THE EFFECT OF GEOMETRIC SINTERING PARAMETERS ON DENSIFICATION

https://doi.org/10.22533/at.ed.804112520038

Data de aceite: 03/09/2025

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ABSTRACT: As a promising research area, sintering demands experimentation to match the planned objectives and prediction to avoid unnecessary experiments. Both are required to background the decision-making process in this area. Therefore, in this paper, the impact of geometric sintering parameters on the densification of flat cylinders is examined by simulating measurements of a caliper and performing densification calculations using SINT software. The results point out that relatively small variations in geometric parameters imply significantly large variations in densification. In view of this, densification proved to be highly dependent on the geometric parameters of sintering, demanding more detailed research about the subject.

KEYWORDS: Sintering, Densification, Shrinkage, Geometric parameters, Powder metallurgy.

O EFEITO DE PARÂMETROS GEOMÉTRICOS DE SINTERIZAÇÃO NA DENSIFICAÇÃO

RESUMO: Como uma área de pesquisa promissora, a sinterização demanda experimentação para corresponder aos objetivos planejados e previsão para evitar

experimentos desnecessários. Ambos são necessários para embasar o processo de tomada de decisão nesta área. Portanto, neste artigo, o impacto dos parâmetros geométricos de sinterização na densificação de cilindros planos é examinado por meio da simulação de medições com um paquímetro e da realização de cálculos de densificação utilizando o software SINT. Os resultados indicam que variações relativamente pequenas nos parâmetros geométricos implicam variações significativamente grandes na densificação. Deste modo, a densificação provou ser altamente dependente dos parâmetros geométricos, demandando uma pesquisa mais detalhada acerca do assunto.
PALAVRAS-CHAVE: Sinterização, Densificação, Encolhimento, Parâmetros geométricos, Metalurgia do pó.

INTRODUCTION

Powder metallurgy addresses the transformation of particles of solid metal, alloy, or ceramic into components, products, or samples of defined shape and mechanical properties that can be used as it is or should be post-processed (Thümmler; Oberacker, 1993).

Adhesive loads are induced over powder particles and voids during the pressing process of the raw powder in a press machine. The elastic part of the energy is recovered when the part is withdrawn from the matrix, remaining cohesive all those particles adhered to each other (Chiaverini, 1992).

The compacted may reach relatively high strength when there is a large contact area between the particles (fine-grained powder), which favors the shrinkage of the particles, thus contributing to a higher densification (Antony; Reddy, 2003).

Even in the case of high strength, the compacted in its green state has few useful properties to fulfill a common product demand, thus mostly requiring some post-processing. In view of this, one of the most useful post-processing includes sintering (Maurya et al., 2025).

Sintering Process and its Stages

Sintering is defined as a heat treatment of a powder mass or a porous compact in which there is shrinkage of void volumes, and decrease in the specific surface, thus enhancing the mechanical properties. Concomitantly to this, fluid-solid interaction, and chemical reactions occur. Particles go from merely adhesive contact to solid-state bonding (Thümmler; Oberacker, 1993).

Sintering can be divided into three stages: (a) localized bonding; (b) formation of a new microstructure; (c) shrinkage. Free surface energy is the driving quantity of sintering, in which material is transported from the particle nucleus through its thickness up to the interface with other particles. Thus, the phenomena of rounding and shrinkage of the pores require mass flow, which addresses volume diffusion as the main mechanism of sintering (Högänas, 2013).

In terms of thermal concept, it is necessary to heat the compacted up to temperatures between 50 and 75% of the melting temperature of the material with the lowest melting point. This temperature level is kept for a certain period, inducing particle bonding, and consequently, density increase, and enhancement of mechanical properties (Rashid; Ikram, 2025) (Restivo et al., 2023).

Sintering Thermodynamics

Solid-vapor surface energy is increased by the presence of pores. Sintering promotes the minimization of this energy, which tends to reduce the grain boundary energy via grain size growth. The energy level is low for pores at the grain boundary. Therefore, it is easier to shrink pores at this location. On the other hand, if the pores are inside the grain, it is harder to shrink (Modak; Wyslouzil; Singer, 2020).

When sintering goes forward to intermediate stage, pores tend to be more tubular-like, forming a network attached to the grain boundaries. This is explained by the fact that as the grains grow the pores shrink. As densification progresses to the final stage, the cylinder shape of pores turns into sphere-like. The limit condition for this transformation is derived from the minimization of energy (Equation 1), where L is the cylindrical pore length, and D_p is the pore size

$$L \geq \pi D_p \tag{1}$$

In the final stage of sintering, when a higher densification is achieved, a relation G between the fractional porosity φ_f, pore size, and grain size is mathematically represented by Equation 2, where is a geometric constant, and R_p is the ratio of the attached pores to the randomly placed ones.

$$G = \frac{1}{S_v} \approx \frac{1}{\varphi_f^2} \tag{2}$$

A relation between and the quantity called solid-vapor surface area per unit volume, S_v, is inversely proportional to the square of the fractional porosity φ_f, as per Equation 3. In other words, if porosity decreases the pore surface area decreases too, which increases the grain size.

$$G = \frac{1}{S_v} \approx \frac{1}{\varphi_f^2} \tag{3}$$

The relation between the change in surface area, ΔS, and the initial surface area, S_i, is quantified by the specific area variation, A_s , a dimensionless parameter, by Equation 4.

$$A_s(\%) = \frac{\Delta S}{S_i} 100 \tag{4}$$

Therefore, the quantification of shrinkage can be made as the ratio between the change in length, ΔL , and the initial length, L_i, as per Equation 5.

$$S_k(\%) = \frac{\Delta L}{L_i} 100 \quad (5)$$

The shrinkage phenomenon induces the densification from the compacted initial density, ρ_i, to the sintered final density, ρ_f, following Equation 6:

$$\Psi(\%) = \frac{\rho_f - \rho_i}{\rho_i} 100 \quad (6)$$

MATERIAL AND METHODS

This section describes the entire workflow employed in this paper, also shown schematically in Figure 1. The flowchart starts with the simulation of the dimensional measurements (simulating the application of a 0.01 mm resolution caliper) of the height and the diameter of the flat cylinders before and after sintering. After the dimensions were generated, the calculation of densification was conducted in the software SINT (Nonato; Restivo, 2023). The statistical parameters were quantified via standard deviation and relative error, which allows the verification of the impact of the input on the output. The interpretation of the results closes the work scope of this paper.

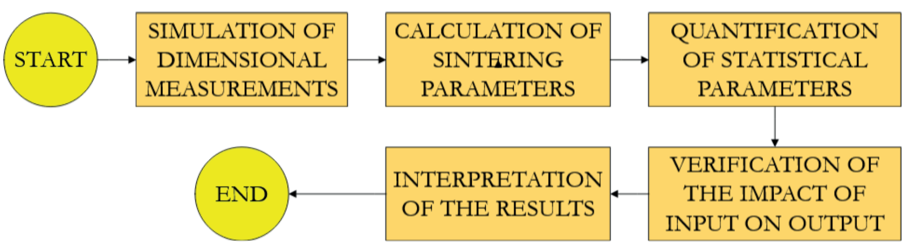

Figure 1: Flowchart of the workflow applied in this work.

Source: Own authorship, 2025.

The input of initial mass, initial height, initial diameter, final mass, final height, and final mass were generated within Microsoft Excel® using the random function. The mass was kept constant to check the effect of geometric parameters only. The height was subjected to a variation of ± 3.33%, and the diameter to ± 1.85%.

The software employed in the calculation of the output described is "SINT", coded in Microsoft Visual Studio 10.0® via emulation of the ambient of Microsoft Visual Basic 6.0®. SINT was built up based on cylinders as the shape of the compacted. Therefore, the input data addresses the following items in the list, which also can be seen in Figure 2: (a) initial mass, g ; (b) initial height, mm; (c) initial diameter, mm ; (d) final mass, g ; (e) final height, mm; (f) final diameter, mm.

Although the interest relies only on densification, this input data is applied in the calculation of the following output data: (a) specific area variation, %; (b) initial density, g/cm^3; (c) final density, g/cm^3; (d) shrinkage, %; (e) densification, %.

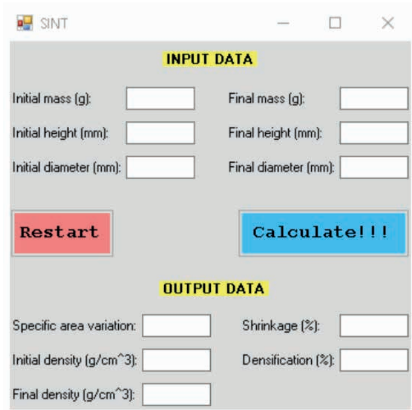

Figure 2: SINT software empty screen.

Source: Own authorship, 2025.

RESULTS AND DISCUSSION

The first of the 15 simulation situations (samples) can be seen calculated in SINT software in Figure 3. The input is in the upper part of the program screen. To obtain the output, the blue Calculate!!!" button should be pressed, and the results can be read in the lower part of the window. Table 1 presents all the input data, and only densification output data. The first line of Table 1 was the base to randomly build the others.

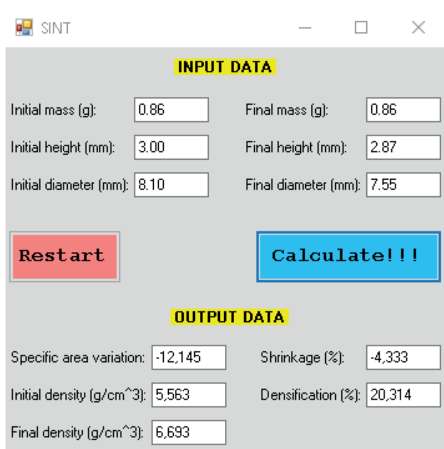

Figure 3: SINT software filled in with values of the first simulated sample.

Source: Own authorship, 2025.

Sample	H_i (mm)	D_i (mm)	m_i (g)	H_f (mm)	D_f (mm)	m_f (g)	Ψ (%)
1	3.00	8.10	0.86	2.87	7.55	0.86	20.31
2	3.08	8.20	0.86	2.82	8.05	0.86	13.33
3	3.09	8.19	0.86	2.81	7.97	0.86	16.12
4	3.07	8.15	0.86	2.84	7.96	0.86	13.32
5	2.94	8.10	0.86	2.78	8.05	0.86	7.07
6	3.01	8.09	0.86	2.82	8.06	0.86	7.53
7	3.05	8.21	0.86	2.85	8.06	0.86	11.04
8	2.95	8.08	0.86	2.79	8.07	0.86	6.00
9	3.01	8.12	0.86	2.81	8.05	0.86	8.99
10	2.95	8.21	0.86	2.81	8.01	0.86	10.29
11	2.93	8.18	0.86	2.86	7.96	0.86	8.19
12	3.02	8.04	0.86	2.85	7.96	0.86	8.11
13	3.03	8.00	0.86	2.84	8.00	0.86	6.69
14	2.98	8.15	0.86	2.77	8.06	0.86	10.00
15	2.94	8.17	0.86	2.85	7.97	0.86	8.40

Table 1: Simulated input and calculated output parameters.

Source: Own authorship, 2025.

To simplify the visualization of the variation of density, a graphical representation of both parameters is made in Figure 4. For example, the comparison between samples 1 and 6 addresses the following: in sample 6, H_i is 0.01 mm higher, D_i is 0.01 mm lower, H_f is 0.05 mm lower, and D_f is 0.11 mm higher. This leads to a densification of 7.53% (37.08% of the densification of the sample 1, which is 20.31%). The differences pointed out in this example could be attributed to the method of measurement, or to the resolution of the instrument, for example. In other words, relatively low variations in the measurement of the geometrical parameters may imply significantly lower or higher values in densification.

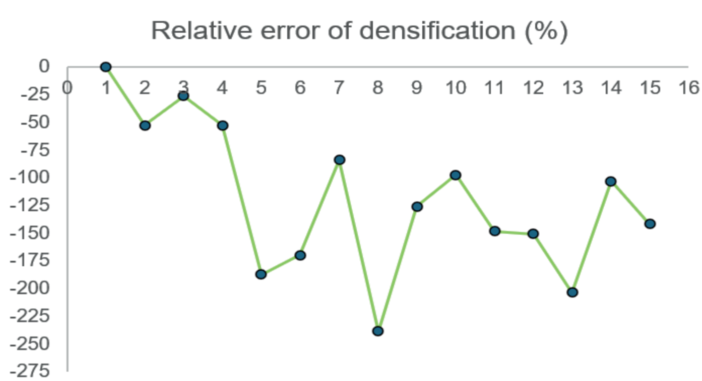

Figure 4: Relative error of densification.

Source: Own authorship, 2025.

In what refers to densification, the highest relative error (in absolute value) occurs in the 8th sample (-238.74%), while the lowest relative error in absolute value occurs in the 3rd sample (-26.03%).

If a caliper with a lower resolution than the one simulated herein is applied in the measurements, for example, 0.05 mm, the discrepancies in densification will be even larger. Indeed, associated with this source of uncertainty, the method of measurement also affects the densification mainly in what refers to the caliper positioning, and part of the caliper used in the measurements.

CONCLUSIONS

This paper addressed the impact of geometric parameters on densification in sintering. The calculation of sintering in flat cylinders was performed in SINT software, while Microsoft Excel® was applied to create the tables and plots. The main conclusions of this work can be given:

a. Relatively small variations in geometric parameters, such as height and diameter of a cylinder may lead to considerably large variation in densification.

b. Difference in measurement method, or in instrument resolution may result in discrepancy in the densification results. This implies inadequate conclusions as input to decision-making processes.

c. The uncertainty in the sintering process should be investigated in a more detailed manner, to check the contribution of each source of uncertainty, aiming at planning the actions to mitigate or even eliminate the identified sources.

ACKNOWLEDGEMENTS

The authors would acknowledge the research councils CNPq (proj. 408406/2021-6), CatalisaICT Sebrae (proj. 29083*128) and FAPESP (proj. 2023/09818-8) for financial support.

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