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

SYAMIMI BINTI MOHD YUSOFF

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By

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June 2022

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
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PERMODELAN UNSUR TERHINGGA BAGI PEMADATAN SERBUK BESI DWILAPISAN DAN PENILAIAN TERHADAP TABURAN KETUMPATAN RELATIFNYA DENGAN MENGGUNAKAN 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 lebihan 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 diperoleh 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 fulfilment 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 & Misiolek, 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 quantitively 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 Hoganas) 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.

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