

# A Review of Finite Element Simulations of Metal Powder Die Compaction

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**Abstract**-A review and classification of 42 finite element simulations of the die compaction of powder metals is presented here. The present work aims to provide the powder metallurgy researcher or practitioner a strategy for which a finite element code and a constitutive material model should be chosen for a given powder type. Ferrous powders are the most-investigated material in the literature, with the vast majority of the papers using a granular constitutive material formulation in their work. Works typically concentrating on the simulation of sintered or high density parts generally use porous material models. Of the papers that report which software is being used in the modelling approach, most use either of the commercial codes ABAQUS or LS-DYNA for mainly granular material models. ABAQUS has been noted as being a popular choice for non-ferrous powders.

**Keyword**- Powder Compaction; Finite Element; Densification; Simulation

## I. INTRODUCTION

Powder compaction is a critical step in the powder metallurgy (PM) process since the overall performance of a PM part is heavily influenced by the quality of the compaction. Mechanical and other material properties increase with density, so it is important that the part is both dense and uniform after the compaction step. If there are large variations in the density found throughout a part, low-density areas will be weak points in the compact, and will lead to reduced overall part quality.

In powder compaction, densification occurs at a high rate at low pressure levels where the powder particles reorganize and begin to deform at inter-particle contacts. With continued increase in pressure, the rate of densification decreases due to work hardening and resulting bulk compression of the compact. The focus of this work is die compaction, the workhorse of the popular “press-and-sinter” technologies, which are of the most economical PM manufacturing techniques and are widely used in the automotive industry.

There are many phenomena that occur during the die compaction process that deal with the mechanics of powder densification, and therefore research has focused on several important aspects of the process. Some of the major areas of research in terms of powder compaction include die wall friction and the effects of lubrication [1-3], the density distribution within the compact [4, 5] and advanced compaction techniques such as high velocity compaction [6, 7]. Ultimately, the density of the compact is the single most important metric which defines the quality of the compaction. Specifically, the distribution of the powder densification throughout the compact is known to be non-uniform due to die wall friction and die geometries. These phenomena are often difficult to measure experimentally, but finite element (FE) analysis can provide researchers with detailed information about many of these phenomena, including forces at the die-powder interface, internal plastic strains, pressure transmission through the powder, and others. Modelling powder compaction has been an active area of research for the last few decades. There is a vast opportunity to study different aspects of powder compaction, as there are several different compaction techniques as well as numerous phenomena that occur using each technique, all of which have been the focus of research in the field.

Recent reviews on analytical (continuum approaches), ceramic, and pharmaceutical powders by Cunningham, et al. [8], Aydin, et al. [9], and Sinka [10], respectively, have given a broad overview of the modelling field. However, surveys of existing modelling efforts in metallic PM applications have been somewhat limited, where industry-centric reviews by Federzoni, et al. [11] and Calero [12] are standouts. The purpose of this paper is to address the need for a concise review of recent modelling works which bridges the gap between fundamental FE modelling methods and desired industrial research outputs. The present work is limited to metal powders and the use of FE methods. As a result, discrete element methods are gaining popularity and compaction of pharmaceutical powders are beyond the scope of this paper. The authors attempted to provide a broad overview of simulation efforts, reviewing 42 works and stress that any omissions are not intentional. Squarely aimed at both the PM researcher and practitioner, this paper attempts to provide a strategy for implementing FE compaction modelling. Practical questions such as which FE codes (commercial or custom) as well as what type of constitutive material simulation (granular or porous) will be addressed for ferrous and non-ferrous powders. These two issues present significant decisions which will impact the costs, times, and experimental requirements on a body of work given that, generally, the researcher has a selected a powder to model a priori.

## II. MODEL CLASSIFICATION

### A. Constitutive Material Model Formulations

The particular constitutive material model formulation employed plays a vital role in the FE compaction simulation as it is the controlling factor in the predicted powder densification. While there are a number of ways in which researchers explain the behaviour of powdered metal undergoing compaction, an attempt is made here to broadly classify them into two main families. Regardless of the model type, all must simulate the densification behaviour of powdered metals which is a non-reversible plastic deformation. The first plasticity family consists of models developed for porous materials, such as Kuhn and Downey [13], Shima and Oyane [14], and Fleck-Gurson [15, 16], which express the hydrostatic and deviatoric stresses in terms of the yield stress of the solid material and the yield stress of the partially dense material found in a part during compaction.

Several variations of the parameters found in the Shima and Oyane model exist in the literature, but these models are all based on the same general form. These models make assumptions which do not hold true at very low densities (i.e. the start of the powder compaction process) [17] and therefore the use for the simulation of a compact being created from loose powder are not suitable. When investigating pre-compacted sintered powder components, this type of model tends to be more applicable.

The second family of plasticity models is for granular materials. These models include Drucker-Prager [18], Mohr-Coulomb, and Cam-Clay [19] among others. Granular models are suitable for all stress and strain paths, not just particular loading paths. Furthermore, the parameters of the model may be determined using a relatively small number of standard or simple material tests, and the model is phenomenological in nature [17]. A material that starts off at a low density, such as soil or PM material, will behave differently than a solid metal. As the powder becomes more and more dense, it begins to act more like a solid metal. Therefore, at low values of pressure, the yield strength is very low; plastic deformation occurs at very small values of stress. As the material is pressed, or compacted, the density increases, and the yield strength of the material grows. Therefore, if one were to visualize what this yield surface would look like, it would appear to be a cone expanding along the hydrostatic axis rather than a constant-radius cylinder. Referred to colloquially as expanding surface models, the Drucker-Prager Cap (DPC) yield surface is represented commonly two-dimensionally using the invariants of the deviatoric stresses  $J_1$  and  $\sqrt{J_{2D}}$ , analogous to hydrostatic pressure and von Mises stress respectively.

The DPC model is bounded by an expanding upper yield surface which, however, does not expand without limit. As the powder reaches maximum density, the radius reaches a maximum which approaches the wrought or solid metal value. Hardening caps are employed to model the powder plastic deformation under uniform (hydrostatic) pressure. These caps are essentially the limit of the maximum pressure that the powder can withstand without an increase in density.

In order to calibrate, or determine, the material model parameters experimental testing is required. Common powder tests include triaxial and uniaxial compaction, where isostatic pressing has been employed less frequently. Whilst triaxial tests necessitate specialized equipment, they provide an ideal powder loading mechanism by which the deviatoric (shear-dominant) and hydrostatic (pressure-dominant) compaction loads can be controlled. Thus, the particular yield surface can be determined through a wide range of loadings.

### B. Powder Type

The scope of this literature review is limited to those papers which focus on metal powder. For PM research scientists the type of powder is generally a key starting point since when using die compaction the maximum achievable density varies across materials. For example, iron powders are in the range of 85-92% density, while aluminium-based powder can achieve 90-95% density [20]. By a wide margin, ferrous powders dominate the global production of PM parts accounting for 74% of the total shipments in 2012 [21] and for this reason compaction models are divided into ferrous- and non-ferrous powders.

### C. FE Code

Interestingly, the age-old debate amongst FE modellers of whether or not to use commercially available codes still remains an active topic today. On the one hand, custom codes are often preferred by long-established researchers since they can be tested and validated thoroughly over a number of years. Additionally, it is often the case that custom codes are vastly more efficient computationally since they have been "leaned out" for a single purpose. On the other hand, a strong case is made for the use of commercially-available codes by industrial practitioners since they have little development time and generally do not require software personnel. Specifically, the implementation of powder constitutive models can be both time consuming and, arguably, of little improvement over built-in versions.

A very important aspect in FE modelling is the validation of the model. Throughout the literature, authors have compared their models to experimental results by studying the density distribution within the compact. These methods vary greatly and include

such techniques as gamma ray absorption [22-24] correlating Rockwell hardness measurements to density [25, 26], Archimedes' method [27-29], optical metallography [30], and powder movement [9, 31]. The PM Modnet Research Group [32] conducted computerized tomography (CT) scans in addition to the first four methods above to study density within a powder compact.

### III. FERROUS POWDERS

Iron is used very commonly in a wide variety of automotive components and therefore has been quite thoroughly investigated. Several experimental-only works, notably Doremus, et al. [33] and Pavier and Doremus [34], characterized iron powders using a high pressure triaxial cell; the results of which were subsequently widely used by other FE works for validation purposes. Sinka, et al. [35] also used a ferrous alloy powder (Distaloy AE) to study triaxial compaction as well as other tests, and compared these to prior results [33]. Korachkin, et al. [36] also used Distaloy AE in experimental work which tested the effects of ad-mixed lubrication on the Young's modulus and tensile failure properties of green compacts.

#### A. Porous Material Model

One of the earliest papers in the literature which studies iron PM as its main focus is Weber and Brown [25] which presented in-depth mathematical constitutive equations for the material model and studied cylindrical components undergoing closed die compaction. This paper utilizes the Kuhn and Downey model. Liu, et al. [28] modelled a cylinder of iron powder using the ellipsoidal model, citing the complexity of cap models as not being cost-effective and opting instead to use the simpler ellipsoidal model which is derived from the von Mises model. Lee, et al. [29] uses, among other models, the Shima-Oyane material model, stating that from their findings, it is a better choice than granular models such as Cam-Clay and the modified Drucker-Prager model. This preference is largely due to the porous model's inherent assumptions which do not hold true at low powder densities (i.e. early stage compaction) [17]. By contrast, granular models are formulated specifically to model the early stages of compaction such as rearrangement and localized deformation [20].

#### B. Granular Material Model

When looking at granular models used to simulate the compaction of iron PM powders, the vast majority of them incorporate a hardening cap in the model. The most common granular model used in the literature is the DPC model, followed by the Mohr-Coulomb cap model and the Cam-Clay model. Krezalek and Sivakumar [31] studied the mass movement of the powder during compaction using the DPC-derived Hehenberger model in the FE simulations, and tested these results experimentally using iron powder layers separated by thin copper layers. Coube and Riedel [27] studied the formation of cracks in compacted iron PM parts during the compaction, unloading, and ejection phases of the compaction process by using a modified DPC model. Doremus, et al. [37] proposed a set of standard tests to fit model parameters of the DPC model. This was tested by simulating the compaction of a drawing die and comparing the density distribution and punch forces with those determined from experimental data. The PM Modnet Research Group [32] used both the Cam-Clay and DPC models to simulate compaction of multilevel parts. Wikman, et al. [38] used the DPC model to model an axisymmetric bottle-neck shape compact in DYNA2D and a pulley in ABAQUS. Khoei and colleagues [39, 40] used the DPC model to simulate several parts and compared them to the results from the triaxial tests performed by Doremus, et al. [33]. Sinka [10] described the evolution of the modelling of powder compaction, and eventually used the DPC model in studies of the compaction of various materials including cellulose, calcium phosphate, and iron. The DPC model and a modified Cam-Clay model were used by Zadeh, et al. [41] to test two FE models. Armstrong, et al. [42] modelled a metal axisymmetric multilevel hub using the Cam-Clay model and compared single- and double-action compaction and how it affected density distributions in the component. Behrens, et al. [43] implemented an advanced die wall-powder friction model in FORGE for both steel and aluminium powders using a DPC material model.

Tran, et al. [23] simulated a plain bushing component using the Mohr-Coulomb Cap model, and compared the measured density at different compaction pressures against experimentally-made components of the same size and shape. Wikman, et al. [44] used an unspecified cap model to model a cylindrical iron PM part, while Ariffin, et al. [45] used the elliptical cap model using a custom FE code.

#### C. Aggregate Data

Aggregate data for ferrous powder compaction simulations is shown in Table 1. While many works did not specify which code was used, the commercially available LS-DYNA and ABAQUS codes dominate. It is interesting to note that for ferrous powder compaction simulations 83% (Fig. 1) employ granular constitutive formulations where of these 63% use the DPC model.

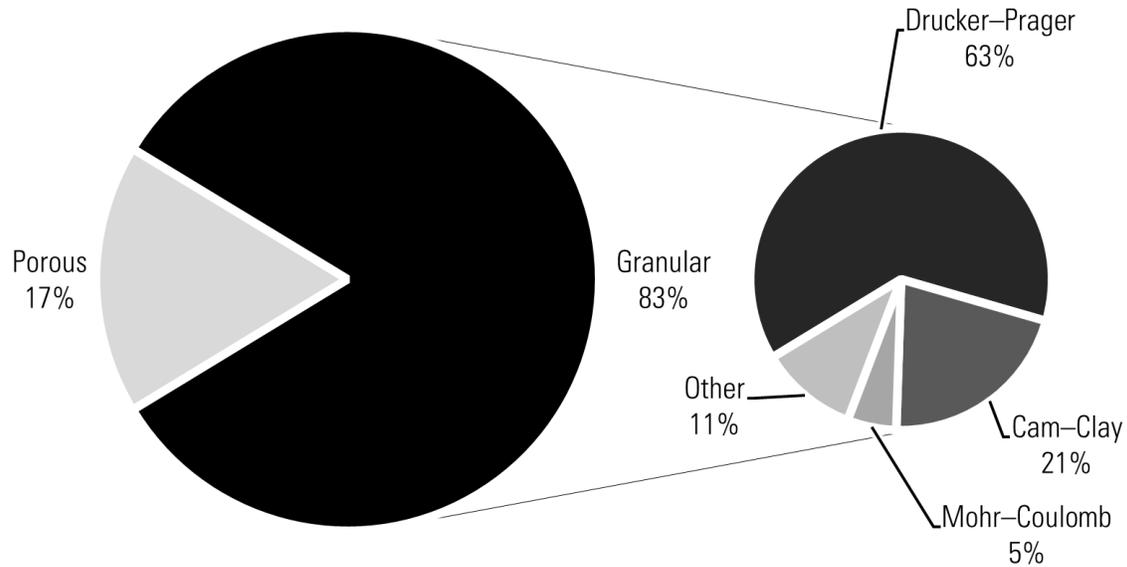


Fig. 1 Breakdown of constitutive material model use for ferrous powder models showing granular model details.

TABLE 1 CATEGORIZATION OF FERROUS PM COMPACTION SIMULATIONS.

FE Code	Material Model		Total
	Granular	Porous	
LS-DYNA	[37, 38, 44]	[46]	4
ABAQUS	[10, 27, 38, 41, 42, 47, 48]		7
DEFORM			0
Other	[31, 43]	[28]	3
Custom	[45, 49]		2
Unknown	[23, 32, 39, 40]	[25, 29]	6
<b>Total</b>	<b>18</b>	<b>4</b>	<b>22</b>

#### IV. NON-FERROUS PM

Although the majority of research is apparently directed towards iron PM compaction, there have been many papers written on other materials. Some of the earliest uses of the DPC model were to describe the behaviour of soil and rock compaction, such as by Sandler, et al. [50] and Sandler and Rubin [51], but these discussions did not include FE simulation, only numerical calculations. Both porous material models and granular material models were used in simulations throughout the years to model a vast array of non-ferrous materials, with no discernable trend correlating the material model used with the various material types. These other materials include non-ferrous metals, ceramics, carbides, and pharmaceuticals, but this paper will only investigate those dealing with metals.

##### A. Copper-Based Alloys

The copper powders which were investigated by several groups were mainly modelled using porous material models. Hwang and Kobayashi [52] developed a porous material model to simulate the compaction of solid cylinders and rings using both single- and double-action compaction. Jinka, et al. [53] modelled the compaction of straight cylinders and flanged cylinders using the Oyane modification of the von Mises porous material model in the FE simulations. Shima and Saleh [54] used another porous material model which had been developed by that group previously, and the aim of this study was to compare density distributions within powder compacts using copper powder particles of different shape and size. Ko, et al. [55] was co-written with Hwang, and as such used the prior model and presented the FE simulation results for several different part geometries. Smith, et al. [56] used the Gurson porous metal plasticity model to simulate the compaction of bronze cylinders with the goal of creating an extensive database to inform designers on proper parameters for different geometries, powders and desired densities.

### B. Aluminium-Based Alloys

In the literature, aluminium PM materials are not nearly as abundant as other metals (especially iron and copper). An aluminium-reinforced composite pre-alloyed powder was investigated by Ma, et al. [30] using two porous plasticity material models (Fleck for low relative densities, Gurson for high relative densities, and interpolated between). Another simulation regarding the compaction of aluminium composites was the work developed by Ramesh, et al. [57] which used a Cam-Clay formulation to investigate density distributions in Al-10% Cu powder compacts.

Lee and Kim [26] used an Al6061 alloy powder in both CIP and die compaction tests. The aim of their work was to compare several available material models to the model being proposed in their paper and how these compared to experimental data. Of the available models, it was found that the Shima-Oyane model agreed well with experimental data at the high-density region, but underestimated at the low-density region, while the Fleck-Gurson with tuned flow stress, the Cam-Clay, and the modified DPC models slightly overestimated the density distribution of the powder compact at the low-density region, but underestimated at higher density. A set of works developed a simulation of the compaction of Alumix 321 powder [58] for gears, which Selig [59] and Beck and Doman [60] subsequently extended to simulate compact springback and the incorporation of internal structures respectively. Behrens, et al. [43] and Bouguecha and Behrens [61] developed compaction simulations that investigated advance friction models as well as the incorporation of internal structures from an optimization perspective.

### C. Other Alloys

Chen, et al. [62] and Sabau, et al. [63] developed simulations of titanium powder alloys and also carried extensive experimental work which was used to validate the FE model parameters.

### D. Aggregate Data

Table 2 gives a breakdown of the FE codes used for non-ferrous powder compaction simulations. Note that while LS-DYNA and ABAQUS are used extensively, it is almost equally popular to use custom codes. The increased popularity of porous models, as compared to ferrous powders, is clear.

TABLE 2 CATEGORIZATION OF NON-FERROUS PM COMPACTION SIMULATIONS.

FE Code	Material Model		Total
	Granular	Porous	
LS-DYNA	[24, 58-60]		4
ABAQUS	[26, 57, 62-64]	[56, 65]	7
DEFORM		[52, 55]	2
Other	[22, 43, 61]		3
Custom		[30, 53]	2
Unknown	[66]	[54]	2
<b>Total</b>	<b>13</b>	<b>7</b>	<b>20</b>

## V. CONCLUSIONS

Through the preceding review and compilation of aggregate data, the clear industrial dominance of ferrous PM parts is maintained in their compaction models (Fig. 2). For these powders, the commercially available FE codes LS-DYNA and ABAQUS show strong adoption which may be due to the ready availability of built-in DPC material models which are very popular (Fig. 3). For non-ferrous powders, the picture is less clear owing to the comparatively small number of works available. However, some recommendations for the prospective FE powder compaction modeller may be made:

- For modelling powder compaction from loose powder states granular models such as DPC are preferred.
- The commercially-available material models in the LS-DYNA and ABAQUS codes have been widely used and results reported for ferrous powders.
- Porous models are more prevalent to non-ferrous powders which may be attributed to the intended application of the model for post-compaction (i.e. high density) analyses.

It is also noted that the calibration of the particular material model used is critical to modelling accuracy. Some models are better suited for ejection rather than the early stages of compaction. Appropriate validation with experimental results is important in order to develop accurate models.

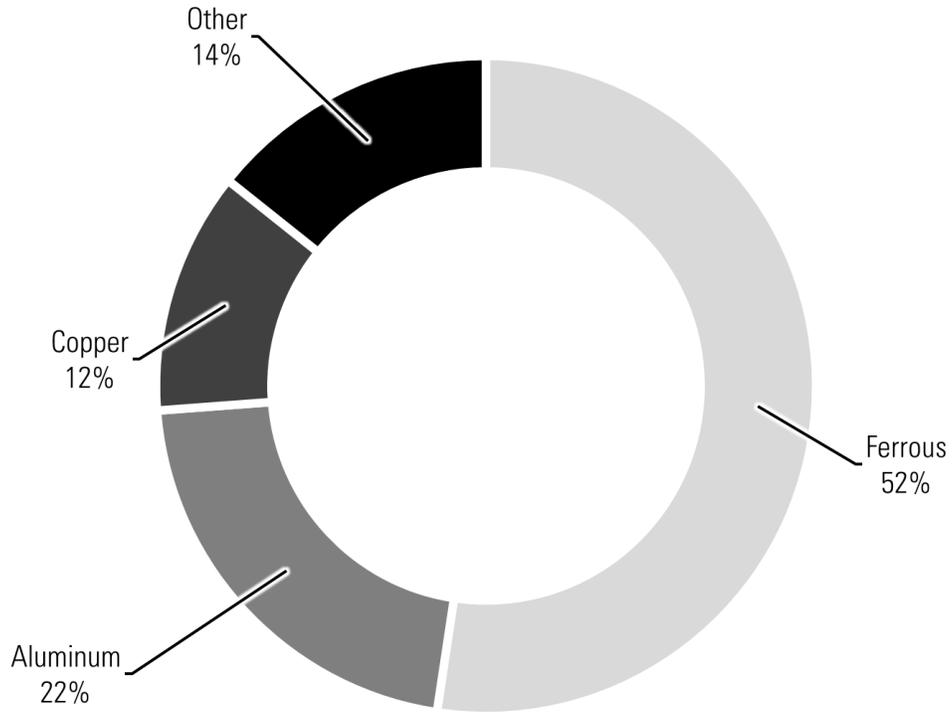


Fig. 2 Distribution of powder material types modelled by works covered in review

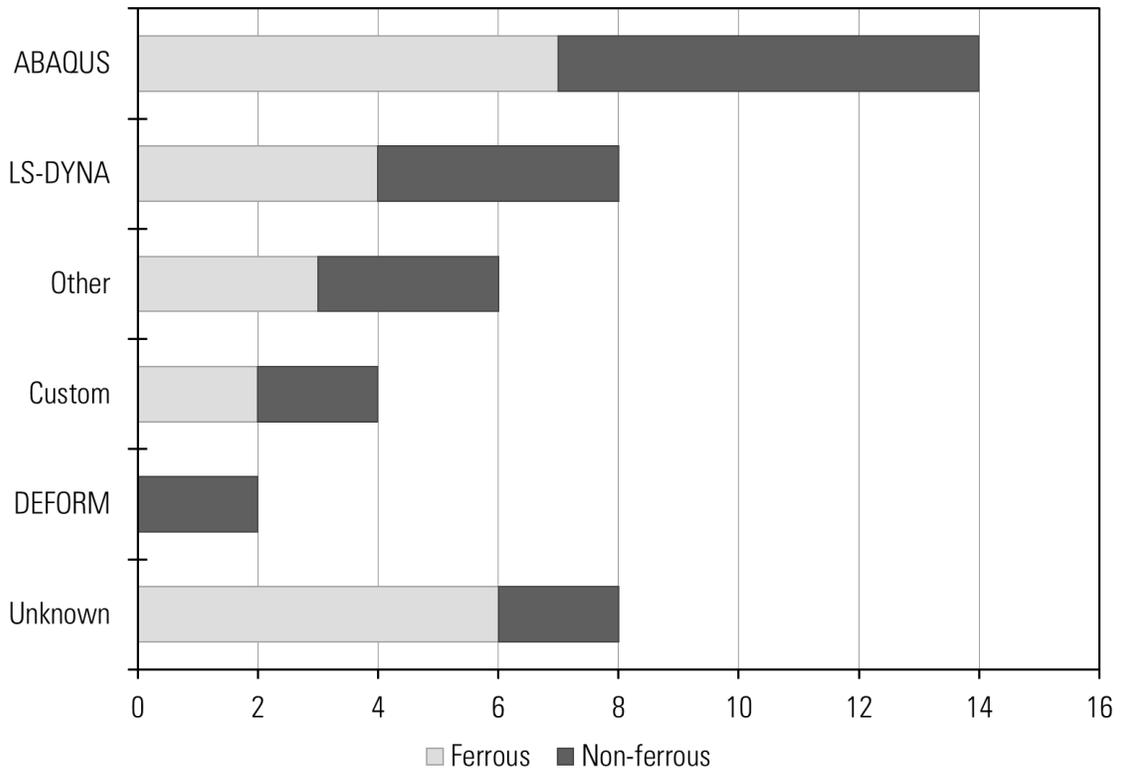


Fig. 3 FE code used for powder compaction simulations

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