Journal of Materials Processing Technology 166 (2005) 135–143

Journal of Materials Processing Technology

www.elsevier.com/locate/jmatprotec

On the mechanics of cold die compaction for powder metallurgy

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Received 20 July 2004; received in revised form 20 July 2004; accepted 16 August 2004

Abstract

The main object of this paper is to present a theoretical model for the cold die compaction of powder materials based on the axisymmetric solution of large deformation. The model produces an expression relating the green density of the compact to the applied pressure. The analysis takes into account the internal (restricted movements) coefficient of friction between the particles and the container-compacted powder interface friction. Also, a modified analytical expression for the yield compression stress based on the internal coefficient of friction and the work-hardening of the powder was introduced in the analysis. Experiments were performed on cold die compaction of powder of different particles, having sizes between 45 and 150 μm. Comparison between experimental and theoretical results demonstrated remarkable agreement for all the tested conditions. In addition, and for the purpose of verification of the present theory, other published experimental values were also compared and found to be in very good correlation with the predicted results. Other relevant parameters will also be discussed.

Keywords: Powder metallurgy; Green density; Compaction; Axisymmetric analysis; Powder particles; Internal friction; Compaction density

1. Introduction

Powder metallurgy (p/m in its abbreviated form) in many industries has not received the praise of which it is worthy, but for many years now, has been an established process for the manufacture of precision quality engineering components. Generally, p/m technique consists of the production of a controlled blend of metal powders, pressing the mixture in suitable dies, and subsequent heating (sintering) the compacted powder in a controlled atmosphere and temperature to obtain the required density and strength.

The Egyptian iron implements, the Delhi column in India and articles made by the Incas, many centuries ago, clearly demonstrate that pressing of powders into desired shapes is not really new. During the 1920s many parts were made and used commercially, such as tungsten carbides, bronze bushes for bearings, and tungsten filaments for bulbs and others. Since then the p/m industries have expanded more rapidly due to the recognition of the distinct advantages in terms of materials utilization, ease of components manufacture and cost/energy saving and other factors. Despite these outstanding merits, the p/m process does have a few limitations, such as, part design and geometry, initial tooling costs, raw material, i.e. powder, costs are higher than conventional solid bulk, and special care must be taken against corrosion [1–8].

Cold die compaction of powder metallurgy is generally simple to put into practice, however it is extremely difficult to analyze the process theoretically. This may be due to the complex variations of the parameters involved during the compaction process. Nevertheless, much has been published and a great deal of effort has been directed to the development of empirical and theoretical compaction equations to describe the green density-applied pressure relationship. Needless to say, the green density of compact has direct influence on the densification of the product and hence the strength. But it seems that all the previously developed expressions depend totally or partially on experimental factors, due to the unknown parameters. Studies were performed involving the simulation of powder compaction using the FEM and based on the elastic–plastic of large displacement, where the powder is considered as a continuum which exhibits plastic deformation under applied external pressure [9–17].

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0924-0136/$ – see front matter
doi:10.1016/j.jmatprotec.2004.08.009

Nomenclature

F	applied external force
H	distance of the element from the top surface compact-instantaneous
H_f	final height of packed powder
H_o	original or tap height of packed powder
L	height of the element under consideration
n	work-hardening exponent
p_a	applied external pressure of the punch
r	current radius of the element
r_f	die radius of container
Z	current height of the element

Greek letters

β	density factor
$\bar{\varepsilon}$	effective strain
μ	container-compacted powder interface
μ_i	internal coefficient of friction-restricted movements coefficient
ρ, ρ_g, ρ_p, ρ_t	powder density at any stage, green, tap, and theoretical densities
$\bar{\sigma}$	effective stress in compression of the bulk material
σ_r	radial stress
σ_{yc}	yield compressive stress
σ_z	axial compressive stress
σ_0	normal yield stress

The main purpose of the present work is to present a theoretical model based on the modified plasticity equations which do not require empirical constants that need to be determined from the powder compaction. However, certain factors such as coefficients of friction are used from previously published work.

2. Theoretical considerations

Generally it is difficult to formulate the mechanism and yielding behavior of the pore bearing materials particularly in cold die compaction process. This may be due to many factors such as fracture, fragmentation, rearrangements, and different deformation behavior of particles. Many published theories have endeavored to express the green density as a function of process parameters. However there has always been difficulty in expressing it fully without relying on experimental values. The present theory relies on the minimum possible experimental parameters and can be used for metallic and other nonmetallic powders with certain properties and geometrical adjustments. Also, the presented equations can be used for isostatic compaction.

To establish the process parameters, it is assumed that the powder is housed freely in a container and external pressures are applied simultaneously from both ends, as shown in Fig. 1. As the process of compaction proceeds the powder particles will rearrange to form compacted media. The equilibrium of a small element at a distance z from the upper or lower surface using the cylindrical coordinate (r, θ and z) will be considered [18,19]. Hence by considering the equilibrium forces in the z-axis, the following equilibrium equation can be derived in a general form as shown in Fig. 1A,

$$\frac{\partial \sigma_{zz}}{\partial z} + \frac{1}{r}\frac{\partial \sigma_{\theta z}}{\partial \theta} + \frac{\partial \sigma_{rz}}{\partial r} + \frac{\sigma_{rz}}{r} = 0 \quad (1)$$

Here axial symmetry will be assumed where the cylinder will maintain its form and by excluding torsion, $\sigma_{\theta z} = \sigma_{r\theta}$ [18], then Eq. (1) reduces to the following:

$$\frac{\partial \sigma_{zz}}{\partial z} + \frac{\partial \sigma_{rz}}{\partial r} + \frac{\sigma_{rz}}{r} = 0 \quad (2)$$

In the present work it is assumed that the shear stress is constant (this will be discussed later), and taking into account the geometry of the element, Fig. 1B, then the reduced equilibrium equation in the z direction results in

$$\pi r^2(\sigma_z + \mathrm{d}\sigma_z) - \pi r^2 \sigma_z + 2\pi \mu r \sigma_r \,\mathrm{d}z = 0 \quad (3)$$

where σ_z is the axial stress at distance z from the surface, σ_r the radial stress and μ the coefficient of friction between the container wall and the compact powder. However, both the radial stress and the coefficient of friction are assumed to be constant for the present analysis. Needless to say the variation of these parameters will be discussed later. A simplification of Eq. (3) yields

$$\mathrm{d}\sigma_z = -\frac{2\mu\sigma_r \,\mathrm{d}z}{r} \quad (4)$$

Since there is no change in the diameter of the compacted powder and using the well known expressions of Levy–Mises for the plastic flow of metal, it may be seen that the radial strain ($\mathrm{d}\varepsilon_r$) = hoop strain ($\mathrm{d}\varepsilon_\theta$). From which it follows that the state of stresses $\sigma_r = \sigma_\theta$, and using the von Mises criterion for the effective stress ($\bar{\sigma}$) of the bulk material, the following relation is obtained:

$$\sigma_r = \sigma_z + \bar{\sigma} \quad (5)$$

Substituting Eq. (5) into Eq. (4) reduces to

$$\frac{\mathrm{d}\sigma_z}{\sigma_z + \bar{\sigma}} = -\frac{2\mu}{r}\,\mathrm{d}z \quad (6)$$

The solution of Eq. (6) for the case in which sticking does not occur (only sliding) and introducing the boundary condition results in

$$Z = \tfrac{1}{2}H, \quad \text{when} \quad \sigma_z = p_a \quad (7)$$

where p_a is the compact external pressure applied by the punch from both ends simultaneously, and H the height of the compact (varies between the final height (H_f) and the original