



UNIVERSITI PUTRA MALAYSIA

***FINITE ELEMENT MODELLING OF BILAYER IRON POWDER
COMPACTION AND EVALUATION ON ITS RELATIVE DENSITY
DISTRIBUTION USING IMAGING TECHNIQUE***

SYAMIMI BINTI MOHD YUSOFF

FK 2022 73



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By

SYAMIMI BINTI MOHD YUSOFF

**Thesis Submitted to the School of Graduate Studies,
Universiti Putra Malaysia, in Fulfilment of the
Requirements for the Degree of Doctor of Philosophy**

June 2022

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Abstract of thesis presented to the Senate of Universiti Putra Malaysia in fulfillment of the requirement for the degree of Doctor of Philosophy

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Chair : Suraya binti Mohd Tahir, PhD
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Multilayer compaction allows the manufacturing of advanced metal-based components ranging from long thin-walled sleeves to cutting tools. Combination of compressed powder layers has been proven to upgrade its mechanical properties in terms of its strength, durability and toughness compared to an individual layer. Following this, modern apparatus has applied layering principles to sustain the usage in daily life. Nevertheless, at the scale of research and development, inspection on unify powder layers are scant in the aspect of its internal density, particularly on its interconnected boundary layers or interface. This invites untimely defects of delamination and capping that would require unnecessary investment of time and effort during the secondary PM operation. All the while, the scope of density measurement has resorted to geometrical definition and hardness; thus, less modelling efforts had been undertaken to examine the sectioned powder layers. This study has developed an imaging technique and modelling procedures to assess the local relative density (or local RD) distribution on green single and bilayer iron ASC 100.29 powder compact. The modelling strategy was developed based on Finite Element Method (FEM) using Abaqus 6.20. The results of experimental distributed local RD values showed close agreement with values mentioned in the literature for green single layer powder compact and the current work was further improved with higher pixels. As expected, the modelled local RD values were validated for experimental local RD values green bilayer iron powder compact. Further, it was revealed that the highest local RD distribution on the interface of bilayer iron powder compact was obtained with H/D ratio of 1.6 under lubricated die condition. Besides, under all H/D ratios and low friction coefficient (μ of 0.08), smaller gradient of local RD distribution has been achieved by green bilayer iron powder compact compared to single layer iron powder compact with the same applied conditions.

Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia
sebagai memenuhi keperluan untuk ijazah Doktor Falsafah

**PERMODELAN UNSUR TERHINGGA BAGI PEMADATAN
SERBUK BESI DWILAPISAN DAN PENILAIAN TERHADAP
TABURAN KETUMPATAN RELATIFNYA DENGAN
MENGUNAKAN TEKNIK PENGIMEJAN**

Oleh

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Pemadatan beberapa lapisan serbuk memberi laluan kepada kecanggihan teknologi pembuatan komponen berlogam yang bersifat pelbagai daripada pembinaan dinding nipis sehingga alat mesin pemotongan. Gabungan beberapa lapisan serbuk yang dipadatkan memberi impak kepada penambahbaikan sifat-sifat mekanikal bahan dari segi kekuatan, ketahanan dan keliatan berbanding pemadatan satu lapisan serbuk. Berikutan ini, alat-alat kelengkapan dibina berasaskan prinsip lapisan bertala untuk mengekalkan keseimbangan ketahanan dalam penggunaan harian. Walau bagaimanapun, pada skala penyelidikan dan pemodenan, pemeriksaan terperinci pada ketumpatan dalaman hasil dari gabungan beberapa serbuk lapisan yang dipadatkan amat jarang dilaksanakan terutama pada garisan sempadan atau permukaan antara lapisan-lapisan yang dipadatkan. Ini membawa kepada kerosakan yang mungkin hadir pada bila-bila masa yang memerlukan lebih masa dan langkah-langkah yang perlu dirangka untuk peringkat pembuatan yang seterusnya. Buat masa ini, bidang pengukuran ketumpatan serbuk hanya merangkumi definisi geometri dan kadar kekerasan permukaan padatan; oleh itu, strategi pelaksanaan simulasi pemadatan serbuk jarang dilaksanakan bagi memeriksa bahagian keratan rentas padatan serbuk secara berlapis. Kajian ini merangkumi teknik pengimejan dan langkah-langkah simulasi untuk memperoleh taburan ketumpatan relatif bagi pemadatan satu dan dwilapisan serbuk besi gred ASC 100.29. Strategi simulasi telah dipertingkatkan berasaskan kaedah unsur terhingga dengan menggunakan Abaqus 6.20. Keputusan telah membuktikan bahawa nilai-nilai taburan ketumpatan relatif yang diperoleh melalui eksperimen adalah hampir kepada nilai-nilai taburan ketumpatan relatif yang direkodkan daripada artikel yang telah diterbitkan untuk satu lapisan padatan serbuk besi dan keputusan nilai semasa adalah jauh lebih baik dengan penambahan jumlah

piksel. Seperti yang dijangkakan, simulasi taburan ketumpatan relatif bagi dwilapisan serbuk besi yang dipadatkan dapat dipadankan bersama hasil nilai daripada eksperimen. Selain itu, kajian ini juga mendedahkan bahawa taburan ketumpatan relatif tertinggi yang direkodkan pada sempadan dwilapisan serbuk besi yang dipadatkan adalah pada nisbah H/D 1.6 yang dijana melalui bekas mampatan yang disapukan dengan serbuk pelincir. Di samping itu, bagi semua nisbah H/D yang telah diuji bersama nilai pemalar geseran yang rendah ($\mu = 0.08$), perbezaan nilai taburan ketumpatan relatif yang rendah diperolehi daripada dwilapisan serbuk besi yang dipadatkan.



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This thesis was submitted to the Senate of Universiti Putra Malaysia and has been accepted as fulfillment of the requirement for the degree of Doctor of Philosophy. The members of the Supervisory Committee were as follows:

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LIST OF ABBREVIATIONS

BC	Boundary condition
DPC	Drucker-Prager cap
FEA	Finite element analysis
FEM	Finite element modelling
GD	Green density
H/D	Height-to-diameter
INP	Input file
ODB	Output database file
PM	Powder metallurgy
RD	Relative density
SPH	Smoothed particle hydrodynamics

LIST OF SYMBOLS

ρ_a	Apparent density
Asp	Aspirin
P	Average or (mean) density
F_c	Compaction force
ρ_c	Current density
F_e	Ejection force
μ	Friction coefficient
F_μ	Frictional force
ρ_f	Full density
ρ_g	Green density
H	Height
ρ_0	Initial density
Fe	Iron
Lac	Lactose
F_r	Radial force
ρ_t	Theoretical density

CHAPTER 1

INTRODUCTION

1.1 Background of study

From ceramic-based electronic equipment to automobile components, powder metallurgy (known as PM) is a dominantly implement over other types of machining processes in manufacturing area due to its general capability to produce parts with dimensional efficient and robust (Ashrafi et al., 2022; Edosa et al., 2022; Frandsen et al., 2013; Nazihah Mas et al., 2018; Olevsky et al., 2013; Pascal et al., 2010; Povstianoi et al., 2021; Torralba et al., 2019). Fundamentally, PM covers powder filling, compaction, ejection and sintering. Powder compaction and its sequent ejection produced a sample of green metal powder. The term green refers to the powder compact sample that released in ejection container, shortly after ejected through employed die mold (Jonsén, 2005.). Its results of non-uniform distribution of porosities with variation in radial pores size are conventionally redeem by its subsequent process of heat sintering. For decades, PM researches were dedicated on single layer of powder compact mainly for metal powder whereby density is a comprehensible variable to describe the green strength (Coube & Brewin, 2002). A layer or single layer of metal powder compact encompassing a simple cylindrical as well as in multi-level forms. With the aim to reduce density gradient without hinder the elevation of powder height, the need to study the interface between compressed layers is essential.

Through compaction process, the strength of green powder compact can be directly control via densification that drive the loose powder compact into a coherent mass under specified load. Minimization on density gradient on green metal powder compact are significance in order to inhibit potential defects such as crack and delamination in incoming sintering process. Double sided compaction method (Rajab et al., 1985), die lubrication (Lemieux et al., 2001.) and high velocity compaction (HVC) (Gustafsson et al., 2014a; J. Z. Wang, Qu, et al., 2009a, 2009b; J. Z. Wang, Yin, et al., 2009) are among ways to minimize density gradient. Numerous investigations had implemented these for one or single layer of green metal powder compact (Selig and Doman, 2014). Hypothetically, additional layers onto a single compressed green metal powder may possibly impose further minimization on density gradient (Sopchak & Misioliek, 2000) based on their investigations. Intervene between layers known as interface become a point of PM investigation since it was essentially determining the strength of green bilayer metal powder compact (Castrati et al., 2017; Marathe et al., 2017.; Meng et al., 2020; Saberi et al., 2018).

To examine the quality of green powder compact after ejection stage, huge amount of experimental works had been done on single powder compact by the variation in use of local RD measurement technique, nevertheless, there are few

experimental works of green bilayer powder compact that can be related. The use of geometrical definition, Archimedes, hardness and mechanical tests had been frequently be utilized as same for single powder compact to examine, however, the capability of an assessment to detect the densification area and its local RD distribution between two compressed layers of metal-based powder must be conducted. This quantitative approach is necessary to study, thus enable to analyse the gradient of local RD distribution throughout the sample.

1.2 Problem statement

Density, ρ of a sample of metal powder compact can be measured either in average or void ratio (known as its local relative density, RD). Most PM investigations had used average density by obtaining through simple geometrical definition. Whereas, the use of hardness and Archimedes methods must be taken to compute the local RD. Aforementioned type of density measurements is applicable conveniently for sintered metal powder compact, however, the evaluation of local RD for soft, scattered porous green metal powder compact had delimit this method causing inaccuracies in this measurement. A quantitative image analysis needs to be invented, thus, not to come in contact with the surface of a green sample. Furthermore, it is claimed that an increase in height of single layer powder for compaction had caused increase in its resulted local RD gradient (Wang et al.,2019). This limited the capability of PM compaction in handling a larger size of loose powder in axial direction to manufacture component of cutting tools as well as other tooling for machining processes up to its accepted final local RD gradient. Experimentally, layering method has been known to reduce the local RD gradient for increasing height of single layer powder compact, however, the relationship between the interface of compressed powder layers and die wall condition is remain uncovered.

1.3 Research objectives

- i. To develop and validate the finite element model of bilayer iron powder compact
- ii. To determine the effect of height to diameter (H/D) ratio of bilayer iron powder compact on the local RD and von Mises's stress distributions
- iii. To analyse the die wall frictional effect on the local RD and von Mises's stress distributions of bilayer iron powder compact

1.4 Significance of study

PM compaction is a type of metal-forming technique to fabricate a single layer of metal-based powder compact from loose powder. PM compaction is well-known for its effectiveness in delivering near-net shape of green single powder compact, thus, any additional machining works are not necessary. In order to enhance the improvement on the strength of green single powder compact, notable

investigations are established and implemented by industries such as green machining technique (Dehestani et al.,2016) and high-velocity compaction (HVC) (Wang et al.,2009). Instantly, the use of PM compaction route is widely contributing in various circles of industries, for instance, automobile (Jang et al.,2000), aerospace (Jiang et al.,2016), military products (Nezafati et al.,2015) and healthcare (Abebe et al.,2004) industries. Nevertheless, friction condition of a die wall is highly deteriorating the density quality of produced green single powder compact under PM compaction according to Edosa et al. (2022). They overviewed past discoveries on the influence of friction on pressed green single powder compact and any attempts to minimize the friction is briefly elaborated. Dubbing or spraying lubricants onto die wall is the most practice in modern PM in order to lower the effect of friction onto green single powder compact (Taniguchi et al.,2005). Following that, other notable works to preserve the density against friction are the designed are the designed compaction technique (Canta & Frunze,2003; Wang et al.,2009; Grigoriev et al.,2019), the initial determination of powder relative bulk density (RBD) (Radchenko, 2004), critical consideration of determined H/D ratio and geometrical powder compact shape (Cristofolini et al.,2018), the mixing method (Chen et al.,2020) and the layering strategy for green single powder compact (Sopchak & Misiolek, 2000). Alongside from its successful in overcome the frictional problem, researchers had profound its usefulness in producing versatile properties of tools in cutting and machining processes. To acknowledge, among from these introduced techniques to preserve the density of green single powder compact from friction, the layering strategy is infrequently reported and validate with FEM modelling in previous literatures (Rowe & Nikfar, 2017). The formation of interface or enclosed interactions between layers become an uncertainty, especially for modelling discussion. Therefore, it is useful for each researcher to perform their experimental part in order to recognize the structural type of interface and its mechanism framework along with doubled compaction steps.

The focus had been placed on the formation of green bilayer powder compact using ASC 100.29 iron powder since it is the best iron grade for consumption in metal forming industries due to its high ductility. Experimentally, addition of layer on green single powder compact to make green bilayer powder compact is known to reduce the local RD gradient, however, quantitative -based approach in terms of local RD distribution and modelling evaluations on interface of green bilayer powder compact of iron is not brought into consideration for documentation. Plus, manipulating the changes in die wall condition onto the green bilayer powder compact of iron is important to be highlight to study the effect of die wall friction on local RD distribution and how the die condition can assist in strengthen the interface in order to deliver a robust green bilayer powder compact of iron.

Thus, in order to elevate an accuracy in quantitatively computation of local RD distribution, an imaging technique is proposed. Also, prediction through FEM-based technique is necessary to release the interlocking effect on the interface of green bilayer powder compact. Via modelling, the evolution of interfacial local RD distribution under different height-to-diameter (H/D) ratios of green bilayer powder compact with constantly applied load compaction of 30 kN and 95 kN for

lower, L and upper, U layers respectively can be analysed. To validate, alternatives had been made by using the standard metallography technique with the image processing analysis. This can potentially be a beneficial contribution to produce defect -free green layered iron powder compacts.

1.5 Scope of study

- i. Iron powder grade of ASC 100.29 (Brand Hognas) is employed.
- ii. The use of constant load compaction of 30 kN and 95 kN on lower and upper layers is used, thus, the resulted interface can be observed clearly under one-sided compaction method.
- iii. Modelling on green single and bilayer iron powder compact based on finite element model in Abaqus 2020 (Abaqus 6.20).
- iv. Tested height-to-diameter (H/D ratio) is 1.0, 1.3, 1.6 and 1.9.
- v. Tested die wall friction is 0.08 and 0.18 for lubricated and unlubricated die conditions.

1.6 Thesis overview

Chapter 1 introduced the powder metallurgy (PM) in general regarding of its important processes for powder production, its advantages and shortfalls. The problem statements, objectives and scope of the research were highlighted.

Chapter 2 highlights several experimental works that deliver profound knowledges involving the measurement and improvement on density in general powder compaction. The underlying motivations of using multi-layered technique via powder metallurgy (PM) compaction are highlighted. In addition, the backgrounds and existing works of renowned computational tools compaction process in powder metallurgy (PM) for bilayer powder compact are reviewed as well.

Chapter 3 presents a systematic procedure on producing samples of single and bilayer green iron powder compact. Also, well established experimental works on retrieve quantitative image analysis were elaborated in details. For modelling part, the development of finite element model is extensively reported.

Chapter 4 reports both experimental and modelling results of all sectioned of bilayer samples were reported. The convergence study is firstly performed, followed by the comparison between the contour images of experimental and modelling density distribution for validation purpose. At this stage, the validity of using analytical equation of Brewin on two layers of green iron powder via finite element analysis (or FEA) can be determined. The effect of H/D ratios and friction coefficient on interfacial densification are presented for further analyses.

Chapter 5 summarizes the conclusions and offers some suggestions for future work.



REFERENCES

ABAQUS Inc. ABAQUS 2020 (6.20) User's Manual.

Akseli, I., Abebe, A., Sprockel, O., & Cuitiño, A. M. (2013). Mechanistic characterization of bilayer tablet formulations. *Powder Technology*, 236, 30–36. <https://doi.org/10.1016/j.powtec.2012.05.048>

An, X. Z., He, S. S., Feng, H. D., & Qian, Q. (2015). Packing Densification of Binary Mixtures of Spheres and Cubes Subjected To 3d Mechanical Vibrations. *Applied Physics A: Materials Science and Processing*, 118(1), 151–162. <https://doi.org/10.1007/s00339-014-8835-z>

An, X. Z., Yang, R. Y., Zou, R. P., & Yu, A. B. (2008). Effect of Vibration Condition and Inter-particle Frictions on The Packing of Uniform Spheres. *Powder Technology*, 188(2), 102–109. <https://doi.org/10.1016/j.powtec.2008.04.001>

Ashrafi, N., Mohamed Ariff, A. H., Jung, D.-W., Sarraf, M., Foroughi, J., Sulaiman, S., & Hong, T. S. (2022). Magnetic, Electrical, and Physical Properties Evolution in Fe₃O₄ Nanofiller Reinforced Aluminum Matrix Composite Produced by Powder Metallurgy Method. *Materials*, 15(12), 4153. <https://doi.org/10.3390/ma15124153>

Atrian, A. (2018). A Novel Approach to Calibrate the Drucker – Prager Cap Model for Al7075 Powder. *Archive of Applied Mechanics*. <https://doi.org/10.1007/s00419-018-1410-x>

Baroutaji, A., & Bryan, K. (2017). Mechanics and Computational Modeling of Pharmaceutical Tableting Process. In *Reference Module in Materials Science and Materials Engineering* (Issue July). Elsevier Ltd. <https://doi.org/10.1016/B978-0-12-803581-8.09269-9>

Baroutaji, A., Lenihan, S., & Bryan, K. (2017). Combination of finite element method and Drucker-Prager Cap material model for simulation of pharmaceutical tableting process: *Materialwissenschaft und Werkstofftechnik*, 48(11), 1133-1145.

Boonyongmaneerat, Y., & Schuh, C. A. (2006). Contributions To the Interfacial Adhesion in Co-sintered Bilayers. *Metallurgical and Materials Transactions A: Physical Metallurgy and Materials Science*, 37(5), 1435–1442. <https://doi.org/10.1007/s11661-006-0088-9>

Castrati, L., Mazel, V., Busignies, V., Diarra, H., Rossi, A., Colombo, P., & Tchoreloff, P. (2016). Comparison Of Breaking Tests for The Characterization of The Interfacial Strength of Bilayer Tablets. *International Journal of Pharmaceutics*, 513(1–2), 709–716. <https://doi.org/10.1016/j.ijpharm.2016.10.005>

- Castrati, L., Mazel, V., Diarra, H., Busignies, V., & Tchoreloff, P. (2017). Effect of the Curvature of the Punches on the Shape of the Interface and the Delamination Tendency of Bilayer Tablets. *Journal of Pharmaceutical Sciences*, 106(5), 1331–1338. <https://doi.org/10.1016/j.xphs.2017.01.020>
- Chávez, J., Olmos, L., Jiménez, O., Bouvard, D., Rodríguez, E., & Flores, M. (2017). Sintering Behaviour and Mechanical Characterisation of Ti64/xin Composites and Bilayer Components. *Powder Metallurgy*, 60(4), 257–266. <https://doi.org/10.1080/00325899.2017.1280585>
- Chen, W., Wang, J., Wang, S., Chen, P., & Cheng, J. (2020). On The Processing Properties and Friction Behaviours During Compaction of Powder Mixtures. *Materials Science and Technology (United Kingdom)*, 36(10), 1057–1064. <https://doi.org/10.1080/02670836.2020.1747779>
- Chikosha, S., Tshabalala, L. C., Bissett, H., Lesufi, M., Mnguni, N. K., Motsai, T. M., Manama, T., & Hoosain, S. (2021). Spheroidisation Of Stainless-steel Powder for Additive Manufacturing. *Metals*, 11(7). <https://doi.org/10.3390/met11071081>
- Coube, O., & Brewin, P. (2002). Modelling And Numerical Simulation of Powder Compaction. *Powder Metallurgy*, 45(1), 18–19. <https://doi.org/10.1179/003258902225002514>
- Cristofolini, I., Molinari, A., Pederzini, G., & Rambelli, A. (2018a). From Experimental Data, The Mechanics Relationships Describing the Behaviour of Four Different Low Alloyed Steel Powders During Uniaxial Cold Compaction. *Powder Metallurgy*, 61(1), 10–20. <https://doi.org/10.1080/00325899.2017.1361507>
- Diarra, H., Mazel, V., Busignies, V., & Tchoreloff, P. (2018). Sensitivity Of Elastic Parameters During the Numerical Simulation of Pharmaceutical Die Compaction Process with Drucker-Prager/cap Model. *Powder Technology*, 332, 150–157. <https://doi.org/10.1016/j.powtec.2018.03.068>
- Edosa, O. O., Tekweme, F. K., & Gupta, K. (2022). A Review on The Influence of Process Parameters on Powder Metallurgy Parts. In *Engineering and Applied Science Research* (Vol. 49, Issue 3, pp. 433–443). Paulus Editora. <https://doi.org/10.14456/easr.2022.44>
- Favrot, N., Besson, J., Colin, C., & Delannay, F. (1999). Cold Compaction and Solid-State Sintering of WC-Co-Based Structures: Experiments and Modeling. *Journal of the American Ceramic Society*, 82(5), 1153-1161.
- Frandsen, H. L., Olevsky, E., Molla, T. T., Esposito, V., Bjørk, R., & Pryds, N. (2013). Modeling Sintering of Multilayers Under Influence of Gravity. *Journal of the American Ceramic Society*, 96(1), 80–89. <https://doi.org/10.1111/jace.12070>

- Grigoriev, Dmitriev, Korobova, & Fedorov. (2019). A Cold-Pressing Method Combining Axial and Shear Flow of Powder Compaction to Produce High-Density Iron Parts. *Technologies*, 7(4), 70. <https://doi.org/10.3390/technologies7040070>
- Groenenboom, P., Choi, K., Lee, I., Choi, S., & Hong, S. (2012). Numerical Simulation of Powder Metal Forming Process Using the SPH Method. *Steel Research International*, 787-790.
- Gustafsson, G., Nishida, M., Häggblad, H. A., Kato, H., Jonsén, P., & Ogura, T. (2014a). Experimental Studies and Modelling of High-velocity Loaded Iron-powder Compacts. *Powder Technology*, 268(1), 293–305. <https://doi.org/10.1016/j.powtec.2014.08.060>
- Han, L. H., Elliott, J. A., Bentham, A. C., Mills, A., Amidon, G. E., & Hancock, B. C. (2008). A Modified Drucker-Prager Cap Model for Die Compaction Simulation of Pharmaceutical Powders. *International Journal of Solids and Structures*, 45(10), 3088–3106. <https://doi.org/10.1016/j.ijsolstr.2008.01.024>
- Han, P., An, X., Wang, D., Fu, H., Yang, X., Zhang, H., & Zou, Z. (2018). MPFEM Simulation of Compaction Densification Behavior of Fe-al Composite Powders with Different Size Ratios. *Journal of Alloys and Compounds*, 741, 473–481. <https://doi.org/10.1016/j.jallcom.2018.01.198>
- Han, P., An, X., Zhang, Y., Huang, F., Yang, T., Fu, H., Yang, X., & Zou, Z. (2017). Particulate Scale MPFEM Modeling on Compaction of Fe and Al Composite Powders. *Powder Technology*, 314, 69–77. <https://doi.org/10.1016/j.powtec.2016.11.021>
- Huang, F., An, X., Zhang, Y., & Yu, A. B. (2017). Multi-particle FEM Simulation of 2D Compaction on Binary Al/SiC Composite Powders. *Powder Technology*, 314, 39–48. <https://doi.org/10.1016/j.powtec.2017.03.017>
- Jia, Q., An, X., Zhao, H., Fu, H., Zhang, H., & Yang, X. (2018). Compaction and Solid- State Sintering of Tungsten Powders: MPFEM Simulation and Experimental Verification. *Journal of Alloys and Compounds*, 750, 341–349. <https://doi.org/10.1016/j.jallcom.2018.03.387>
- Jonsén, P. (2006). Fracture and Stress in Powder Compacts (Doctoral dissertation, Luleå tekniska universitet).
- Jonsén, P., Häggblad, H. Å., & Gustafsson, G. (2015). Modelling the Non-linear Elastic Behaviour and Fracture of Metal Powder Compacts. *Powder Technology*, 284, 496–503. <https://doi.org/10.1016/j.powtec.2015.07.031>
- Lemieux, P., Pelletier, S., Thomas, P. E. M. Y., Lefebvre, L. P., & Chagnon, F. (2001). A New Approach to Die Wall Lubrication for P/M Applications. *Advances in Powder Metallurgy and Particulate Materials*, (3), 3-1.

- Lu, A., & An, X. (2018). Two-Dimensional Multiparticle Finite Element Modeling on the Cold Isostatic Pressing of Al Powder. *Metallurgical and Materials Transactions A: Physical Metallurgy and Materials Science*, 49(10), 4838–4848. <https://doi.org/10.1007/s11661-018-4753-6>
- Marathe, P. P., Patil, S. V., Nayak, K. C., Date, P. P., & Pirumov, A. Interface Behavior of Aluminum and Iron Powder Compacts at Room Temperature.
- Meng, Z., Gong, M., Guo, W., Liu, W., Huang, S., & Hua, L. (2020). Numerical Simulation of The Joining Interface of Dissimilar Metals in Vaporizing Foil Actuator Welding: Forming mechanism and factors. *Journal of Manufacturing Processes*, 60, 654–665. <https://doi.org/10.1016/j.jmapro.2020.11.009>
- Michrafy, A., Dodds, J. A., & Kadiri, M. S. (2004). Wall Friction in The Compaction of Pharmaceutical Powders: Measurement and Effect on The Density Distribution. *Powder Technology*, 148(1), 53–55. <https://doi.org/10.1016/j.powtec.2004.09.021>
- Nazihah Mas, N., Mohd Foudzi, F., Bakar Sulong, A., Muhamad, N., Fadhlin Mohamed, I., Mohd Salleh, F., & Bonaventure Emeka, U. (2018). Two Component Materials in Powder Metallurgy: A Review Paper Focused on the Processing Technique Applied in Powder Metallurgy (Dua Komponen Bahan di dalam Metalurgi Serbuk: Kertas Kajian Tumpuan kepada Teknik Pemprosesan yang Digunakan dalam Metalurgi Serbuk). *Jurnal Kejuruteraan SI*, 1(6), 23–31. [https://doi.org/10.17576/jkukm-2018-si1\(6\)-04](https://doi.org/10.17576/jkukm-2018-si1(6)-04)
- Olevsky, E., Molla, T. T., Frandsen, H. L., Bjørk, R., Esposito, V., Ni, D. W., Ilyina, A., & Pryds, N. (2013). Sintering of Multilayered Porous Structures: Part I-constitutive Models. *Journal of the American Ceramic Society*, 96(8), 2657–2665. <https://doi.org/10.1111/jace.12375>
- Pascal, C., Chaix, J.-M., Bouvard, D., Thomazic, A., le Guennec, Y., Kamdem, Y., Chaix, J. M., Doremus, P., Imbault, D., Bouvard, D., & Doré, F. (2010). Fabrication Of Bimaterial Components by Conventional Powder Metallurgy.
- Popescu, I. N., & Vidu, R. (2018). Compaction Behaviour Modelling of Metal-Ceramic Powder Mixtures. A Review. *Scientific Bulletin of Valahia University - Materials and Mechanics*, 16(14), 28–37. <https://doi.org/10.1515/bsmm-2018-0006>
- Povstianoi, O. Y., Rud, V. D., Imbirovych, N. Y., Halchuk, T. N., Chetverzhuk, T. I., Smal, M. v., & Dziubynskyi, A. v. (2021). Optimization of the Properties of Multilayer Porous Permeable Materials. *Materials Science*, 56(4), 530–535. <https://doi.org/10.1007/s11003-021-00460-2>
- Radchenko, A. K. (2004). Mechanical Properties of Unsintered Pressings. I. Phenomenological Relations for Unsintered Pressing Strength. In *Powder Metallurgy and Metal Ceramics* (Vol. 43, Issue 9).

- Rahman, M. M., Ariffin, A. K., & Nor, S. S. M. (2009). Development Of a Finite Element Model of Metal Powder Compaction Process at Elevated Temperature. *Applied Mathematical Modelling*, 33(11), 4031–4048. <https://doi.org/10.1016/j.apm.2009.02.005>
- Rajab, M., Coleman, D. S., & Rajab, M. (1985). Density Distributions in Complex Shaped Parts Made from Iron Powders. *Powder Metallurgy*, 28(4), 207–216. <https://doi.org/10.1179/pom.1985.28.4.207>
- Rowe, J. M., & Nikfar, F. (2017). Modeling Approaches to Multilayer Tableting. In *Predictive Modeling of Pharmaceutical Unit Operations*. Elsevier Ltd. <https://doi.org/10.1016/B978-0-08-100154-7.00009-0>
- Saberi, M., Annan, C. D., & Konrad, J. M. (2018). On The Mechanics and Modeling of Interfaces Between Granular Soils and Structural Materials. *Archives of Civil and Mechanical Engineering*, 18(4), 1562–1579. <https://doi.org/10.1016/j.acme.2018.06.003>
- Selig and Doman. (2014). A Review of Finite Element Simulations of Metal Powder Die Compaction. 3 (June), 32–40.
- Selig, S. G., & Doman, D. A. (2015). Finite Element Simulation of the Compaction and Springback of Alumix 321 PM Alloy. *Journal of Applied Mathematics*, 2015. <https://doi.org/10.1155/2015/283843>
- Sinha, T., Curtis, J. S., Hancock, B. C., & Wassgren, C. (2010). A Study on The Sensitivity of Drucker-prager Cap Model Parameters During the Decompression Phase of Powder Compaction Simulations. *Powder Technology*, 198(3), 315–324. <https://doi.org/10.1016/j.powtec.2009.10.025>
- Sinka. (2007). Modelling Powder Compaction. *KONA Powder and Particle Journal*.
- Sinka, I. C., Cunningham, J. C., & Zavaliangos, A. (2003). The Effect of Wall Friction in The Compaction of Pharmaceutical Tablets with Curved Faces: A Validation Study of The Drucker-Prager Cap Model. *Powder Technology*, 133(1–3), 33–43. [https://doi.org/10.1016/S0032-5910\(03\)00094-9](https://doi.org/10.1016/S0032-5910(03)00094-9)
- Sopchak, N. D., & Misiulek, W. Z. (2000). Density Gradients in Multilayer Compacted Iron Powder Parts. *Materials and Manufacturing Processes*, 15(1), 65–79. <https://doi.org/10.1080/10426910008912973>
- Tahir, S. M., Ariffin, A. K., & Anuar, M. S. (2010). Finite Element Modelling of Crack Propagation in Metal Powder Compaction Using Mohr-coulomb And Elliptical Cap Yield Criteria. *Powder Technology*, 202(1–3), 162–170. <https://doi.org/10.1016/j.powtec.2010.04.033>
- Taniguchi, Y., Dohda, K., & Wang, Z. (2005). Effect of lubrication on the Improvement of Uniformity in Uniaxial Powder Compaction. *JSME*

International Journal Series A Solid Mechanics and Material Engineering, 48(4), 393-398.

- Thomazic, A., le Guennec, Y., Kamdem, Y., Pascal, C., Chaix, J. M., Doremus, P., Imbault, D., Bouvard, D., & Doré, F. (2010a). Fabrication Of Bimaterial Components by Conventional Powder Metallurgy. Proceedings of the World Powder Metallurgy Congress and Exhibition, World PM 2010, 5(March 2015), 2–9.
- Torralba, J. M., Alvaredo, P., & García-Junceda, A. (2019). High-entropy Alloys Fabricated Via Powder Metallurgy. A critical review. In Powder Metallurgy (Vol. 62, Issue 2, pp. 84–114). Taylor and Francis Ltd. <https://doi.org/10.1080/00325899.2019.1584454>
- Tura, A. (2014). A Review of Finite Element Analysis Method. Computer Aided Design Course (Lecture Notes), University of Victoria.
- Tweed, J. H., Burch, S. F., Gethin, D. T., Guyoncourt, D. M. M., & Rolland, S. (2008). Cracking in Green Compacts. Proceedings of the Euro International Powder Metallurgy Congress and Exhibition, Euro PM 2008, 3, 102–108.
- Wang, D., An, X., Han, P., Fu, H., Yang, X., & Zou, Q. (2020). Particulate Scale Numerical Investigation on the Compaction of TiC-316L Composite Powders. Mathematical Problems in Engineering, 2020. <https://doi.org/10.1155/2020/5468076>
- Wang, J. Z., Qu, X. H., Yin, H. Q., Yi, M. J., & Yuan, X. J. (2009a). High Velocity Compaction of Ferrous Powder. Powder Technology, 192(1), 131–136. <https://doi.org/10.1016/j.powtec.2008.12.007>
- Wang, J. Z., Yin, H. Q., Qu, X. H., & Johnson, J. L. (2009). Effect Of Multiple Impacts on High Velocity Pressed Iron Powder. Powder Technology, 195(3), 184–189. <https://doi.org/10.1016/j.powtec.2009.05.028>
- Wang, W., Qi, H., Liu, P., Zhao, Y., & Chang, H. (2018). Numerical Simulation of Densification of Cu–Al Mixed Metal Powder During Axial Compaction. Metals, 8(7). <https://doi.org/10.3390/met8070537>
- Wu, C. Y., Best, S. M., & James A Elliot. (2005). Modelling The Mechanical Behavior of Pharmaceutical Powders During Compaction. April. <https://doi.org/10.1016/j.powtec.2005.01.010>
- Yohannes, B., Gonzalez, M., & Cuitino, A. M. (2017). Discrete Numerical Simulations of the Strength and Microstructure Evolution During Compaction of Layered Granular Solids. From Microstructure Investigations to Multiscale Modeling: Bridging the Gap, 123–141. <https://doi.org/10.1002/9781119476757.ch5>
- Zadeh, H. K. (2010). Finite Element Analysis and Experimental Study of Metal Powder Compaction. Queen's University.

Zadeh et al. (2013). Improvement In Robustness and Computational Efficiency of Material Models for Finite Element Analysis of Metal Powder Compaction and Experimental Validation. <https://doi.org/10.1007/s00170-013-4977-y>

Zhou et al. (2017a). A Density-Dependent Modified Drucker-Prager Cap Model for Die Compaction of Ag57.6-Cu22.4-Sn10-In10 Mixed Metal Powders. Powder Technology, 305, 183–196. <https://doi.org/10.1016/j.powtec.2016.09.061>

Zhou, M., Huang, S., Liu, W., Lei, Y., & Yan, S. (2018). Experiment Analysis and Modelling of Compaction Behavior of Ag60Cu30Sn10 Mixed Metal Powders. IOP Conference Series: Materials Science and Engineering, 317(1). <https://doi.org/10.1088/1757-899X/317/1/012011>



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