Study the densification behavior and cold compaction mechanisms of solid particles-based powder and spongy particles-based powder using a multi-particle finite element method

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Abstract

Powders could be based on solid particles or spongy particles depending on the powder manufacturing procedures. In this article, the numerical study of the cold compaction process for copper solid particles-based powder (i.e. Cu solid powder) and spongy particles-based powder (i.e. Cu sponge powder) has been carried out using a two-dimensional multi-particle finite element method (2D-MPFEM) based on single action die compaction. The effects of internal pores content, external pressure, initial packing structure on the packing densification were systematically presented. Relative density, stress distribution, internal pore deformations, and force chain movements, particle rearrangement, and interfacial behavior within spongy particles were characterized and analyzed. The results reveal that the densification behavior of the spongy powder depends basically on the internal pore’s content. Moreover, at low and medium relative density ($\rho < 0.95$), the densification behavior of the sponge powder is faster than solid particles-based powder. However, at higher relative density near unity, the force required to cause further compaction is significantly larger in the sponge powder. In addition, from the microscopic analysis, the deformation behavior of the particles and the internal pores and the force chain development rely mostly on the structure configuration, internal pore content and its position.

1. Introduction

Recently, powder metallurgy (PM) becomes an appealing process technology for both advanced and traditional materials [1]. The PM technique is competitive with conventional metallurgical manufacturing methods such as casting, forging, and machining. Moreover, it has distinctive merits such as high production rate and near-net-shape forming for complex geometrical shapes, special metals, alloys with high melting points, and porous structures. In addition, it can be considered cost-effective, materials saving, easy operation, and environment-friendly mechanism [2]. Thus, PM techniques have a lot of applications that can be used in the areas of materials, marine industries, aeronautics, astronautics, and automotive parts [3]. Powder cold compaction is one of the major stages of PM production processes that plays a key role. Through the compaction, loose powders are compressed into a cohesive and dense state using tools such as compression punches and dies [4]. The powder compact structure resulting from the powder cold compaction affects the sintering process and the properties of the final product. Therefore, any optimization of the powder compaction process requires a deep understanding of the relations between the influential factors and the densification behaviors during the powder compaction process. Consequently, a large variety of physical and numerical studies have been carried out in this regard.

It is very complicated for physical experiments to characterize parameters and properties of the green compacts such as the evolution of stress distribution and local relative density and plasticity and elasticity phenomena [5]. Accordingly, the internal friction of the porous medium and the frictional effects between the die walls may take place which can be considered as results of the inhomogeneous distributions of the density
and the residual stress. Thus cracks may appear in the compacted zone during the pressing process [6]. On the 
other hand, the numerical methods can be considered as a cheap and easy solution to understand the 
complicated behavior of the powders and help the prediction of the product properties.

At present, for the densification analysis of powder compaction, three numerical approaches are available 
which are continuum finite element method (FEM), discrete element method (DEM) and multi-particle finite 
element method (MPFEM). The continuum finite element analysis considers the compacted part as a 
continuous media with a certain percent of gas porosity. The continuum approach can describe the macroscopic 
densification behaviors but can’t represent the detailed microscopic information such as the particle 
deformation, displacement path, and inter-particle frictional interactions. Two continuous models are available 
in the previous studies which are the micromechanical model [7, 8] and phenomenological model [9, 10]. The 
micromechanical model is based on mechanical behavior at particle-particle contacts. Therefore, it can be 
considered as an inaccurate model for the simulation of the powder with the higher densities. In addition, it 
usually treats each powder contact mechanically independent of the other neighboring contacts, so, such a 
hypothesis isn’t accurate at higher densities. Therefore, many studies have been conducted to include the contact 
effects of micromechanical modeling of powder compaction [11, 12]. In the phenomenological model, several 
functions are used to describe the porous materials’ responses upon the stress and the relative density 
distribution. In addition, the load impacts in the green compact can be predicted as presented in [13, 14]. 
However, the mechanical properties can’t accurately be predicted since the physics and geometry of the 
compacts are ignored. The second method that usually used for the densification analysis of powder compaction 
is the discrete element analysis (DEM). The DEM deal with each powder particle as a rigid body without any 
plastic deformation. A lot of microscopic activities during the compaction process can be assessed such as 
particle sliding, rolling and flow tendency however the precise estimation is restricted to the lower relative 
density than 0.9 [15–17]. These challenges can be compensated by the third numerical technique for the 
densification analysis of the powder compaction, which is MPFEM, where it can be used for simulating high-
density compaction of powders.

MPFEM considers a full finite element discretization of each particle without any simplification in contact 
interactions. The powder compact is described as a discrete particle with discretized mesh division in each 
particle, thus the detailed particle information such as deformation and inter-particle contacts can be 
obtainable. A significant number of the research works have been reported on the powder compaction using a 
MPFEM. For instance, Procopio and Zavaliangos [8] used the MPFEM simulations to describe the variation of 
the densification yield surfaces and stress state under different strain states. Zavaliangos [18, 19] performed a 2D 
simulation of 400 particles using the MPFEM and revealed that inter-particle frictional play an important role 
in the macroscopic response in the earlier stages of compaction, and the tensile stresses were developed in 
powder and lead to fragmentation in low ductility particles. Chen et al [20] carried out a comparison between 
pressing force that was applied on two models (single-particle model and a BCC packing model of nine particles) 
using MPFEM and the numerical results have found to be in good agreement with the experimental data. Zhang 
et al [21] studied the compaction of a composite mixture of soft and hard micro-size particles using the MPFEM, 
in addition, investigated the effect of inter-particle frictional coefficient, Poisson’s ratio and material hardening of 
hard particles on compaction pressure. Lee et al [22] used the MPFEM to compact the aluminum powders under 
different pressing conditions such as different punch speeds and particle diameters and confirm that the small 
particle size can add more frictional energy dissipation during powder compaction and for the same punch 
stroke, higher compaction velocity provided higher loads and lower punch stroke for a specific load. Y. X. Zhang 
et al [23] carried out the MPFEM simulation to study the densification behavior of random and ordered packings 
solid particles-based powder. A. Lu et al [24] modeled the cold isostatic pressing (CIP) process of Al powders by 
using MPFEM to study the effects of initial packing structures on the packing densification. Yu Lei et al [25] used 
the MPFEM for densification analysis for three different initial packing structures (hexagonal, tetragonal, and 
random) and the numerical results were compared with experimental data. The simulation results of MPFEM 
for a random packing structure showed a good agreement with the experimental results and can give insight into 
the particle-level densification mechanism in physical compaction tests. P. Han et al [26, 27] carried out 
systematic studies using MPFEM on Fe-Al composite powders and the effects of the compaction pressure, 
compaction methods, initial packing structure of the powder, powder composition and size ratio for composite 
powders were characterized and analyzed. X An et al [28] modeled Uniaxial die compaction of (2D) Al/SiC 
composite powders with Core/Shell Structure using MPFEM and various macro and micro properties, 
deformation and mass transfer, and interfacial behavior within composite particles were characterized and 
analyzed.

However, these previous studies mainly focused on presenting the powder particle as a solid particle and did 
not consider that the powder particles could have internal pores or be sponge powder based on the way of 
manufacturing. Basically, there are three principal methods by which metallic powders are commercially 
produced which are atomization, reduction of oxides, and electrolytic [29]. The reduction of oxides compounds
exceptionally is one of the most widely used of producing metal powders. It is a convenient, and extremely flexible method to control the properties of the product such as size, shape, and porosity over a wide range. It is employed particularly for powders of iron, copper, nickel, cobalt, tungsten, molybdenum, tantalum, thorium and titanium. Usually, the powders produced by the oxide reduction method have internal pores within each powder particle [30]. This sponginess can be controlled by the amount and size of the pores. Copper powders produced by oxide reduction are suitable for high-green-strength applications [31, 32]. Otarawanna [33] studied cold compactions of the regular-density, high-density spongy particles-based powder, and solid particles-based powder using the porous constitutive model and the ‘explicit particle modelling’ approach. Gerdemann et al [34] compress the spongy particles-based powder and different titanium powders to collect stress and deformation data during the cold compaction in a single-acting die. Machaka et al [35, 36] analyzed the behavior and mechanisms of densification in sponge titanium powder and selected nanocomposite titanium powder samples by means of the comprehensive inter-model comparison of existing compaction equations.

In spite of the spongy particles-based powder is the most virtually common because using the oxide reduction method for producing copper powder, to best of our knowledge, there are no methodical studies were found on the compaction of copper sponge powders by using MPFEM simulation, especially study the micro-dynamic analysis on the compaction process, and corresponding densification mechanisms for internal pores are still lacking. Therefore, the main contributions of this article are

• Attempt to truly represent the sponge copper powder densification behavior in the cold compaction using 2D-MPFEM simulation. The sponge copper powder has been represented as arrangement of individual spheres particles which includes internal pores.

• The compaction pressure and densification mechanism have been studied under different initial internal pores content (vol%).

• Various macroscopic and microscopic properties and the densification dynamic of the powder compact and the internal pores was characterized for different initial packing’s of sponge copper powders (i.e. tetragonal packing (SC), hexagonal close-packed (HCP) structure, and face-center-cubic (FCC) packing and random loose packing) with 5 vol% internal pores content before compaction.

2. Simulation method and conditions

The MPFEM is used to simulate the cold compression process of particle combination under quasi-static circumstances. The compaction computations were carried out using an explicit integration scheme of a commercial finite element program (ABAQUS Explicit). The explicit method of the numerical analysis is appropriate in case of the large number of actual or possible contacts succumbing to large deformation. Furthermore, the explicit method is the best option for the finite element mesh, material parameters, and boundary conditions, because this analysis is computationally intensive and aids to increase the efficiency with maintaining the accuracy.

Depending on the powder production techniques, powders used in the powder compaction could be either solid or sponge particles. There are different powder fabrications that lead to producing powders with different characteristics. For simplicity, the details of the different powder fabrications are not given here, interested readers can refer to ref. [30–32] for more information. Oxide reduction is one of the economical and extremely flexible methods to control the properties of the product powder. However, powders produced by this method have internal pores within each powder particle and can be called sponge powder. Figure 1(a) represents the solid particle that fabricated by atomization and figure 1(b) the spongy particle fabricated by oxide reduction. The particle surface is irregular and has some convex platonic polyhedral which leads to more complex particle shape. However, in current work, the particle surface is treated as a regular surface because the complex particle shapes raise the difficulties in producing different orders and disordered initial packing for the simulation. In addition, a very fine mesh may be required for the accurate simulation of the complex interaction between the particles which leads to long computational time.

Figure 2 gives the schematic diagram of individual Cu particles in solid and sponge state with different internal pores contents (vol%) where the internal pores were represented inside the particles as circular holes. Furthermore, figure 3 provides the corresponding mesh division of the individual Cu solid particle in the initial tetragonal packing structure that is a very fine mesh. The analysis is implemented on the plane strain condition for its convenience that the element type was a 4-node bilinear plane strain quadrilateral, reduced integration, hourglass control, mesh distortion control, (CPE4R) and the mesh size was set 0.035 mm which kept the same for all simulation cases. The total mesh domain is distributed as 3093 nodes and 3002 elements on the surface.
particle; however, the number of nodes and elements is different depending on the number of internal pores in a particle.

In the MPFEM simulation, the particle deformation and stress distribution can be registered during compression by considering all particles in the models are establish as deformable contact bodies whereas the die and the punch are set as rigid bodies. Moreover, in this study, the Coulomb friction model is used where the

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**Figure 1.** SEM photomicrographs of (a) Solid particle and (b) Spongy particle.

**Figure 2.** Schematic diagram of individual Cu particles with different internal pores content (vol.%): (1) 0% (i.e. solid particle), (2) 1%, (3) 2%, (4) 3%, (5) 4% and (6) 5%.

**Figure 3.** Mesh division used in the MPFEM simulation.
friction coefficient among the particles is set to be $\mu = 0.2$. In addition, the die wall and the upper punch are set to be smooth to reduce the wall friction effect. The position of the rigid die is kept stationary while the punch is movable. The punch moves according to the downward motion and the forces are appearing on those particles in contact with this punch and then will be transmitted downward to their neighboring particles. Meanwhile, with the downward motion of the punch, the forces will gradually appear around the internal pores in every particle. This process will continue until the forces reach all die walls. Upon compaction simulation, the contacts were controlled between particles by setting ‘surface to surface contact’ and in the internal pores by setting ‘self-surface contact’. As the elastic–plastic model has been successfully used for the numerical simulation of most metallic solids as in [8, 21, 22]. Therefore, throughout our simulation study, the particles are substantially dealt as elastic–plastic material where the deformation of a particle can be given by [37]:

$$\varepsilon = \varepsilon^e + \varepsilon^p$$  \hspace{1cm} (1)

where $\varepsilon$ is the total strain, $\varepsilon^e$ is the elastic strain and $\varepsilon^p$ is plastic strain. The elastic deformation is characterized by Hooke’s law [37], which can be given by

$$\sigma^e = E\varepsilon^e$$  \hspace{1cm} (2)

where $\sigma^e$ is elastic stress, $E$ is the modulus of elasticity and $\varepsilon^e$ is elastic strain. In this study, the plastic model used by Chen et al [20] was used to describe the plastic deformation of particles, which can be depicted by:

$$\sigma = K(\varepsilon^p)^n + \sigma_Y$$  \hspace{1cm} (3)

where the $\sigma$ is the total stress, $\sigma_Y$ is yield pressure, $K$ and $n$ are the material parameters. The parameters of Cu powder used in our simulation are listed in table 1.

The MPFEM is used to analyze the single action die compaction of mono-sized spherical Cu particles with a Radius ($R$) of 1 mm. Firstly, the cold compaction simulation is carried out for six tetragonal packing structures with different initial internal pores content which can be defined either per particle as follows:

$$\text{Internal pores content per particle} = \frac{\text{Internal pores volume in each particle}}{\text{Total particle volume}} = \frac{n.V_{ip}}{V_p}$$  \hspace{1cm} (4)

or per structure as

$$\text{Internal pores content per packing structure} = \frac{\text{Internal pores volume in packing structures}}{\text{Total structure volume}} = \frac{N.n.V_{ip}}{V_d}$$  \hspace{1cm} (5)

where $V_p$ is the particle volume, $n$ is the number of the internal pores per particle, $N$ is the number of particles per structure, and $V_d$ is the die volume. In addition, the internal pores content in every particle can be adjusted by the thickness ($r$) of mono-sized internal spherical pore which has a volume of $V_{ip}$. The packing density ($\rho$) for packing structures can be calculated as follows

$$\rho = \frac{\text{particle volume in packing structure}}{\text{Total structure volume}} = \frac{N.V_p}{V_d}$$  \hspace{1cm} (6)

The corresponding parameters and information are listed in table 2.

Four initial packings with random and different ordered packing structures with 5 vol% internal pores content per particle are simulated by MPFEM. The relative packing density $\rho$ and the number of particles $N$ in each structure are listed as: (a) Tetragonal packing (SC), $\rho = 0.7461, N = 16$; (b) Hexagonal close packing (HCP), $\rho = 0.8360, N = 20$; (c) Face centered cubic packing (FCC), $\rho = 0.7461, N = 18$ and (d) Random packing, $\rho = 0.7090, N = 32$.  

| Material | Young’s modulus (E/GPa) | Poisson’s ratio ($\nu$) | Strength coefficient (K/MPa) | Work-hardening index ($n$) |
|----------|-------------------------|-------------------------|-------------------------------|---------------------------|
| Cu       | 120                     | 0.36                    | 448                           | 0.126                     |

Table 1. Material parameters of Cu powder.
3. Results and discussion

3.1. Relationship between the pressure and the relative density

In the actual situation, the compaction process is influenced by many factors, where the compaction pressure $P$ plays a dominant role. Figure 4(a) shows the relationship between the relative density $\rho$ and compaction pressure $P$ of SC packing structures for Cu solid and sponge particles-based powder with different internal pores content (vol.%) per powder particle during the cold compaction. Three stages can be clearly observed for each $\rho$-$P$ curve. This can be defined as follows:

(1) Small $\rho$ ($\rho < 0.86$), $P$ increases slowly in all simulation models with different initial relative density till the pressure reaches a certain value at about 350MPa, at this pressure, all the simulation models virtually...
achieve the same relative density. It can be observed that the densification behavior of the model with the highest internal pore content is much faster than the model with the lowest internal pore content.

(2) Medium \( \rho \) (0.86 < \( \rho \) < 0.95) at this stage, the faster densification behavior of the model with the highest internal pores content continues but with a lower rate than the first stage. The model with the higher internal pores content gains relative density higher than others at the same pressure. The rapid densification behavior is remaining till the pressure reaches 720 MPa, at this pressure, all the simulation models virtually achieve the same relative density and that’s because the filling rate of the internal pores is reduced dramatically which delays the deformation unless higher pressure is applied.

(3) High \( \rho \) (\( \rho > 0.95 \)) at this stage, when the pressure exceeds the critical value at about 720MPa, in general for all models, the increasing rate of the relative density decreases, especially the models with the higher internal pores content. The filling and deformation rates of the internal pores are reduced dramatically as the internal pores deformed to irregular small areas with some sharp corners due to the non-uniform distribution of the stresses around the pores which require more pressure to deform. In other words, the \( \rho- P \) curve tends to settle down because the large deformation of particles creates work hardening which delays further deformation unless extra high pressure is applied. Additionally, at the end of this stage, the powder mass shows bulk behavior. At this stage, it can be led that the packing structure with less initial internal pores content can achieve higher relative density than other at the same pressure.

In general, it can be concluded that at low and medium relative density, the densification rate of the sponge powder is higher than solid powder. However, as the relative density goes approximately towards the value of unity (fully dense), the force required to cause further compaction is significantly larger. This is because the amount of space left behind the internal pores after the compaction is very small, so the matrix material only has limited areas to flow and becomes effectively incompressible. Therefore, in the range of very high relative density (approximately more than 0.98), the sponge powder requires higher pressure than the solid powder to achieve the same relative density.

Figure 4(b) provides the development of the relative density \( \rho \) with the pressure \( P \) of the cold compaction for different initial packing structures (i.e. tetragonal (SC), hexagonal close-packed (HCP) and face-centered cubic (FCC) and disordered packing structures) for Cu powders with 5% internal pores content per particle. The initial packing arrangement considerably impacts on the early stage of the cold compaction densification behavior. Three stages of each \( \rho- P \) curve can be stated. In the first stage (i.e. particle arrangement stage), at low \( P \), the relative density \( \rho \) increases rapidly with a small increase of applied pressure. The rearrangement and elastic deformation of the particles play a dominant role during the densification process. This stage not apparent for ordered initial packing structures such as SC, HCP, and FCC structures as the ordered initial structure is relatively stable and the particle rearrangement is rather limited compared to that in the cold compaction of powders with disordered initial packing structure. In the second stage (i.e. plastic deformation stage), with the increasing of the applied pressure, the particles in the compact are interlocked and the relative density continuously increases with the pressure to a high value. In this duration, the plastic deformation of the particles dominates the densification process and the internal pores and the voids in between the particles can be filled efficiently. In the third stage, at very high relative density (\( \rho > 0.93 \)), the very high pressure further densifies the packing and only some isolated internal pores and some isolated voids are left in the final compact.

The three curves of SC, FCC, and random packing structures simulations tend to coincide. The large deformation of particles leads to severe work hardening and the formation of small areas with sharp corners resulting in a decrease of the densification rate. Meanwhile, it can also be seen that the FCC and SC initial packing structures have the same initial relative density, but there is a difference in densification behavior. The SC structure requires a higher level of pressure than the FCC structure to cause deformation and that’s because the powder particles are arranged in a manner that all the centers gravity of the particles are coordinated vertically with the direction of the applied stress.

The numerical results of SC packing structures for Cu solid and sponge particles-based powder with various internal pores content and different initial packing structures during the cold compaction are fitted by using double logarithmic equation given by [35]:

\[
m \log \ln \left( \frac{\rho_m - \rho_0}{\rho_m - \rho} \right) \rho = \log P - \ln M
\]

(7)

where \( \rho_m \) is the theoretical density of fully the dense material, \( \rho_0 \) is the initial relative density of the compact, \( \rho \) is the compact relative density at the compaction pressure \( P \), \( M \) is the modulus of compaction and \( m \) is the hardening index. Figures 5(a) and (b) shows the fitted results of Cu solid and sponge powder with various internal pores content and the fitted results of different initial packing structure for Cu spongy powder with 5% internal pores, respectively. One can be seen that the agreement between our numerical data and the fitted results
which demonstrate the durability of our numerical model and the accuracy of the simulation results that can be shown by the high confidence (specified by $R^2$). Furthermore, in figure 5(a), with the increasing of the internal pores content in the fitting results, the data non-linearity behavior increases and the agreement confidence with logarithmic equation reduced in case of spongy powder.

3.2. Macrostructure and microstructure characterization

The advantage of MPFEM lies in that it can obtain the macro properties of the compaction under different conditions. Figure 6 depicts the morphology analysis and the equivalent Von Mises stress distributions for Cu powder in SC structure for solid and sponge powder with different internal pore content during compaction. In general, as the tetragonal packing structure is highly geometrical symmetry, the relative slip between the particles isn’t observed. In addition, the coordination number (CN) of each Cu particles is four and remains the same during the compaction process. Figure 6(a) shows the morphology analysis and Von Mises stress distributions for solid Cu powder, the pressure increases rapidly at the early stage of compaction. The forces are transferred between neighboring particles situated at adjacent layers throughout the compaction process. With the further increase in the pressure, large plastic deformation of particles flowed, in addition, the in-layer forces between neighboring particles constituted and increased. The contacts between particles transfer from a point to a line thus the large plastic deformation achieved which causes a large mass transfer of particles to fill adjacent low pressured void areas between the particles. The shapes of the solid particles in the compact after the compaction become rectangles. Figure 6(b) shows the compaction stages of Cu sponge powder in the SC structure with 1% internal pores content per particle. At the early stage of the compaction, the forces are transmitted between neighboring particles located in the vertical contact areas and move from these areas to the internal pore. The contact area increases with the pressure increasing, and the plastic deformation of its adjacent particles fill each external voids and internal pores to realize the densification. However, with the further increase in the pressure, large plastic deformation of particles occurred, and the shape of the force become (H) shape which makes the
Figure 6. The evolution of morphology and equivalent Von Mises stress for Cu powder in tetragonal packing structures with different internal pores percent contain per particle during cold compaction, where:

(A) solid particles: $\rho_1 = 0.7854$, $\rho_2 = 0.8184$, $\rho_3 = 0.8640$, $\rho_4 = 0.9166$, $\rho_5 = 0.9894$; (B) 1% internal pores contain in a particle: $\rho_1 = 0.7775$, $\rho_2 = 0.8114$, $\rho_3 = 0.8587$, $\rho_4 = 0.9126$, $\rho_5 = 0.9884$; (C) 2% internal pores contain in a particle: $\rho_1 = 0.7697$, $\rho_2 = 0.8043$, $\rho_3 = 0.8528$, $\rho_4 = 0.9083$, $\rho_5 = 0.9867$; (D) 3% internal pores contain in a particle: $\rho_1 = 0.7618$, $\rho_2 = 0.7901$, $\rho_3 = 0.8412$, $\rho_4 = 0.9040$, $\rho_5 = 0.9853$; (E) 4% internal pores contain in a particle: $\rho_1 = 0.7540$, $\rho_2 = 0.7830$, $\rho_3 = 0.8353$, $\rho_4 = 0.8961$, $\rho_5 = 0.9820$. 

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transition of the internal pore from initial round to roughly final line with some voids and sharp corners and the particle shapes changes from initial round to final square. Figure 6(c) and figure 6(d) depict the compaction stages of Cu sponge powder for SC structure with 2% internal pores content and 3% internal pores content, respectively. The forces are mainly transmitted between neighboring particles located in the contact areas and move from these areas to the internal pores in the corner afterward to the central internal pore. It can be seen from the von mises stress distributions, that the higher stresses are diffused and form a chain starting from the higher and lower contact areas of the particle and trace the internal pores. For example, as in 2% internal pores content structure, the high stresses are concentrated in the upper and lower contact areas of the particle as there are no internal pores in the center however in the 3% internal pores content structure, the higher stress moves to the center of the particle as a result of the central internal pore. Furthermore, with the large plastic deformation of particles occurred, the shape of the force becomes as horizontal lines in the contact areas in both structures which cause the internal pore shape to deform and lose circularity. The shape of the internal pores excluding the central internal pores becomes oval and inclined with approximately 45° to the direction of applied load where the shear stress is maximum and with further loading, the internal pores deform to nearly arc line for internal pores near the edges and to line in the central internal pore. The particle shape changes from the initial round to the final square with a wavy width line due to non-uniform densification behavior as a result of the non-uniform distribution of the internal pores. Figures 6(e) and (f) display the compaction stages of Cu sponge powder for SC structure with 4% and 5% internal pores content, respectively. Overall, it can be realized that the forces chain development is highly similar in 2% and 4% internal pore content. Also, the forces chain development in the structure with 3% and 5% internal pore content are similar. Nevertheless, one can be seen the difference between the 4% and 2% internal pore content structure and the with 5% and 3% internal pore content structure in the final shape of the particle. In structures with uniform distribution of the internal pores within the corners (i.e. 4% and 5% internal pores content structures), the shapes of the particles change from circle to equilateral square. Figure 7 shows the deformation progress of the single particle and internal pores for 5% internal pores with SC structure.

Figures 8(a) and (b) indicate the evolution of the whole structure and the distributions of the equivalent Von Mises stress of the SC and HCP initial packing structure of Cu sponge powder with 5% internal pores during the cold compaction. It worth to be mention that the HCP initial packing of equal disks with 5% internal pores content with the theoretical density of $\rho = 0.836$ is the densest packing structure in two dimensions. The coordination number (CN) of each Cu particle in SC structure is four and in HCP structure is six. In initial SC and HCP ordered packing structures, the position of each particle and its contacts neighboring particles is constant during the compaction so that the CNs in these two compacts remain the same during compaction. As a result, the final shape of each particle in the compact of SC and HCP structures after compaction transferred from circle to square and regular hexagon, respectively. The forces in the two structures are mainly transmitted between neighboring particles located in the contact areas and the forces in every particle move from the contact areas to the corner internal pores than to the central internal pore. Also, it can be noticed that the deformation development and the final shape of the internal pores are different and depend on the applied force direction. For example, in the SC structure, the shape of the internal pores excluding the central internal pores changes from circular to inclined oval with approximately 45° to the direction of the applied load. With further loading,
the corners internal pores deform to nearly inclined arc lines and central internal pores deform to horizontal lines in whole the structure. That is because the corners internal pores mostly affected by the contact forces coming from the nearest contacted particle, however, the central internal pores affected mostly by the vertical forces.

For HCP structure, the same behavior is depicted in the particles near upper and lower punches, however, the particles which exist in the middle of the HCP structure exposed to different contact forces directions which cause different deformation behavior of the internal pores, almost from circle to horizontal oval to very small circle including the central internal pores. Consequently, less densification behavior for internal pores is depicted. However, it worth to be mention that in HCP structures the densification behavior for the voids between the particles is higher than SC structure. Furthermore, the FCC packing structure is ordered packing structure, its densification behavior during compaction is different from SC and HCP. The structure evolution and the equivalent Von Mises stress distributions for FCC initial packing structure of Cu sponge powder with 5% internal pores content are shown in figure 8. At the early stage of compaction, with the increase in the pressure, a very small relative slip between particles is observed. However, when the pressure is larger than a critical value, relative slip at the local area appears. Meanwhile, one can also see, with the further increase in the pressure, the contact forces acting on the particles change from near horizontal to vertical, which cause the deformation behavior of the internal pores change from nearly inclined arc lines to horizontal lines.
pressure, the forces transmitted from the contact areas between the particles to the corner internal pores. Then, as the pressure increases, large plastic deformation of particles occurred to fill the adjacent low pressured void area between the particles and the internal pores. The corners internal pores deformed to almost lines parallel to the larger contact areas, however, the central internal pores become roughly horizontal lines directed to the shortest contact area. After compaction, the shapes of the particles in the compact are irregular quadrilles, pentagons, and hexagons.

Figure 8(d) illustrates the structure evolution and the equivalent von Mises stress distributions for the random initial packing structure of Cu sponge powder with 5% internal pores content. At the primary stage, the relative sliding and rolling of the particles occur due to the non-uniform distribution of stresses acting on individual particles. In this stage, no noticeable deformation of particles is detected. After that, the pressure increases rapidly, and the particles deform plastically with the pressure to form the final dense packing. The Morphology evolution and equivalent von Mises stress distributions analysis show that the forces transmitted from the particle firstly contacted with the punch to its downward neighbors. During densification, the contacts between particles increase, which leads to a complex force chain. At the final stage, all the particles are deformed to be different shapes due to the interaction of their neighboring particles. In addition, the internal pores gain different deformation behavior because of the non-ordered distribution of the structure. The densification mechanism during compaction can be attributed to the filling of interstitial spaces between the particles and the internal pores that existed in every particle. With the above four initial structures, the compaction mechanism of random initial packing structure is the most complicated due to its anisotropy of void structures and the internal pores upon compaction, therefore, this structure is taken as an example to identify its densification dynamics and mechanism. Subsequently, for reinforced analysis, a limited cohort in random initial packing was chosen as the research purpose, within which the evolution of local structure and corresponding stresses/forces during the cold compression process were characterized, as shown in figure 9. At the early compaction stage (see figure 9(a) (1) and (2) ), the stresses within the particles appear in the linking particles, however, no stresses are observed in the middle particle and that because it is shielded by the preceding bridging structure formed by particles 1, 2, 3, 4, 5, 6 and 7. In this stage, the stresses were between the contact areas of particles and didn’t appear remarkably to the internal pores. As the compaction pressure reaches a certain value, the stresses begin to appear in internal pores in particles. The internal pores in particle 7 disappear mostly as shown in figure 9 (a) (3) and (4). With further increase of the pressure, the voids between the particles and the internal pores in most particles are becoming smaller and smaller due to the large plastic deformation of particles which observed in figure 9(a) (5). Meanwhile, the CN of particle 8 increases from four to six.

Finally, the dense packing structure is formed as displayed in figure 9(a) (6). The deformation of particles nearby is not-uniform because of the non-uniform voids between the particles and non-uniform internal pores in the particles in structures. Similarly, figure 9(b) shows that the development of normal forces that, at the early cold compaction stage, large normal forces exist between the particles in the bridging structure and the forces

Figure 9. (a) Equivalent von mises stress distribution and (b) Normal force distribution in the local loose cluster in random initial packing compact, where: $- (1) \rho_1 = 0.7088, (2) \rho_2 = 0.7625, (3) \rho_3 = 0.7867, (4) \rho_4 = 0.8263, (5) \rho_5 = 0.9032, (6) \rho_6 = 0.9820$. 
within particle 8 within the bridging structure is relatively small. With the increase of pressure, the bridging structure is broken and the normal contact forces between particle 8 and its neighbors increase, which leads to large plastic deformation, voids filling between the particles, and vanishing of the internal pores within the particles.

4. Conclusions

The numerical study of sponge powder cold compactions has been carried out by using 2D-MPFEM simulation on the single action die compaction. The cold compaction simulation is carried out for six tetragonal packing structures with different initial internal pores content. The compaction pressure, densification mechanism, macroscopic and microscopic properties of the powder compact have been investigated and the results reveal that

(1) At low \((\rho < 0.86)\) and medium relative density \((0.86 < \rho < 0.95)\), the densification behavior of the sponge powder is faster than solid powder.

(2) At higher relative density near value of unity (fully dense), the force required to cause further compaction is significantly larger in the sponge powder. That is because the amount of the space left behind the internal pores after the compaction is very small. In addition, the filling and deformation rate of the internal pores are reduced dramatically as the internal pores deformed to irregular small areas with some sharp corners due to the non-uniform distribution of the stresses around the pores which require more pressure to deform. Thus, the matrix material only has limited and unsmooth areas to deform and becomes effectively incompressible. Consequently, in the range of very high relative density (approximately more than 0.98), the sponge powder requires more pressure than the solid powder to arrive at the same high relative density.

(3) It can be seen from the microscopic analysis, that the higher stresses are diffused and form a chain starting from the higher and lower contact areas of the particle and trace the internal pores. Furthermore, with the large plastic deformation of particles occurred, the shape of the internal pores excluding the central internal pores becomes oval and inclined with approximately 45° to the direction of applied load where the shear stress is maximum and with further loading, the internal pores deform to nearly arc line for internal pores near the edges and to line in the central internal pore.

(4) It can be summarized that the densification behavior of the sponge powder depends mainly on the internal pores content, the internal pores position, and the formed force chain in the compact.

Furthermore, cold compaction simulations of three different ordered packing structures (i.e. tetragonal packing (SC), hexagonal close-packed (HCP) structure, and face-center-cubic (FCC) packings) and random loose packing with 5% internal pores content per particle have been studied. The distribution of relative density, the distribution of stress, deformation, mass transfer and the densification of the internal pores and the voids between the particles were characterized and analyzed. The results can be briefly described as follows:

(1) The compaction behaviors and deformation characteristics of the particles and the internal pores were different for the packing structures. For instance, SC and HCP ordered packing structures, the final shape of each particle after compaction transferred from circle to square and regular hexagon, respectively. In addition, the deformation development and the final shape of the internal pores are different and depend on the applied force direction. In the SC structure, the shape of the internal pores excluding the central internal pores changes from circular to inclined oval and the central internal pores deform to horizontal lines in a whole the structure. For HCP structure, the same deformation behavior is depicted in the particles near upper and lower punches, however, the particles which exist in the middle of the HCP structure exposed to different force directions which cause different deformation behavior of the internal pores, almost from circle to horizontal oval to very small circle including the central internal pores.

(2) The FCC packing structure is ordered packing structure, a very small relative slip between particles is observed, at the early stage of the compaction. Along with large plastic deformation of particles, the corners internal pores deformed to almost lines parallel to the larger contact areas however the central internal pores become roughly horizontal lines directed to the shortest contact area.

(3) The compaction mechanism of random initial packing structure is the most complicated due to its anisotropy of void structures and the internal pores upon compaction. So complex force chains were formed during the densification and all the particles are deformed to be different shapes due to the
interaction of their neighboring particles. In addition, the internal pores gain different deformation behavior because of the non-ordered distribution of the structure.

It can be recognized that the deformation behavior of the particles and the internal pores depends on the structure configuration, and that is because the particle and the internal pores exposed to contact forces with different magnitude and direction depending on the configuration and the coordination number.

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**References**

[1] German R M 1984 Powder metallurgy science Mater. Des. 5 294
[2] Yamaguchi K, Takakura N and Imatani S 1997 Compaction and sintering characteristics of composite metal powders J. Mater. Process. Technol. 63 364–9
[3] Yang C, Lee S and Lee J 2013 Entry barrier’s difference between ICT and non-ICT industries Ind. Manag. Data Syst. 113 461–80
[4] Grum J 2006 Book review: powder metallurgy and particulate materials processing: the processes, materials, products, properties, and applications Int. J. Mater. Prod. Technol. 27 290
[5] Brewin P R, Coube O, Doremus P and Tweed J H (ed) 2007 Modelling of Powder Die Compaction. (London: Springer London) ([https://doi.org/10.1007/978-1-84628-099-3](https://doi.org/10.1007/978-1-84628-099-3))
[6] Martin C 2004 Elasticity, fracture and yielding of cold compacted metal powders J. Mech. Phys. Solids 52 1691–717
[7] Szanto M, Bier W, Fragie N, Hartmann S and Yoshbash Z 2008 Mar. Experimental based finite element simulation of cold isostatic pressing of metal powders Int. J. Mech. Sci. 50 605–21
[8] Procopio A T and Zavaliangos A 2005 Simulation of multi-axial compaction of granular media from loose to high relative densities J. Mech. Phys. Solids 53 1523–51
[9] Chiotourou H, Guillot M and Gakwaya A 2002 Modeling of the metal powder compaction process using the cap model. Part I. Experimental material characterization and validation Int. J. Solids Struct. 39 1059–75
[10] Wu W, Jiang G, Wagoner R and Daehn G 2000 Experimental and numerical investigation of idealized consolidation Acta Mater. 48 4323–30
[11] Hartthong B, Jérier J-F, Doremus P, Imbault D and Donzé F-V 2009 Modeling of high-density compaction of granular materials by the discrete element method Int. J. Solids Struct. 46 3357–64
[12] Hartthong B et al 2012 Contact impingement in packings of elastic–plastic spheres, application to powder compaction Int. J. Mech. Sci. 61 32–43
[13] Sinka I, Cunningham J and 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 Technol. 133 33–43
[14] Sinka I C, Cunningham J C and Zavaliangos A 2004 Analysis of tablet compaction. II. Finite element analysis of density distributions in convex tablets J. Pharm. Sci. 93 2040–53
[15] Huang H and Tutumluer E 2011 Discrete element modeling for fouled railroad ballast Constr. Build. Mater. 25 3306–12
[16] Olsson E and Larsson P L 2013 A numerical analysis of cold powder compaction based on micromechanical experiments Powder Technol. 243 71–8
[17] Gehin D T, Lewis R W and Ransing R S 2003 A discrete deformable element approach for the compaction of powder systems Model. Simul. Mater. Sci. Eng. 11 101–14
[18] Zavaliangos A 2002 A Multiparticle simulation of powder compaction using finite element discretization of individual particles MRS Proc. 731 p. W7.1
[19] Zavaliangos A 2003 A numerical study of the development of tensile principal stresses during die compaction Part. Sci. Technol. 21 105–15
[20] Chen Y, Imbault D and Doremus P 2007 Numerical simulation of cold compaction of 3D granular packings Mater. Sci. Forum 534–536 301–4
[21] Zhang J 2009 A study of compaction of composite particles by multi-particle finite element method Comp. Sci. Technol. 69 2048–53
[22] Lee K-H, Lee J-M and Kim B-M 2009 Densification simulation of compacted Al powders using multi-particle finite element method Trans. Nonferrous Met. Soc. China 19 668–75
[23] Zhang Y X, An X Z and Zhang Y L 2015 Multi-particle FEM modeling on microscopic behavior of 2D particle compaction Appl. Phys. A 118 1015–21
[24] Lu A and An X 2018 Two-dimensional multiparticle finite element model on the cold isostatic pressing of al powder Metall. Mater. Trans. A Phys. Metall. Mater. Sci. ([https://doi.org/10.1007/s11661-018-4753-6](https://doi.org/10.1007/s11661-018-4753-6))
[25] Lei Y et al 2018 Experimental and numerical investigation of densification behaviors during powder compaction J. Adv. Mech. Des. Syst. Manuf. 12 1AMDSM0022–1AMDSM0022
[26] Han P et al 2017 Particulate scale MPFEM modeling on compaction of Fe and Al composite powders Powder Technol. 314 69–77
[27] Han P et al 2018 MPFEM simulation of compaction densification behavior of Fe-Al composite powders with different size ratios J. Alloys Compd. 741 473–81
[28] An X, Liu Y, Huang F and Jia Q 2018 MPFEM modeling on the compaction of AI/ SiC composite powders with core/shell structure, Powder Technol. (Rijeka: InTech)
[29] Groover M 2010 Fundamentals of Modern Manufacturing Materials,Processes and Systems (United States of America: Wiley)
[30] Angelo P and Subramaniam R 2008 Powder Metallurgy: Science, Technology and Applications. (New Delhi: PHI Learning Pvt. Ltd)
[31] Mowbray G A 1986 Production methods for powders of copper and copper alloys: a critical review Metal. Technol. 29 105–7
[32] Campbell F C 2013 Metals Fabrication:Understanding the Basics (Ohio: ASM International)
[33] Otarawanna S, Tanwongwan W, Manonukul A and Carmaj I 2005 Modelling of powders with internal pores in cold compaction the 19th Conference of Mechanical Engineering Network of Thailand
[34] Gerdemann S J and Jablonski P D 2011 Compaction of titanium powders Metall. Mater. Trans. A 42 1325–33
[35] Machaka R and Chikwanda H K 2015 Analysis of the cold compaction behavior of titanium powders: a comprehensive inter-model comparison study of compaction equations Metall. Mater. Trans. A 46 4286–97
[36] Machaka R and Chikwanda H K 2015 An experimental evaluation of the gerdemann–jablonski compaction equation Metall. Mater. Trans. A Phys. Metall. Mater. Sci. 46 2194–200
[37] Aydin I, Briscoe B J and Ozkan N 1997 Modeling of powder compaction: a review MRS Bull. 22 45–51