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An investigation of contact interactions in powder compaction process through variable friction models

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ABSTRACT

In this study, multiparticle finite element (MPFE) approach was used to analyze contact interactions of spherical copper particles in powder compaction process. To this goal, 74 spherical copper particles of 200 µm in diameter were modeled as individual elastic–plastic bodies, and randomly filled into a die cavity. Interparticle and die-wall-particle contact interactions were investigated, and coefficients of friction were obtained using variable friction models; Wanheim–Bay's general friction model and Levanov's friction model. Variable friction models were incorporated into FE analyses through user-subroutines. It was found that the variation of contact stresses inside the die leads to different contact conditions at different zones. The range of coefficient of friction encountered in the analysis was found to be slightly higher in Levanov's friction model than that for Wanheim–Bay's general friction model. On the other hand, Levanov's model was found to be more appropriate for elevated temperature analyses.

1. Introduction

Friction, a multi-parameter involved phenomenon, plays an important role in deformation characteristics of powder compaction process. Therefore, it needs to be understood and controlled, accordingly. In powder compaction process, an interparticle contact interaction dictates the deformation characteristics and mechanical properties of parts produced. This effect is more pronounced when the part dimensions get smaller along with the miniaturization trend in industrial products. On the other hand, a successful mathematical modeling of compaction process requires the careful selection and/or development of a constitutive model, identification of the material parameters and the numerical treatment of complicated contact boundary conditions. A number of experimental and numerical studies have been performed in the literature to investigate the contact conditions and its effects on powder compaction process. Although experimental studies were performed much earlier, numerical studies were started in early 1980s [1,2].

In modeling efforts, researchers mostly utilized continuum media approach with finite element method (FEM) or distinct/discrete element method (DEM) to understand the friction behavior in powder compaction [3–6]. In continuum media approach, the particles in a specified volume are modeled as single body with certain relative density [7,8]. In DEM, on the contrary, each particle is modeled as an individual rigid-plastic body. It was recently shown that individual particles can also be modeled as elastic–plastic bodies in DEM [9]. Thus, Tan et al. simulated crack initiation and propagation of polycrystalline alumina during the machining process by DEM [10]. FEM, on the other hand, have been widely used as numerical modeling tool for problems involving deformation [2]. MPFEM, was found to be more accurate in simulation of non-linear contact interaction since every single particle can be modeled as deformable body [11]. Stress distributions and friction behavior can, therefore, be obtained for each particle in micro-scale. These variables were investigated by many authors to determine mechanical behaviors in micro-scale [12–14].

The most widely used friction model in literature is Amonton's–Coulomb model. This model defines the coefficient of friction based on surface roughness. Roughness originates from the material asperities of contacting surfaces in micro-scale. Those contacting asperities constitute real contact area of contacting surfaces. Khoei et al. [15] and Keshavarz et al. [16] used constant coefficients of friction to determine the effect of friction on metal forming processes. Harthong et al. utilized Coulomb friction model to study of relations between loading history and yield surfaces in powder materials [17]. Nevertheless, instead of assuming coefficient of friction as constant throughout the process, some researchers developed friction models that use the ratio of real contact area to apparent contact area. Wanheim and Bay developed a friction model (details given in Section 3.2) in which frictional shear stress is a function of real contact area [18].

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Wanheim–Bay's General friction model was utilized in micro/nano scale forming processes [19–21]. In an another variable friction model developed by Levanov, friction parameters e.g. coefficient of friction, adhesion forces and lubricant effect was introduced into the model at low temperatures [22]. Moreover, Hallström et al. investigated the effect of friction on die filling process in forging numerically and experimentally by using these friction models [23]. The above mentioned studies definitely show that tribological investigations in metal forming have attracted several researchers as friction plays important role in deformation characteristics, material flow during the forming process, final shape of the products etc. [24–27]. These investigations would benefit from numerical modeling approaches as determining deformation characteristics and/or tribological parameters throughout the forming process are not feasible by means of experiments in micro-scale for most cases. Therefore, present study aimed for investigating the variation of coefficient of friction in powder compaction process.

Apart from friction models, material models are crucially important to simulate the processes accurately. Powder material models such as modified Cam Clay, Mohr–Coulomb and Shima–Oyane are considered appropriate models in continuum approach whereas von Mises yield criteria is noted appropriate for MPFE due to its feature of defining every particle as individual deformable body [28–30]. Besides determining contact conditions the coefficient of friction has a significant effect on forces those arise during forming process [31].

Copper powder compaction, as closed-die forming techniques in most cases, is difficult to be monitored during the process so that most experimental studies could only investigate the initial and last step of compaction. As it was stated by Hu et al., due to the small scale involve it was difficult to study the rheological properties in experiments [32–34]. Main focus on the current study is to obtain the coefficient of friction variation and deformation characteristics for individual powders, inter-particle, and particle-die wall interactions numerically based on the model used in authors' earlier work.

A great deal of progress has been achieved in the numerical modeling of powder forming processes in recent years. Nevertheless, as far as the authors' knowledge, there is no study comparing the aforementioned friction models in metal powder compaction process. The description of friction phenomenon at the die wall surface and more importantly at the interfaces of particles with a realistic accuracy still remain insufficient. Moreover, the aforementioned studies mostly used friction models in which the coefficient of friction is constant throughout the process. In addition, inter-particle contact interactions between the individual spherical particles were not investigated, in most cases. This study, therefore, intended to investigate the effects of different friction models, namely; Amonton's–Coulomb, Wanheim–Bay and Levanov's friction models on contact conditions of metal powder compaction process including particle-die wall, and particle-particle interactions.

2. Description of physical process and MPFE model

The geometry of interest was taken from the author's previous study, and it was shown by the authors that such porous surfaces in microscale with certain modulations exhibited advanced heat transfer rates [35]. 74 solid particles were randomly filled into a die cavity and meshed with 3D tetrahedral elements in order to investigate process parameters. Every single particle was defined as an individual deformable body and von Mises material model associated with power law was used for elastic–plastic deformation of all elements in accordance with MPFE modeling approach.

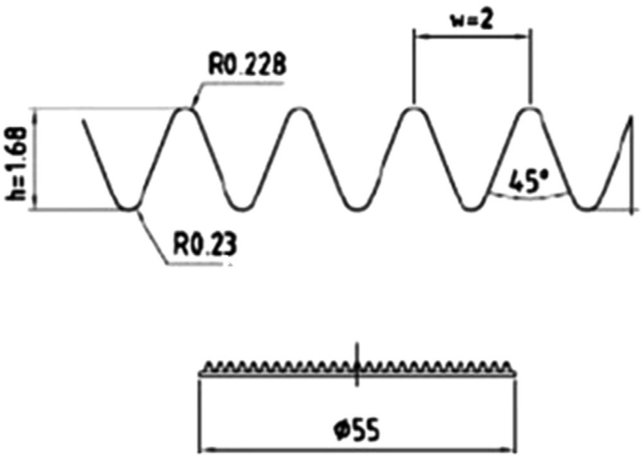

Fig. 1. Details of porous surface geometry (top) and die (bottom) (dimensions are in mm) [35].

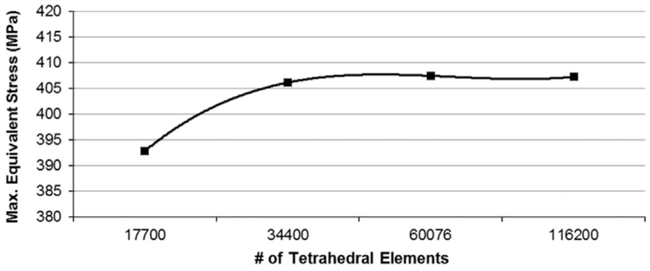

Fig. 2. Max. equivalent stress with respect to number of elements used in FE model [28].

Amonton's–Coulomb, Wanheim–Bay and Levanov friction models were incorporated to MPFE model via user-subroutines to determine coefficient of friction and frictional forces in compaction process. The process was simulated at both room temperature and at 270 °C along with the implemented friction models.

It is a well-known fact that porous surfaces enable large surface areas for a given volume and enhance heat transfer capability. In this context, copper particles were demonstrated to be one of the most common materials used in heat transfer related applications [35–37]. The die geometry of copper powder compaction process used in this study was implemented from the study by Cora et al. [35]. The shape and dimensions of die geometry was shown in Fig. 1. This die geometry was also reported as a suitable one to analyze different material models and different coefficients of friction in compaction process by authors earlier [28].

Solidworks software (Solidworks Corp., Waltham, MA, USA) was used to model spherical copper particles of 200 μm in diameter. In order to achieve random distribution of particles, the spheres were filled into die cavity through free-falling motion. The created 3-D model of 74 copper spheres was then imported into MSC Patran (MSC Software Corp., Santa Ana, CA, USA) in which the spheres were meshed with 60076 3-D tetrahedral elements. Fig. 2 shows the variation of maximum equivalent (von-Mises) stress values with respect to number of elements used in FE models [28]. Mesh convergence studies showed that 60076 number of 4-noded 3D tetrahedral elements were appropriate for modeling the powders used. The meshed 3-D model was then imported to commercial FEA package, MSC Marc Mentat (MSC Software Corp., Santa Ana, CA, USA) to perform the FE analyses. Implicit solution technique in combination with full Newton–Raphson iterative procedure was preferred as numerical solution algorithm. In convergence testing, the residual or displacement testing option was used. In the residual option, the largest residual force divided by the maximum reaction force where the division has to be