (1994) and Nohara et al. (1988). The first approach, microscopic, deals with the assembly of individual particles. Various mechanisms of densification such as creep, diffusion, and grain

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☆*Innovative aspects*: The anisotropic shrinkage of HIP-ed components due to the influence of the temperature gradient, the initial relative density (RD) gradient and capsule's thickness on the final shape of HIP products is shown and proven in this paper. The results are of particular importance for companies producing big and complex (near) net shape components by powder-HIP.

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Nomenclature

$\dot{\epsilon}_{ij}$	Creep plastic strain rate
σ_{ij}	Cauchy stress tensor
A	Dorn's constant
N	Creep exponent
σ_{kk}	Hydrostatic stress
q	Von Mises stress
σ_{eq}	Eq. stress for the porous material
f	Porosity co-efficient
c	Porosity co-efficient
S_{ij}	Deviatoric stress tensor
T	Temperature
RD	Relative Density of the powder
RD_{o}	Initial relative density of the powder
δ_{ij}	Kronecker Delta

growth etc. described by Swinkels et al. (1983) and Wilkinson and Ashby (1985) are analyzed in terms of a single particle and its contact with surrounding particles. The total rate of densification is obtained by combining the rate equations of the individual mechanisms. In contrast to the microscopic approach, the macroscopic approach assumes that the powder compact behaves as a continuum body containing porosity as described by Abouaf and Chenot (1986) and Cassenti (1982). Therefore, the general plasticity theory for solids is modified for a porous continuum and a constitutive equation is constructed that relates the strain increment to the stresses overviewed by Shima and Oyane (1976). The earliest development of a macroscopic model was the work of Green (1972) and Kuhn and Downey (1971). Most of the publications show that good agreement between numerical simulation and experiments can be obtained under certain conditions. So far no comparison of the results of the different FEM simulations was given as reported by Atkinson and Davies (2000) and an international cooperation mentioned in Bouvard et al. (1996). In theory, hot isostatically pressed components should have isotropic shrinkage under isostatic pressure load but in practice this is often not the case. Non-uniform shrinkage of components and even high distortion (Fig. 1) have been observed, which is not predictable with the current FEM simulation method because the models assume that the powder distribution inside a capsule prior to HIP is homogeneous and temperature is usually assumed to be evenly distributed inside the HIP vessel.

Anisotropic shrinkage has been observed and verified in the sintering process overviewed by German (2005). Local variations in powder density (inhomogeneous powder distribution) cause distortion of pressed sintered parts as described in the work of Tkare and Braginsky (2002). The same problem was observed in the work of Zavaliangos and Bouvard (2002). For cases in which the powder body was not homogeneous created artificially by Tkare and Braginsky (2002), the bilayer powder compact which has different initial relative density was bent after sintering toward the lower relative density. In the HIP process, pressure and temperature are combined to achieve a full density material at a lower temperature than would be required for sintering alone. Therefore the influence of an inhomogeneous powder distribution on the final shape of hot isostatically pressed components can differ from its influence on pressureless sintered components. The simulation results of previous studies from Van Nguyen et al. (2010) showed that inhomogeneous powder distribution caused bending of the hollow tubes which is similar to the case of sintering. The simulation and experimental results of later studies (Van Nguyen et al., 2011, 2014) confirmed that an initial inhomogeneous powder distribution after pre-consolidation results in anisotropic shrinkage or even high distortion (bending). The hot isostatically pressed tubes and long cylinder capsules bent toward the side which has lower relative density (RD). Furthermore, not only the initial powder distribution, but also capsule shape (Abouaf et al., 1986), size (Samarov et al., 2014) and thickness (Xu and McMeeking, 1992) and the process parameters pressure and temperature (Li and Ashby, 1987) will contribute to the final shape of hot isostatically pressed components which are quantitatively mentioned by Trasorras et al. (1994) and Li and Easterling (1992). So far, the temperature in the HIP vessel is assumed to be homogeneous and the temperature applied to a FEM model as initial condition is usually assumed to be homogeneous around the surfaces of the capsule. But it may not be true in practical production because more than one capsule is often hot isostatically pressed in the same cycle in order to increase the productivity and reduce the cost of the HIP process. In this case, the distance from heating elements to the capsule surface is no longer the same for all capsules. The surface which is closer to the heating elements will be heated quicker. This situation may cause a temperature gradient on the surfaces of the capsule. Therefore, the motivation of this study is to further investigate the influence of an inhomogeneous powder distribution on the final shape of HIP-ed capsules. Particularly, a density gradient in the horizontal plane and inclined gradients will be discussed as they have a high influence on the final shape of a long cylindrical component. Furthermore, the influence of the temperature gradient on the capsule surface and the influence of capsule thickness will be studied.

Fig. 1. Bended tubes after HIP (courtesy from Köppern Entwicklungs-GmbH).

In this work, the pre-consolidation process, characterized by vibration frequency, vibration time, number of refilling cycles,