

MODELLING OF PROCESS VARIATIONS IN THE POWDER PRESSING STEP OF A FULL METALLURGICAL PROCESS CHAIN

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Abstract

Powder metallurgy offers a promising approach to produce components with complex near-net-shape geometry after forming and excellent microstructural properties. The process chain consists of powder pressing of a green body, sintering, and sinter forging. However, the stochastic nature of powder combined with process parameter variations introduces uncertainties from the first step that propagate through the process chain and can lead to discrepancies in finished products. As a first step towards tracking and quantifying such uncertainties, this study focuses on modelling powder pressing of two aluminium belt pulley gear geometries. The geometries can be pressed using the same tooling by varying press stroke and display features commonly found in industrial applications. Numerical simulations identify key factors governing density distribution and reveal significant differences between the two geometries. Assessment of different bilateral pressing strategies demonstrates trade-offs in achieving uniform density distributions. These findings provide the foundation for understanding how initial density variations propagate through subsequent process steps and establish the basis for process chain optimization. A metallurgical process chain with aluminium powder is modelled for two different final products. Analysis of the resulting green bodies identifies potential process risks arising from friction and rel. powder displacement during compaction, as well as from indirect compaction, resulting in inhomogeneous density gradients that can lead to discrepancies in the final parts.

Keywords: Powder metallurgy, powder pressing, finite element method

1. INTRODUCTION

Powder metallurgy (PM) is a well-established process for mass production of near-net-shape products [1]. In many cases, no finishing steps are required, or merely a single finishing operation after the final forming step [2]. This shortens and accelerates the production chain compared to conventional machining, increasing efficiency and reducing overall production costs. PM finds one of its largest consumer markets in the automotive industry, with components such as gears and valve seats, but it also finds widespread use in fields such as the aerospace industry, medical technology, and home appliances [3, 4]. PM allows for a variety of composite and alloyed powder combinations, enabling easy tailoring of material properties such as hardness and strength in finished products [1]. This study examines the first step of a multi-stage powder metallurgy process chain consisting of powder pressing, sintering, and subsequent sinter forging. The stochastic nature of powder, with variations in particle morphology and size, introduces uncertainties from the first step of the metallurgical process chain [2, 5, 6]. These variations can lead to major product discrepancies, whilst non-uniform final densities can cause workpiece failure or reduced quality. This makes optimising the process chain challenging, since uncertainties introduced at early stages carry over to subsequent steps. As a first step

towards tracking, quantifying, and modelling such uncertainties, this study focuses on modelling powder pressing of two related belt pulley gear geometries. Furthermore, different strategies for bilateral pressing are assessed to identify the optimal pressing strategy.

2. MATERIAL AND METHODOLOGY

The Aluminium powder Alumix 123 containing 4.8 % copper, 0.7 % silicon, and 0.6 % magnesium was used in this study. The powder has an average particle size of $<200 \mu\text{m}$. To model powder compaction behaviour during powder pressing of green bodies, the Drucker-Prager cap model, originally developed for soils, was used [7]. This model is widely used for metal powder compaction modelling [1, 8]. The model describes how compaction increases relative (rel.) density and thereby enhances load-bearing capability [7]. Bouguecha and Behrens conducted extensive experimental and numerical analysis to verify and validate the material model, which is used for the simulations in this study [8]. The two demonstrator geometries are shown in **Figure 1 a)** and **b)**.

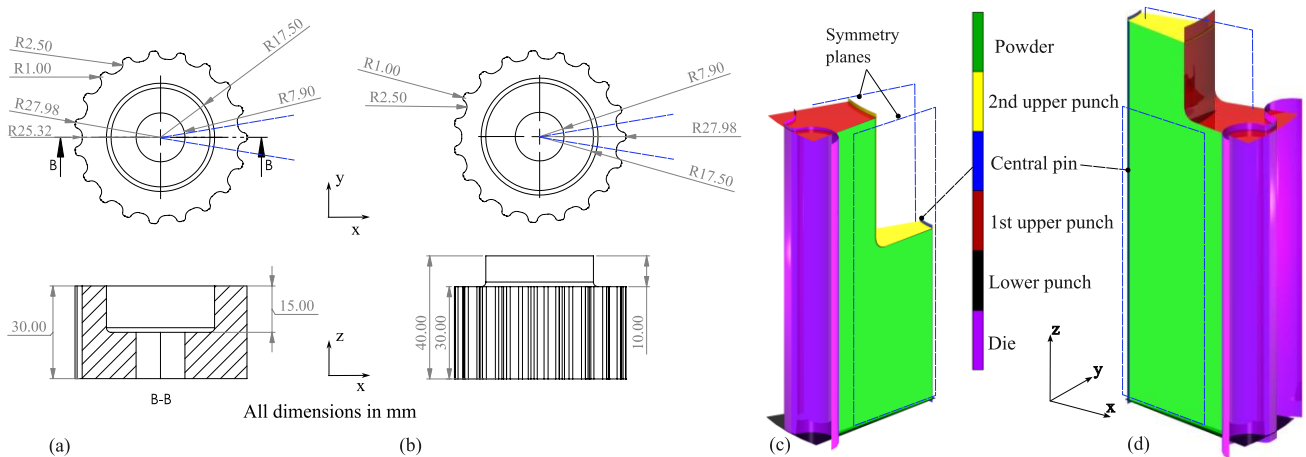


Figure 1 Belt pulley gear a) geometry 1, b) geometry 2, and powder pressing simulation setup for c) geometry 1 and d) geometry 2 at the start of the pressing step

Both geometries are belt pulley gears, differing only in the central feature: one has an undercut whilst the other has an elevation. The same tooling can powder-press both geometries by restricting specific punch movements for each variant.

The numerical investigation was carried out using the FE software Mentat, a pre-processor for the Marc non-linear solver. Modelling of powder pressing is solely a structural numerical simulation. Here, the tools used for compaction consist of five separate individual tools, which were modelled as rigid bodies using analytical NURBS surfaces. The tooling consists of a die, a lower punch, two independently moving upper punches, and a central pin, which are each assigned a displacement-controlled press stroke. To reduce computation time, the radial symmetry of the belt pulley gear was used by modelling a single tooth of the full 19-tooth gear. The powder was in contact with all tools and was constrained by two radial symmetry boundary conditions at the respective cutting planes. **Figure 1 c)** and **d)** depicts the basic setup for the powder compaction simulation of both geometries respectively. Punch movement was constrained to the z-axis, whilst the die and central pin remained stationary.

Contact was modelled via node to segment, geometric to deformable contact and coulomb bilinear friction with a density dependent friction coefficient which follows **Equation 1** [8].

$$\mu = 0.1851 \cdot (\rho_{rel})^{-0.6955} \quad (1)$$

The displacement was applied to both upper punches and the lower punch to achieve better compaction results than single-sided compaction. The average mesh size has been selected to $d_{mesh,avg} = 0.5$ mm, and the minimal edge length to $d_{mesh,min} = 0.18$ mm. **Table 1** lists the different travel distances of the different punches depicted in **Figure 1 c)** and **d)**. Two pressing strategies are investigated. In the first, both upper and lower punches travel equal distances. In the second, punch travel is asymmetrical. The initial relative density was set to $\rho_{start,PP} = 0.45$, a value determined by measuring the settled apparent density of the powder, thus simulating normal die filling [1].

Table 1 Punch movement parameters

Tool part	Punch travel values in mm equal length	Punch travel values in mm asymmetric
<i>Geometry 1</i>		
1 st upper punch	$d_{up1,eq} = 5$	$d_{up1,as} = 7.5$
2 nd upper punch	$d_{up2,eq} = 2.5$	$d_{up2,as} = 5$
Lower punch	$d_{low,eq} = 5$	$d_{low,as} = 2.5$
<i>Geometry 2</i>		
1 st upper punch	$d_{up1,eq} = 5$	$d_{up1,as} = 2.5$
2 nd upper punch	$d_{up2,eq} = 5$	$d_{up2,as} = 7.5$
Lower punch	$d_{low,eq} = 5$	$d_{low,as} = 7.5$

3. RESULTS AND DISCUSSION

The powder pressing results for geometry 1 are shown in **Figure 2**. **Figure 2 a)** and **2 b)** depict geometry 1 with its relative density distribution after compaction for both pressing strategies respectively. The equivalent results for geometry 2 can be found in **Figure 4**.

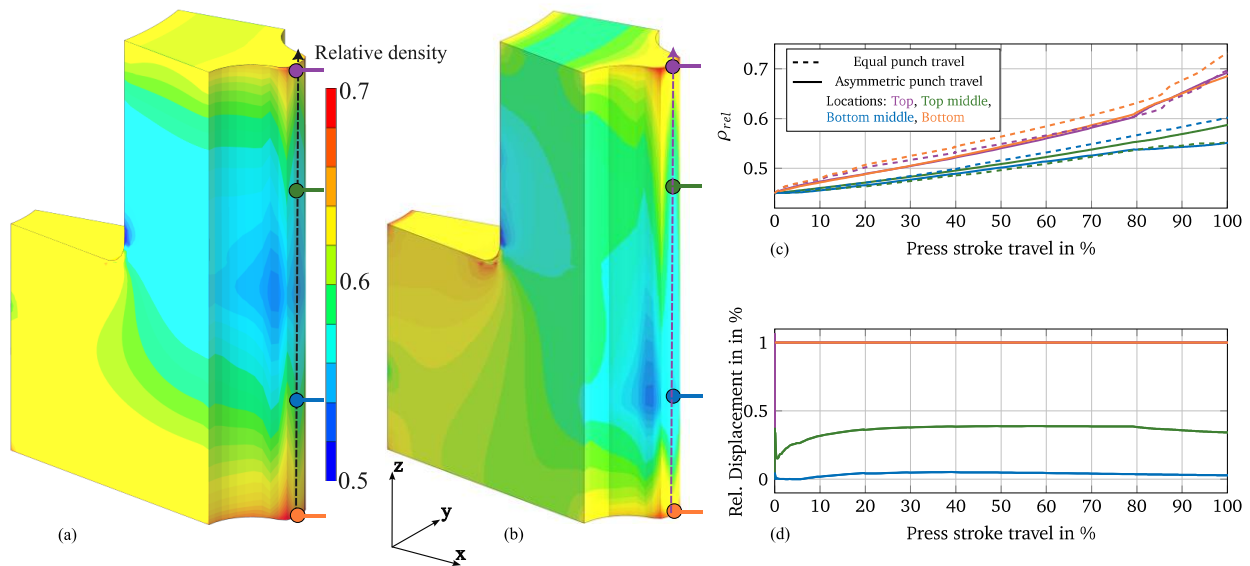


Figure 2 Geometry 1 a) Relative density distribution after compaction with strategy 1, b) strategy 2, c) development of the relative density over the compaction stroke, and d) relative displacement of the evaluation points over the compaction stroke

The results show a region in the middle right, along the gear tooth, that was in contact with the die during forming and displays fairly low rel. density values. This effect is caused primarily by two interacting conditions. First, die wall friction creates a neutral plane within the powder compact where vertical displacement is minimal. This stagnation zone forms between the moving punches, and friction exacerbates inadequate compaction in

this region. Conversely, zones between the upper and lower punches and the die display high compaction due to the opposite effect: friction coupled with large rel. displacement to the die produces high local compaction. **Figure 2 c)** and **d)** show the relative density evolution and the displacement of the green body of geometry 1 respectively.

Figure 2 c) shows rel. density evolution at selected points during the pressing step. The locations of the evaluation points are highlighted in **Figure 2 a)** and **b)**. These are located at 0, 8, 18, and 30 mm height in z direction respectively for geometry 1. These curves correspond to the highlighted locations on the green body. **Figure 2 d)** shows the rel. displacement of the evaluation points to their respective contacting bodies during pressing. Here it can be seen that the node in the area of lower compaction, at the centre of tooth, undergoes almost no displacement. This specific location shows reduced compaction and comprises a significant area of the toothed section and undercut. This location represents the kinematic neutral point between the moving upper and lower punches. The aforementioned effect in the tooth edge regions can be observed (top, bottom), which conversely show the greatest increase in rel. density alongside the greatest displacement (top). A second pressing strategy is tested, in which the punches have asymmetric travel distances. This is carried out to verify if unequal punch travel improves compaction and to study neutral plane position with respect to punch travel whilst maintaining constant initial volume. Modifying punch travel so that the first upper and lower punches have unequal travel ($d_{up1,as} = 7.5$ mm, $d_{low,as} = 2.5$ mm) yields significantly different density distributions. The neutral plane shifts away from the green body centre towards the lower punch, whilst compaction at the tooth bottom is slightly reduced compared to the equal punch travel version as can be seen in **Figure 2 b)**. The final zone of effect of the neutral plane, which is shifted downwards, is reduced significantly, where reduced compaction is no longer concentrated on the whole depth of the tooth. Analysis of the density distribution across the toothed section reveals that this modification reduces overall density in the gear's lower part but increases it in the thinner, more susceptible undercut region. This makes the second variant superior to the first. Furthermore, the minimum value of the rel. density after compaction is higher in the second variant. This can be seen in **Figure 3**, the evaluation paths along the height of the green bodies can be seen in **Figure 2 a)** and **b)** respectively.

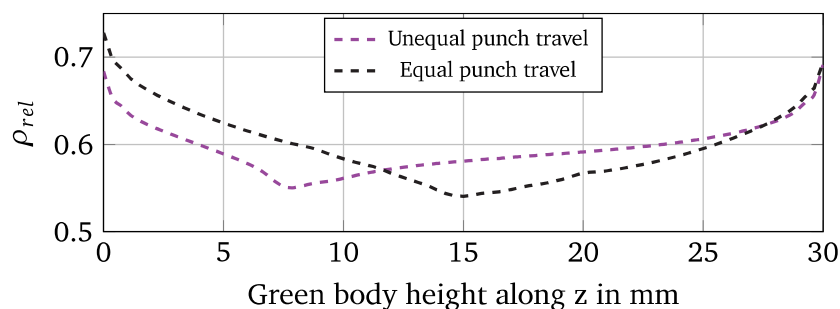


Figure 3 Final density distribution of symmetrical and asymmetrical punch travel variants for geometry 1

For geometry 2, a similar relative density distribution can be observed along the gear tooth. **Figure 4** shows the rel. density evolution and displacement during the press stroke. **Figure 4 c)** shows the density evolution of the elevation, which exhibits low compaction. This arises because the first and second upper punches have identical stroke lengths, meaning they display no rel. displacement to each other. Thus, the elevated section of the green body is compacted only indirectly, occurring when the powder below is compacted and exhibits higher yield stress than the elevated section. Zones of indirect compaction invariably show less increase in rel. density than directly compacted zones, except for the stagnation zone.

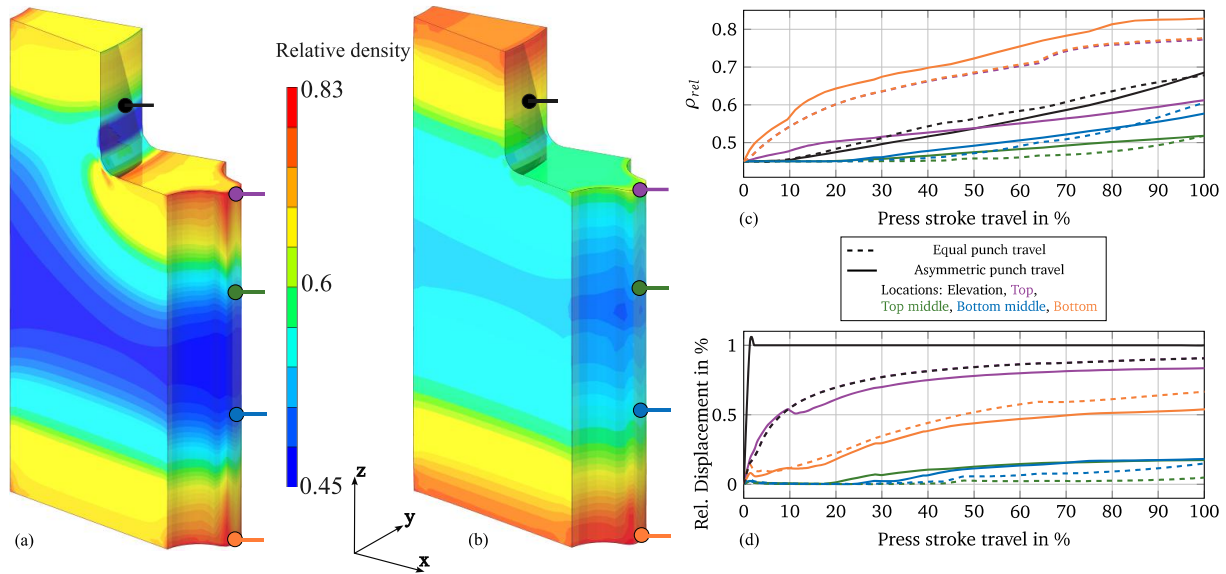


Figure 4 Geometry 2 a) relative density distribution after compaction, b) development of the relative density over the compaction stroke, and c) relative displacement of the evaluation points over the compaction stroke

An asymmetrical punch travel strategy is tested for geometry 2, similarly to geometry 1. The results, shown in Figure 4b, demonstrate three improvements: raised overall compaction of the main body, increased minimum relative density in the neutral zone, and increased final relative density in the elevation.

Geometrically, both green bodies display good agreement with the desired geometries, although the final density distributions are not satisfactory and the initial powder volume must be increased to maximize final density. Analysis of both geometries under various pressing conditions reveals that density distribution is governed by three interacting factors: punch displacement ratio, die wall friction, and local geometry constraints. The neutral plane location can be controlled through punch travel, but geometric features such as the undercut or elevation determine how effectively this control can improve overall part quality. Whilst bilateral pressing will always exhibit a neutral plane, optimal selection of punch stroke can shift its location towards portions of the green body less susceptible to failure from inadequate compaction. Understanding these interactions provides the basis for predicting density variations in the green body, which will influence material behaviour in subsequent sintering and sinter forging steps and ultimately affect final component quality.

4. CONCLUSION AND OUTLOOK

A metallurgical process chain with aluminium powder is modelled for two different final products. Analysis of the resulting green bodies identifies potential process risks arising from friction and rel. powder displacement during compaction, as well as from indirect compaction, resulting in inhomogeneous density gradients that can lead to discrepancies in the final parts. These aspects can be mitigated by increasing rel. punch displacement to reduce the stagnation zone, increasing the initial powder volume in sections requiring higher rel. density, and optimizing punch stroke to minimize neutral plane effects. All of these factors represent sources of uncertainty; thus, properly controlling and minimizing them is essential for reducing variability in subsequent process steps and improving final component quality. Additionally, the numerical findings will be validated through experimental testing in future work.

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