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Effects of friction models on the compaction behavior of copper powder

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ABSTRACT

A comparative numerical and experimental analysis of metal powder compaction processes was presented. Closed-die compaction of spherical copper particles with a nominal diameter of 200 μm was analyzed using Multi Particle Finite Element Method (MPFEM). The von Mises material model associated with contact sensing algorithms was employed to investigate variation of coefficient of friction, and contact interactions between powder particles as well as particles with the die walls. Three different friction models (Amonton-Coulomb, Wanheim-Bay, and Levanov) were used to provide a better insight and the latter two were integrated into the commercial finite element package via user-subroutines. To verify the established model, some compaction experiments were carried out. Optical, and scanning electron microscopy analyses were performed, and images obtained were compared with the numerical results. The values of the coefficient of friction obtained using Wanheim-Bay and Levanov friction models fall into the range of 0.04–0.07. From the stress distribution perspective, it was observed that the results obtained with Wanheim-Bay friction model were more conforming to experimental cases where high relative density compaction takes place while Levanov friction model was found to be preferable at low relative density compaction process.

1. Introduction

Numerical analyses are frequently used in designing machine parts in automotive, space and other industries, and they have become an essential tool in engineering as product-to-market duration for products can significantly be shortened with such modeling tools. The results of reduced number of experiments and/or existing knowledge on certain material can be transferred to modeling tools and product can be tested, and/or subjected to experimentation virtually. Hence, product performance can be investigated with certain accuracy before the real product is manufactured, and necessary measures can be taken in case of any malfunctioning or undesired condition. The results of numerical modeling can also be used to improve product performance, and reduce production costs. For example, Mercedes-Benz has reported that a total mass saving of 20% in leaf cover and 65% in a tailgate area simply based on numerical analyses [1,2]. On the other hand, knowledge on frictional conditions, and level of forces/stresses experienced are of critical importance in producing parts through powder metallurgy (P/M). Although the numerical methods have been widely used for variety of conventional production processes in macro-scale, analysis dimension are usually much smaller (e.g. micro-scale) when P/M products are considered. Discrete Element Method (DEM), Smooth Particle Hydrodynamics (SPH) and Finite Element Method (FEM) are the main methods frequently used in numerical analysis associated with P/M process.

DEM has been proposed by Cundall in 1971 for the first time where the flow behavior of particle was initially assumed to obey rigid-plastic material behavior [3]. With the improvements since then, DEM has become capable to perform elasto-plastic analyses [4,5]. SPH technique was developed specifically to study astro-physics matters and has then also been used for viscous flow [6]. On the other hand, FEM has been proven to be a powerful tool in analyzing various process parameters such as deformation characteristics, effects of friction and temperature [7]. In general, FEM has been used to analyze powder problems with two different approaches: The first one is continuum approach in which the medium is assumed to be a continuum with a certain relative density [8, 9]. The latter approach is called as multi particle finite element method (MPFEM) which considers each particle used in the particular process into account as an independent body [10]. Two important specifications, namely, the material and friction models should be specified in the finite element model to analyze the deformation behavior of the material, and particle interactions. MPFEM has flexibility to define every particle as an individual body with a material property (rigid, elastic, elastic-plastic, or

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perfectly-plastic, etc.) [11–13]. As a result, particle-particle, particle-die wall interactions as well as deformation characteristics of particles (e.g. frictional force, stress, strain distributions etc.) can successfully be analyzed with MPFEM [13–15].

Amonton-Coulomb friction model (ACFM) is one of the most widely used friction models and it takes friction as constant throughout the whole deformation process. This approach is often inadequate and does not represent the real conditions. Therefore, some alternative models were suggested by the researchers. Krienkov and Zhavoronok, constructed a dry friction model on the basis of differential formulation of Amonton-Coulomb dry friction law to get more accurate numerical solutions for the contact pressure [16]. Irazábal et al. presented a new model, called the Bounded Rolling Friction (BROF) to compute rolling friction for spherical discrete elements [17]. Hu et al. developed an interactive friction model to characterize the lubricant film breakdown phenomena in which the effect of lubricant thickness, sliding speed and contact pressure were considered [18]. In another research, Lee and Chen formulated an analytical model and generalized friction law to investigate the friction between the contacting interfaces [19]. Piatkowski studied the effectiveness of friction modeling and computational efficiency using Generalized Maxwell-Slip (GMS) model [20]. Petersen et al. introduced the friction factor which provides variable coefficient of friction which is known as general friction model, (or Wanheim-Bay friction model WBFM) [21,22]. This model involves a major improvement to simulate processes where low tool-work piece interface stresses may prevail. Similarly, Levanov proposed a friction model for investigating the friction phenomenon in metal forming processes [23]. Chumachenko, on the other hand, developed an empirical model to obtain the optimum superplastic properties of the titanium alloy at lower temperatures using Levanov's friction model (LFM) [24]. Besides numerical studies, many researchers carried out experimental studies offering information about characteristic, microstructure and wear properties of powder in compaction processes [25–27]. Saha et al. investigated the effects of parameters such as relative density, tensile strength, pressure, particle size and size distribution during compaction of alumina powder [28]. Recently, Yohannes et al. investigated the role of fine particles on compaction through experimentation and numerical studies [29].

It is difficult to identify the role of friction in powder compaction process solely by either experimental or numerical studies. Most of the available studies suggest that in-depth analyses should be performed to reveal the effect of friction on the compaction behavior of powder particles through an integral approach [27,30]. It is, therefore, current study was devised to include both experimental and numerical stages. First, compaction of spherical copper powder particles with 200 μm nominal diameter at 270 °C was analyzed numerically to obtain stress distribution, coefficient of friction variation along with different friction models. Material model employed was work-hardening elasto-plastic von Mises, similar to previous studies of authors [13,14]. In order to investigate friction behavior, three different friction models were employed. Firstly, ACFM which dictates constant friction coefficient was used, since it's a common friction model for describing engineering problems. Then, general friction model developed by Wanheim-Bay, and Levanov's friction models which provide variable coefficients of friction were integrated into the FEA package via user-defined subroutines. After numerical analyses, spherical powder compaction with same geometry and the same boundary conditions was carried out, experimentally. Results obtained from the compactions tests were compared with those obtained from numerical analyses. Optical and scanning electron microscopy images were acquired after the compaction experiments to reveal the deformation characteristics of powder particles.

2. Numerical studies

2.1. Finite element model

Die geometry used to compact powder in both numerical and experimental studies is given in Fig. 1. The teeth in the die were formed with 45° angle with the horizontal and, ratio of the tooth width to its height was 0.5. This study intended to investigate the effects of different friction models, on contact conditions of metal powder compaction process including particle-die wall, and particle-particle interactions. For this purpose, 130 spherical copper powder particles with 200 μm in nominal diameter were used in numerical model, and they filled into the predetermined geometry of the die under the effect of gravity using SolidWorks software (Solidworks Corp., Waltham, MA, USA). Then, 3-D model of powder compaction process including die and particles was prepared using Patran (MSC Software Corp., Santa Ana, CA, USA). After mesh converging studies shown in Fig. 2, the optimum numbers of 3-D tetrahedral elements were determined as 99300 to simulate copper particle compaction process. The discretized model was then imported to commercial FEA package MSC Marc (MSC Software Corp., Santa Ana, CA, USA). Powder compaction process was then analyzed numerically using MSC Marc Mentat solver. Deformable-rigid body and deformable-deformable body contact sensing algorithms defined by MSC Marc software [31] were utilized for contact elements. The subroutines for friction models that provide variable coefficient of friction were prepared in Intel Fortran Composer (Intel Corp., Santa Clara, CA, USA) and incorporated with MSC Marc software along with Microsoft Visual Studio (Microsoft Corp., Redmond, WA, USA). User-defined subroutine UFRIC was used to activate the variable friction modeling in MSC Marc. Hence, changing frictional conditions were provided at each contact point. To reduce the computational time, only the one channel of the compaction die show in Fig. 1 was taken into consideration in FE analyses.

As the FE model include several thousands of contact points, the analysis of frictional conditions were limited to 3 individual reference particles (powder) as specified in Fig. 3. The selection of these reference particles were based on the distance from the punch such that the bottom particle is closest to the punch, and in contact with the other particles and die wall while the top particle is at the farthest to the punch, and the middle particle is only in contact with other surrounding particles.

2.2. Material model

In FE analyses, the constitutive equation of von-Mises yield function along with power-law was utilized. The power-law material model is given in Eq. (1)

$$\sigma_Y = A(\varepsilon_0 + \overline{\varepsilon})^m + B\dot{\overline{\varepsilon}}^{\,n} \tag{1}$$

where, A, B, m and n are material parameters, σ_y is the yield stress, ε_o is initial yield strain, $\overline{\varepsilon}$ is equivalent strain, and $\dot{\overline{\varepsilon}}$ is equivalent strain rate. Since the punch velocity of compaction process was set as 0.35 mm/s, parameter-B takes a very small value [32], and therefore it was ignored in this study. The values for material parameters of $A = 296.7$ MPa, $m = 0.3655$, *Young's Modulus,* $E = 99.3$ GPa*, and Poisson's Ratio* $\nu = 0.35$ were taken from the study of Güner et al. at 270 °C [14]. For the process under investigation, the initial yield stress was calculated as $\sigma_y = 10.4$ MPa by using the Hooke's law and Eq. (1).

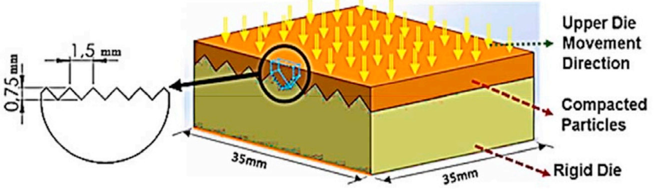

Fig. 1. Die geometry that is used to produce copper powder compaction samples in experiments.