



Derivation, testing and application of a practical compaction equation for cold die-compacted metal powders



Ludovit Parilak^a, Eva Dudrova^{b,*}, Robert Bidulsky^c, Margita Kabatova^b

^a Zeleziarne Podbrezova, a. s., ZP Research and Development Centre, Ltd., Kolkaren 35, 976 81 Podbrezova, Slovakia

^b Institute of Materials Research of Slovak Academy of Sciences, Watsonova 47, 040 01, Kosice, Slovakia

^c Technical University Kosice, Metallurgical Faculty, Department of Plastic Deformation and Simulation of Processes, Vysokoskolska 4, 040 01, Kosice, Slovakia

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ABSTRACT

Derivation, validity testing and usage in practice of the powder compaction Eq. $P = P_0 \exp(-Kp^n)$ is presented. P is the porosity at pressure p , P_0 the porosity at $p = 0$, parameters K and n represent the synergistically acting compaction parameters. The relationship between K and n , $\ln(K) = 1.2952 - 7.3349.n$ or $K = 3.6517 \cdot \exp(-7.3349.n)$, was found on the basis of cold die-compaction testing of 205 various metal powder mixes. This analysis enables calculation of additional criteria characterizing the compressibility of various metal powders. To facilitate the analysis, a graphical processing of the relationship between the relative porosity P/P_0 of the compact, p and n is also presented. In practice, its use could provide a rapid assessment of the compressibility behaviour of various metal powders.

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1. Introduction

Each type of metal powder represents a statistical set of autonomous particles with a characteristic shape, size distribution, and microstructure. All of these determine the mechanical properties of the powder mix, such as the specific surface, the apparent and tap densities, the flow rate, but above all, the deformation behaviour of a metal powder in a shaping process. Powder metallurgy (PM) uses a lot of different shaping techniques, ranging from cold die-compaction to pressureless processes, such as loose sintering and slip casting [1]. Die-compaction, where densification and shaping occur simultaneously, is one of the most important steps in the mass production of PM structural parts.

The terms “compactibility” and “compressibility” are used to classify various powders according to their compaction ability. Compactibility is defined as the minimum pressure needed to produce the required green strength of the compact, whilst compressibility indicates the extent to which the density of the compact is increased by a given pressure. Consequently, compressibility is quantified by the value of the compacting pressure required to achieve the desired green density. In practice, powder compressibility is an important factor in the design of the pressing tool, which will ensure a defined shape and adequate strength of the green compact [2]. Therefore, the study of powder compaction processes has been of great interest since the start of industrial production of PM parts, and this persists to the present.

Many publications, from the thirties of last century until now, e.g. [2–41], have provided extensive knowledge about the behaviour of metal powder during compaction, taking into account various aspects. A number of attempts to describe compaction processes, such as simple fitting experimental pressure–density curves with their mathematical expression, but also physical models quantifying the deformation behaviour of individual particles or solid body with spherical pores, when exposed to external pressure, have been published from the middle of last century, e.g. [8,12–14,16,17,20,21,24,25].

Current modern approaches are based mostly on computer modelling. Gethin [34] presented an overview the use of modelling softwares, and as reported by Federzoni et al. [35] the Cam-Clay and Drucker–Prager–Cap models are the most frequently used. Martin et al. [36] and Riera et al. [37] have used a Discrete Element Method for the study of powder densification; Helle et al. [38] have processed a micromechanical model, assuming initial random packing of spherical particles, Fleck et al. [39,40] published an analytical model of plastic and viscoplastic compaction of powders, Cocks [41] demonstrated a model based on the theory of plasticity. Secondi [31] proposed a model applying the relationship between the applied stress and the strain acting in a pressed compact. Modelling approaches are of great importance for the theoretical understanding of powder behaviour under the influence of external pressure, however, they are mostly highly complicated and often use simplified assumptions and their direct use in practice is rather difficult.

As the properties of sintered parts depend strongly on green density determined by powder behaviour during compaction, which is reflected in the pressure–density relationship, the majority of fundamental

* Corresponding author.

E-mail address: edudrova@saske.sk (E. Dudrova).

studies have focused on interpretation and analytical expression of the experimental dependence of density or porosity on compacting pressure. Such an approach was prompted by the practical need to find an adequate and generally valid compaction equation enabling characterization of the compressibility of different powder mixes. The starting point was a general impression that the compressibility curves of various real metal powders have a similar “course”, as is the fast onset of densification rate at the beginning of compaction and its continual decrease with increasing pressure.

This led to a commonly accepted view, e.g. [6,12,13,15,16,19–25], that the change from powder to compact, when exposed to pressure during cold die-compaction, is the result of overlaying several mechanisms. These, namely the particles rearrangement (by rotations and translations), elastic and plastic deformations developed through the particle contacts, and in addition to that associated with the strain hardening of the metal matrix, are related to a certain value range of applied pressure. Numerous compaction equations have been reported, e.g. [3,4,5,7,9,10–13,17,18,27–33], most of which were obtained by simple fitting of experimental pressure-density relationships for metal powders, ceramics, pharmaceuticals, chemical compounds, mostly with a good correlation. Some of these, particularly those designed for metal powders, are listed in Table 1. Many other compaction equations, especially for pharmaceutical powders, have been reported and their overview has been presented e.g. by Çomoglu [42].

Walker, probably as the first in 1923 [3], and later Balshin in 1938 and 1949 [5,10] have derived Eqs. (1), (2), (4) expressing that the rate of change of a relative volume of pressed compact with an increase of pressure is proportional to the applied compacting pressure. In Balshin's Eq. (4) the constant a_4 signifies the “pressing modulus” and corresponds to Young's modulus. Shapiro and Kolthoff [7] in 1947 and independently Konopicky in 1948 [9] proposed the Eq. (3), later known as “KSK equation”, or “KSK compaction model”, where the constant a_3 is functionally linked with the ability of particle material to deform plastically. Thus the constant a_3 can be quantified through the yield strength σ_y of the particle material, as stated by Torre [8], Bockstiegel [16] and Secondi [31]. The KSK Eq. (3) can give the correct expression of powder behaviour for $p = 0$ and $p \rightarrow \infty$. Admittedly, the KSK expression became a starting point in a number of other compaction equations (such as e.g. those in Table 1), however, using various mathematical processing of

the pressure-porosity or density relationships. Kawakita and Tsutsumi [17] reported that the change of porosity P related to the pressure p could generally be expressed by two equation types, Eqs. (15) and (16), where x, y, z are constants:

$$-\frac{dP}{dp} = k \cdot P^x \quad (15)$$

$$-\frac{dP}{dp} = k \cdot \frac{(P-1)^y}{p^z} \quad (16)$$

The majority of compaction equations in Table 1 are two-parametric, with almost identically defined physical nature of the parameters a_j and b_j (for $j = 1-14$). The parameters a_j are related to the densification by plastic deformation, while the parameters b_j reflect the compaction behaviour at low pressures and are mainly related to the geometry of particles.

The predominantly two-parametric type of the existing compaction equations indicates that the densification is a continuous process controlled by the superposition of deformation mechanisms associated with continuous changes occurring in geometry and plasticity of metal particles at increasing compacting pressure. This physical principle of densification behaviour during cold die-compaction is the same for various metal powders, however, with different efficiencies of acting mechanisms, which is the result of a specific combination of geometry and plasticity of particles and this is different for different powders. Although the authors [3–5,7,9–13,17,18,22,27,29–31], mostly interpreted the physical background of the constants a_j and b_j , most often for a defined set of powders, and underlined an importance their synergetic action during compaction, the functional relationship between this pair of parameters has not yet been found.

To obtain a generally valid compaction equation, it is necessary to define the relationship between the parameters associated with simultaneously operating densification mechanisms, and with their different participation measures, depending on the instantaneous combination of geometry and plasticity of compacted powder particles. When the diversity of the combinations of geometry and plasticity of particles in different powders is considered, the functional relationship between the synergistically acting pair of parameters can be obtained by analysing

Table 1
The most frequently applied compaction equations for metal powders; $P = f(p)$.

Author, [ref.]	Compaction equation	No.
Walker (1923) [3]	$\log(p) = -L + \frac{V_0'}{V_0} + a_1 = -a_1 \cdot \frac{1}{D} + b_1; P = \frac{a_1}{\log(p) - b_1} + 1$ <i>V</i> - volume of compact, <i>V</i> ₀ ' - volume of powder, <i>L</i> - compression modulus	(1)
Balshin (1938) [5]	$\log(p) = -a_2 \cdot \frac{1}{D} + b_2; P = \frac{a_2}{\log(p) - b_2} + 1$	(2)
Shapiro, Kolthoff (1947) [7] Konopicky, (1948) [9]	$P = P_0 \cdot \exp(-a_3 \cdot p); -\frac{dP}{dp} = k_1 \cdot P$	(3)
Balshin (1949) [10]	$\ln(p) = \frac{a_4}{(1-p)} + b_4; P = 1 - \frac{a_4}{b_4 - \ln(p)}; -\frac{dP}{dp} = k_2 \cdot P$	(4)
Athy (1949) [4]	$P = P_0 \cdot \exp(-b \cdot x); P = P_0 \cdot \exp(-a_5 \cdot p); -\frac{dP}{dp} = k_3 \cdot P; (proposed for clays);$ <i>P</i> ₀ - average porosity of surface clays, <i>P</i> - porosity in depth <i>x</i> ; <i>b</i> - constant	(5)
Kawakita (1956) [17]	$C = \frac{a_6 \cdot b_6 \cdot p}{1 + b_6 \cdot p}; C = \frac{V_0 - V}{V_0}; -\frac{dP}{dp} = k_4 \cdot P^2$ <i>C</i> - relative reduction of volume by compression; <i>V</i> ₀ - initial apparent volume	(6)
Jones (1960) [11]	$\ln(\rho) = m \cdot \ln(p) + b; P = 1 - \left(\frac{a_7}{b_7 - \ln(p)}\right)^{1/2}; -\frac{dP}{dp} = k_5 \cdot (1-P)^2 \cdot p^{-1}$ ρ - bulk density; <i>m, b</i> - constants	(7)
Heckel (1961) [12,13]	$\ln\left(\frac{1}{D}\right) = a_8 \cdot p + \ln\left(\frac{1}{D_0}\right) + b_8; P_0$ - corresponds to rel. Density <i>D</i> ₀ at $p = 0$	(8)
Kawakita, Lüdde (1970) [18]	$\frac{1-p}{P_0-p} = p^{-1} \cdot \frac{1}{a_9 \cdot b_9} + b_9; P_0$ - initial porosity; <i>P</i> - corresponds to tap density	(9)
Shapiro (1993) [27]	$P = P_0 \cdot \exp(-a_{10} \cdot p - b_{10} \cdot \sqrt{p}); P_0$ - porosity at zero external pressure	(10)
Parilak, et al. (1994) [28,32]	$P = P_0 \cdot \exp(-b_{11} \cdot p^{a_{11}}); \ln\left[\ln\left(\frac{P}{P_0}\right)\right] = \ln(b_{11}) + a_{11} \cdot \ln(p);$ with $\ln(b_{11}) = k_6 - k_7 \cdot a_{11};$	(11)
Ge (1995) [26]	$\log\left[\ln\left(\frac{1}{D}\right)\right] = a_{12} \cdot \log(p) + b_{12}$	(12)
Panelli, Ambrozio Filho (1998) [29,30]	$\ln\left(\frac{P}{P_0}\right) = a_{13} \cdot \sqrt{p}; \frac{dP}{dp} = k_8 \cdot \frac{P}{p^m}; m = 0.5$	(13)
Secondi (2002) [31]	$\ln\left(\frac{P_0 - D_0}{D_0 - D}\right) = a_{14} \cdot \sigma^{n_1}; \ln\left(\frac{P - P_0}{P_0 - P}\right) = a_{14} \cdot p^{b_{14}}; \sigma$ - applied stress, <i>D</i> ₀ - initial relative density, <i>D</i> _s - maximum relative density to be reached by activated mechanisms, <i>D</i> - relative density at applied stress, <i>n</i> ₁ - work hardening coefficient	(14)

Note: a_1 - a_{14} , b_1 - b_{14} , and k_1 - k_8 are constants.

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