Quantificação de Incertezas na Compactação de Pó de Ligas Metálicas

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Resumo: No contexto da incerteza nos dados de entrada inerentes ao processo de compactação de pó metálico, torna-se relevante mensurar o impacto desta variação nos dados de saída. Assim, este artigo objetiva quantificar as incertezas no processo de compactação de pós de ligas metálicas. A simulação de Monte Carlo é aplicada para propagar as incertezas selecionadas. Diante dos resultados, verifica-se não mais um valor único para a porosidade da peça compactada, mas sim uma faixa de possíveis valores. Portanto, dependendo da dispersão dos valores, a porosidade pode não ser aceitável para introduzir a peça em processos subsequentes, o que pode acarretar em perda de tempo por retrabalho.

Palavras-chave: Quantificação de incertezas; Compactação de pó; Ligas metálicas.

Uncertainty Quantification in Powder Compaction of Metal Alloys

Abstract: In the context of uncertainty in the input data inherent to metal powder compaction process, it is relevant to measure the impact of this variation on the output data. Thus, this paper aims to quantify the uncertainties in the compaction process of metal alloys powders. Monte Carlo simulation is applied to propagate selected uncertainties. In view of the results, there is not a unique value for the porosity of the compacted part, but a range of possible values. Therefore, depending on the dispersion of values, the porosity may not be acceptable to introduce the part into subsequent processes, which may result in lost time due to rework.

Keywords: Uncertainty quantification; Powder compaction; Metal alloys.

Introduction

According to the European Powder Metallurgy Association (EPMA), in Europe, around 248 thousand tones represent a €11 billion powder production in 2016 and a still-growing area [1]. This important sector encompasses the compaction process, which main objective is to provide the required mechanical strength to the part. Generally, at the end of the process, the part has final or almost final geometrical characteristics. Additionally, the contact between powder particles is intended to provide the adequate density to prepare for the next stages. There are two types of pressure-based forming operations: cold and hot compaction methods. In cold pressing: (a) the axial pressing is described by punches that axially load the powder mass; (b) in isostatic pressing, the powder is sealed in an elastic mold and a hydrostatic pressure originates from a liquid. In hot pressing, pressure is simultaneously applied with a temperature higher than the room temperature. In terms of quantification, if the agent is a punch in a die compaction, the compaction pressure is the ratio between the force and the face area of compact while the force from an isostatic compression corresponds simply to the hydraulic medium pressure [2].

Metal powder densification in a rigid die is the initial stage of the compaction. This tooling has a cavity in which the powder is put under high pressure by one or two vertically moving punch(es) from top and/or from bottom. This condition implies the squeezing of the particles, which may imply in cold welding of their surfaces. After compaction, the compacted mass ejection is performed. Enough strength is required from the green preform to be stable to posterior stages [3].

As the densification increases, the particles are plastically deformed and increasingly strengthened by deformation (leveling up their yield strength). In the microstructural context, larger powder particles establishes physical connections around smaller ones, which increase their contact areas, leading to decreasing shear stresses inside the particles. The densification ceases if the rising yield strength reaches a level high enough to overcome the effect of the decreasing shearing stresses. To increase the compacting efficiency, a rearrangement of particles is usually performed, in addition to elastic-plastically deformation, work hardening, and fragmentation [4].

Let the mass of the material be m, and the bulk and theoretical volumes be, respectively, V_{bu}, and V_{th}. Equations 1, and 2 give the bulk and theoretical densities, respectively, ρ_{bu}, and ρ_{th}:

$$\rho_{bu} = \frac{m}{V_{bu}}, \tag{1}$$

$$\rho_{th} = \frac{m}{V_{th}}. \tag{2}$$

Then, in terms of percentage, porosity, ϕ, is expressed by Equation 3:

$$\phi(\%) = \left(1 - \frac{\rho_{bu}}{\rho_{th}}\right)100, \tag{3}$$

Objective

The main objective of this work is to quantify the uncertainties in the prediction of porosity in compaction process of metal alloys powders when random uncertain parameters are the following: (a) powder mass, (b) cylinder diameter, and (c) cylinder height.

Material and Methods

As per Figure 1, the metal powder is simulated to be compacted into the form of flat cylinders, with the uncertain input data presented in Table 1. The only deterministic input data is the theoretical density ($\rho_{th} = 7.85\,x\,10^{-3}\ g/mm^3$). The uncertain parameters are modeled as normally distributed, being propagated using Monte Carlo simulation. A sample of one hundred thousand realizations is generated for each uncertain input variable in order to obtain the same number of realizations for porosity. This enables the knowledge of the behavior of porosity, for example, aiming at establishing an acceptance criterion for the flat cylinders.

Table 1. Uncertain input data for the compacted cylinder. Source: own authorship (2021).

Uncertain parameters	Mean	Standard deviation
Cylinder height *H* (mm)	2.000	0.004
Cylinder diameter *D* (mm)	8.000	0.016
Powder mass *m* (g)	0.789	1.578 x 10^{-3}

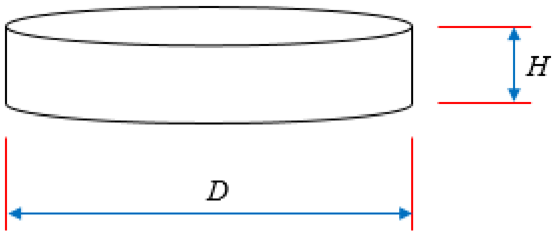

Figure 1. Uncertain geometrical parameters in the flat cylinder. Source: own authorship (2021).

Results

The probability distribution function $f(\phi)$ (PDF) and cumulative distribution function (CDF) $F(\phi)$ of porosity ϕ are exhibited in parts (a) and (b) of Figure 2, respectively.

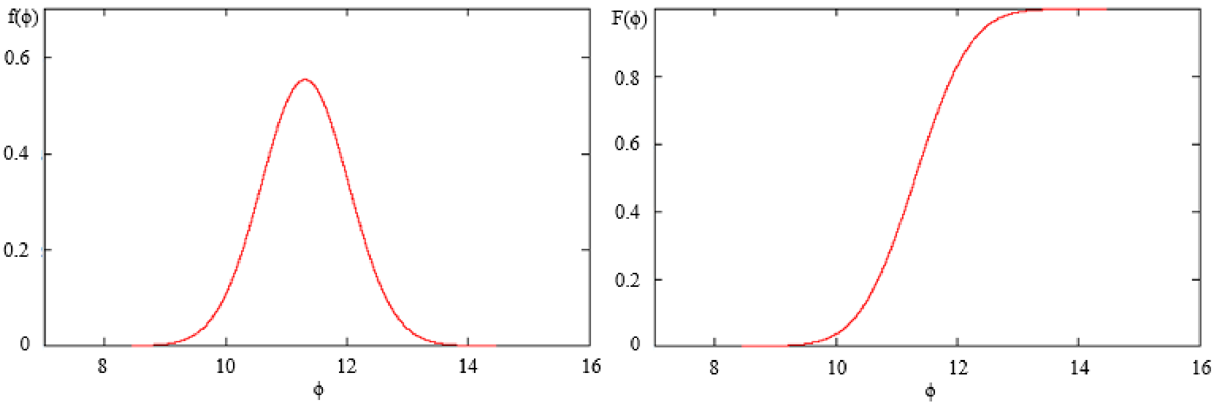

Figure 2. PDF and CDF of porosity. Source: own authorship (2021).

Table 2 presents the minimum, mean, maximum, and standard deviation values obtained via simulation for the involved uncertain parameters.

Table 2. Simulated output data for the compacted cylinder. Source: own authorship (2021).

Uncertain parameters	**Minimum**	**Mean**	**Maximum**	**Standard deviation**
Cylinder height H (mm)	1.984	2.000	2.018	4.000 x 10^{-3}
Cylinder diameter D (mm)	7.918	8.000	8.072	15.998 x 10^{-3}
Powder mass m (g)	0.694	0.700	0.706	1.399 x 10^{-3}
Bulk volume V_{bu} (mm^3)	97.378	100.53	103.212	606.237 x 10^{-3}
Bulk density ρ_{bu} (g/ mm^3)	6.716 x 10^{-3}	6.963 x 10^{-3}	7.189 x 10^{-3}	56.638 x 10^{-3}
Porosity ϕ (%)	8.417	11.300	14.446	721.504 x 10^{-3}

Discussion

If the deterministic calculation framework was applied, the parameters would correspond to their mean values (presented in third column of Table 2). However, in the context of a large amount of cylinders, in which their uncertain input parameters (diameter, height, and mass) behave as normally distributed variables, all the subsequent related parameters are affected in what concerns to possible assumed values. Figures 3 shows the behavior of the input parameter with the highest variability, D, in terms of their PDFs and CDFs.

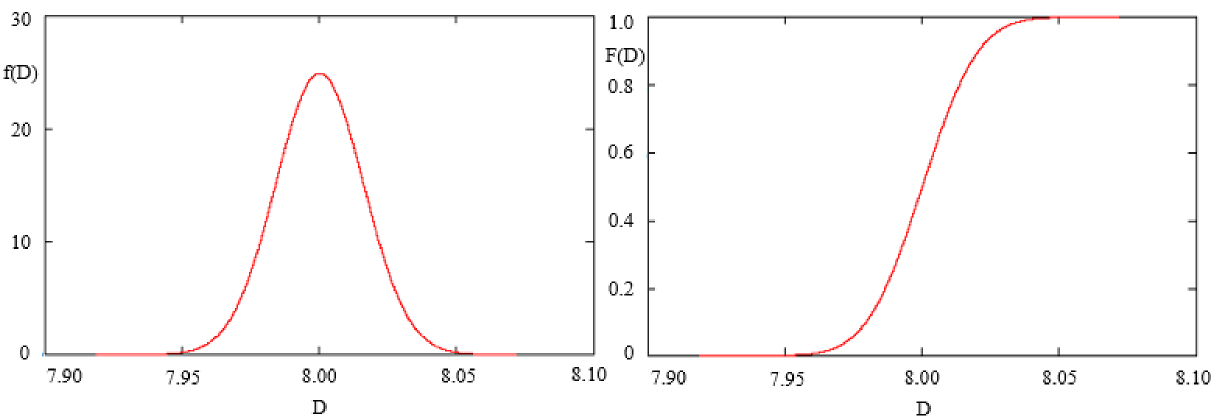

Figure 3. PDF and CDF of cylinder diameter. Source: own authorship (2021).

Standard deviations of H, D, and m, respectively, 4.000 x 10^{-3} mm, 15.998 x 10^{-3} mm, and 1.399 x 10^{-3} mm produce a standard deviation of 721.504 x 10^{-3} related to ϕ. In other words, even a low variation in the input data may imply in variation several orders of magnitude higher when there are multiple algebraic operations to be performed. In this case, observing the prescribed conditions, porosity ranges from 8.417 to 14.446%, which can be considered wide when strict control is imposed over the part. In terms of percentage, the simulations for H, D, and m, produce variations of, respectively, 1.714, 12.875, and 1.729%, which results in a variation of 71.629% in the porosity.

Thenceforth, it is relevant to assume the non-deterministic nature of these variables and calculate the range of possible values. In view of this, if the objective is to model the behavior of these variables throughout the compaction process in a more realistic manner, the uncertainties should be considered, since they are inherent to common applications. Therefore, if possible variations are considered in the analysis scope, the process may reflect the behavior of the involved parameters with more trustworthiness.

Conclusions

The behavior of porosity was simulated observing the prescribed variability conditions for the powder mass, cylinder height, and cylinder diameter. For example, these results may serve as valuable information for decision about acceptance criteria of the parts, which in turn may influence the quality of the eventual subsequent processes.

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