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Discrete element modeling of 3D media motion in vibratory finishing process

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ABSTRACT

A model has been developed to investigate the three-dimensional media motion during the vibratory finishing processes. This work presents a vibratory finishing machine model using a discrete element method (DEM) that calculates the media interactive normal and tangential contact forces among the media particles. The DEM model predicts the dynamic motion of individual particles inside the vibratory machine container based on Hertzian contact mechanics. The influence of contact parameters such as contact stiffness, friction and damping on media motion has been investigated to determine the critical operating parameters for the vibratory finishing process. The simulation results have been validated with experimental data. This model provides an understanding of vibratory finishing process fundamentals, guidelines for vibratory finishing machine design and optimal operating conditions.

1. Introduction

The vibratory finishing process is widely used in industries where product specification requires a certain surface finish [1,2]. The advantages of employing a vibratory finishing process to final products have been studied by researchers. One of the advantages of applying vibratory finishing process is the creation of an isotropic surface texture along with achieving the desired roughness with minimum process time and cost [1]. Optimal vibratory finishing process set-ups are usually determined based on empirical trial and error methods because of the complexity of the machine/process system. Although the researchers have investigated ‘optimal’ vibratory finishing processes, most of the work was experimentally based [3–5]. Since the media motion modeling approach has not been widely implemented for optimizing the vibratory finishing process, the media motion inside the machine container is not well understood. However, there are growing demands for a vibratory finishing machine model that predicts optimal process parameters, surface roughness and stock removal rate accurately. Therefore, it is necessary to develop a fundamental vibratory finishing machine model to control, predict and optimize the process.

Although an initial vibratory finishing machine model has been developed to predict surface roughness and surface removal rate [1] media interactions inside the machine were not considered in this model. Later more advanced models have been proposed by the same author [6,7]. The equations of motion for the container having media and workpieces in vibratory finishing have been derived, and the motion of the container has been analyzed. However, individual particle interactions with surrounding particles have not been included. In order to predict more accurate and deterministic contact forces and travel velocities of workpieces among contacting particles, the development of an advanced dynamic vibratory finishing machine model describing the motion of discrete elements under specific vibration modes is required. In other applications, flow of granular materials has been studied for various applications such as hopper discharge, rotating drums and so on by many researchers [8–10]. The discrete element method (DEM) has been applied to these models because this approach is the most suitable where a large number of discrete elements contact each other simultaneously. Models using DEM have provided useful and accurate results such as bulk media flow velocity [11–13]. Recently, a model using a different approach has been developed to understand the grain dynamics [14].

In this study, a vibratory finishing machine model has been developed using DEM and ABAQUS/Explicit in order to understand the dynamic mechanisms of the media system in a vibratory finishing process. DEM has been applied to the contacts between the particles, and between the particles and container wall, to determine the contact forces and impact velocities of the particles. It has been found that the impact forces and velocities of particles vary significantly with the setup and fundamental contact parameter values.

2. Description of vibratory finishing machine model

A schematic diagram of the vibratory finishing machine is depicted in Fig. 1. The container that is filled with the media and workpieces is attached to the ground through a spring system. The vibratory motion of the container is generated by an imbalanced

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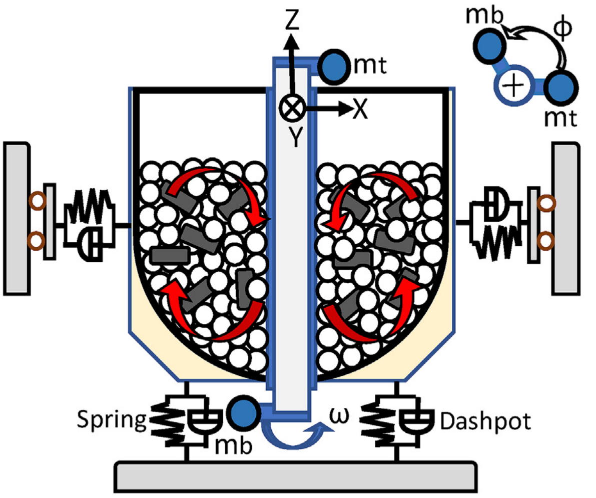

Fig. 1. Schematic of a bowl-type vibratory finishing machine with media (cross-sectional view).

rotating shaft with eccentric top and bottom weights placed in the center of the machine system. The particles experience two distinct motions; large scale bulk media flow induced by the container vibration and small scale vibratory motion from particles impacting surrounding particles [6,7]. The arrows show the lateral and vertical motion of the bulk media and workpiece flow. Fig. 2 shows a three-dimensional, bowl-type vibratory finishing machine model filled with spherical media particles using ABAQUS/Explicit. The motion of the container is constrained by four equi-spaced horizontal springs and four horizontal dampers, as well as four equi-spaced vertical springs and four vertical dampers. Two top and bottom weights, m_t and m_b, are attached to the rotating shaft with an adjustable phase angle ϕ between the weights. The shaft speed is fixed at $\omega = 144.9$ rad/s. The detailed information about this bowl-type vibratory finishing machine model is described in Ref. [6]. Table 1 shows the setup and fundamental parameters used in the developed model.

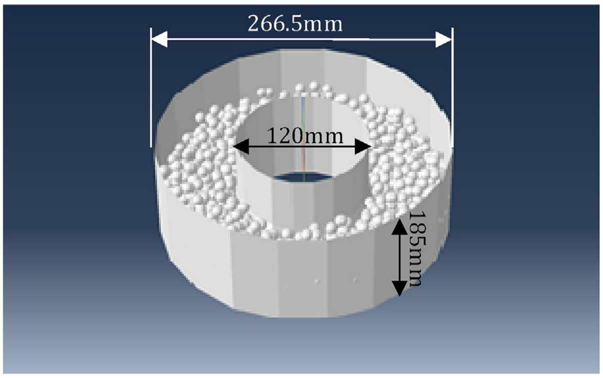

Fig. 2. A three-dimensional vibratory finishing machine model with media using ABAQUS/Explicit.

Table 1
Setup and fundamental parameters used for the vibratory finishing machine model.

Parameter	Value
Arm radius of weight (mm)	50
Angular velocity of spindle (rad/s)	146.9
Top weight (N)	8.4
Bottom weight (N)	9.3
Phase angle between weights (degree)	67
Vertical spring distance from the center (mm)	180
Top weight distance from gravity center (mm)	145
Bottom weight distance from gravity center (mm)	255
Weight of container with excitor (N)	564.5
Spring constant for vertical supports (N/mm)	39.17
Spring constant for horizontal supports (N/mm)	15.91
Damping coefficient for vertical supports (N-s/mm)	0.00545
Damping coefficient for horizontal supports (N-s/mm)	0.02217

The material removal rate and plastic deformation of workpieces within the vibratory finishing machine are determined by excitation modes induced by machine setup parameters such as phase angle and vibration frequency, media contact stiffness, and resulting media velocity [6,7]. The interacting forces between particles as well as between container boundary surfaces and particles were determined by the discrete element method (DEM) [11–13,15]. The container wall is assumed to be a rigid body surface with a very high friction coefficient of 0.35 on the surface. The simulation model requires two steps. The first step is to fill the container with particles considering gravitational force. The second step is to spin the imbalanced rotating shaft with $\omega = 144.9$ rad/s in order to induce container vibratory motion and the consequent excitation of the media. The vibratory finishing machine model simulation has been conducted using the initial setup and operating parameters described in Table 1. Nonlinear contact relationships used for the simulations have been optimized after analyzing the particle trajectories. The model produces three-dimensional motion of individual particles and bulk flow of media inside the vibrating container. Since a discrete element particle represents an individual particle, a rigid element was used for each particle [16]. Each particle is described as a single-node element that has a rigid spherical shape with a specified radius. Also, a gravity induced load was applied to the system with an acceleration of 9800 mm/s^2 in the Z-direction.

3. Discrete element method

Normal and tangential contact forces F_n, F_t between interacting particles and between particles and the container wall are calculated based on Hertzian contact theory. This non-linear, elasticity based theory calculates the normal and tangential contact forces using contact stiffness, overlap, damping coefficient and friction. Fig. 3 explains schematically the contact interactions between two discrete element particles. The pressure–overclosure relationships in tabular form have been used to define the contact stiffness of the media. In ABAQUS/Explicit, the energy of the impacting particles in the container is dissipated through contact friction and damping between the particles, as well as between the particles and the container. Tangential force is constrained by the Coulomb friction force $F_t = \mu F_n$ where μ is the friction coefficient between particles and/or between particles and the container wall. Tangential contact forces acting on the particle surfaces cause moments about the particle centers. Interactions involving DEM particles account for moment transfer across the contacting interfaces.

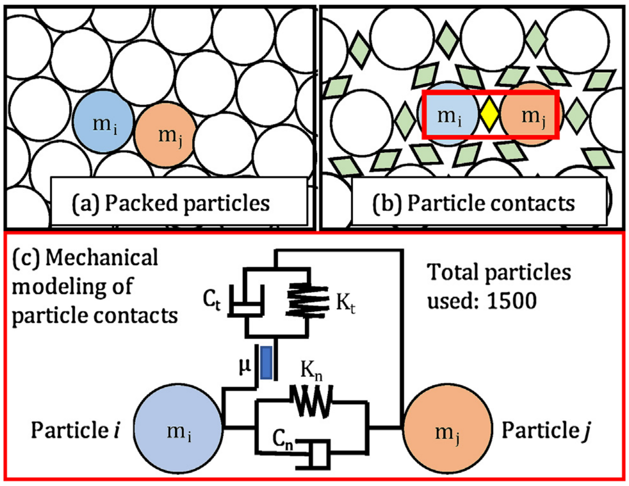

Fig. 3. Schematic of contact interactions between two discrete element particles.

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