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Dynamic analysis and grinding tracks in the magnetic fluid grinding system Part II. The imperfection and ball interaction effects

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ABSTRACT

To model the effects of the geometrical imperfections on the ball motion and its grinding track, it is therefore necessary to combine a dynamic model of the support system of balls with the previous model. For the geometrical imperfections on the ball, because of the interaction between the contact loads and the ball-spin speed, it causes the friction contact condition to remain at the interfaces with lower contact loads and lower ball-spin speeds in the separation case at the initial stage. Consequently, the variation in the ball-spin angle and the area covered by the grinding tracks is small. However, when the intermittent separation occurs at the geometrical imperfections on the ball orbit, it causes a large oscillation in the ball-spin angle and the ball-spin speed. Consequently, the effect of the imperfections in the ball orbit on the area covered by the grinding tracks is larger than that of the ball geometry. Ball–ball contacts cause a large oscillation in the ball-spin angle resulting in a uniform distribution of the grinding tracks. Hence, the effect of ball–ball contacts is one of the most important mechanisms in achieving a uniform distribution of the grinding tracks.

1. Introduction

Magnetic fluid grinding has been developed to finish ceramic balls with a high removal rate and better roundness. This finishing process was carried out in one continuous operation to generate a ball with roundness from 500 to 0.14 μm, in 3 h. According to the experimental results obtained by Umehara and Kato [1], the roundness of a ball decreased rapidly with grinding time using a float in a magnetic fluid grinding system, but it increased gradually when no float was used. It is obvious that the float is very effective in increasing the removal rate and producing better roundness. Clearly, a float is indispensable for finishing a ball in a magnetic fluid grinding system.

To understand the role of the float, its support system can be modeled as a mass, a spring, and a damper. When the shaft rotates, it drives the balls so that the balls move on the inner surface of the container in which the system is contained. In the real world, the balls, shaft, and container are never perfect and contain various types of geometrical imperfections on their surfaces. This is especially true when the primary processing route for original ceramic balls is sintering, or hot isostatic pressing of powders, so that the out-of-roundness that results from the shrinkage associated with the sintering process must be removed in the finishing process. Since the balls are placed on a float, the geometrical defects on their surfaces will cause the float to move up and down, resulting in variation in the grinding load. Generally, this has a marked effect on the transient motion of the balls and the float, in turn significantly affecting the distribution of the grinding tracks.

Umehara [2] observed that the support stiffness of a float is crucial during the grinding process. Generally, this stiffness is much smaller than that of the traditional method. Such low stiffness prevents the ceramic ball from sustaining severe damage during the grinding process, due to smaller vibration and less powerful impact. His results showed that a stiffness of 6120 N/m provides higher removal rates and rapidly decreasing rates of roundness. Since the magnetic fluid is costly, non-magnetic fluid grinding systems have been developed by Chang and Childs [3] to replace the support stiffness of a float in achieving the same removal rates as magnetic fluid grinding.

To understand the surface generation mechanism of the ball in the magnetic fluid grinding system, four different support systems were used by Zhang and Nakajima [4] to investigate the effect of stiffness on ball roundness. They concluded that to understand the mechanism by which the spherical surface is generated, a dynamic analysis of the grinding system must be considered. Furthermore, adjacent balls can touch one another during the grinding process due to unequal ball loading effects [5]. Their results showed that

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Nomenclature

c_{cr}, c_f critical damping and damping coefficients of the magnetic fluid support system, respectively
$D_{b,i}$ fluid drag force on the ith ball
D_i normal contact force between the ith and $i+1$th balls
$F_{c,i}$, $F_{f,I}$, $F_{s,i}$ friction force components due to drag at contacts of the ith ball with the container, float and shaft, respectively
I_b, I_f moment of inertia of ball and float, respectively
k_f stiffness of the magnetic fluid support system
L_0, $L_{0,i}$ preload of the ball and the ith ball, respectively
m' effective mass of the ball in the fluid
m_b, m_f mass of ball and float, respectively
$M_{c,i}$, $M_{f,i}$, $M_{s,I}$ contact torque of the ith ball with the container, float and shaft, respectively
N number of balls in a cell
N_f, $N_{f,i}$ force variation due to shape error of a ball and the ith ball, respectively
p natural frequency of the support system
$Q_{br,i}$, $Q_{bz,i}$ fluid drag torque component on the ith ball in the direction of r and z, respectively
Q_f fluid drag torque on float
r radial distance from the cell centre-line to the ball center
r_b nominal radius of a ball
r_c, r_f, r_s the distances from the ball center to the ball contact with the container, float and shaft, respectively
R_f radial distance from the cell centre-line to the ball contact with float
t time
$W_{c,i}$, $W_{f,i}$, $W_{s,I}$ contact load of the ith ball with the container, float and shaft, respectively
z_b, z_f displacement of the ball center and the float center in the direction of z due to the shape error of a ball, respectively

Greek symbols
β_i direction of the axis of spin of the ith ball
γ_i direction of the contact friction force between the ith and $i+1$th balls
δ shape error from the perfect ball
Δ_r the amplitude of the shape error for the imperfection in the ball orbit
Δ_n the amplitude of the shape error in the nth wave number
θ_s slope of conical-ended drive shaft
λ_f magnification factor
μ_b the friction interaction coefficient of balls
ϕ_1,ϕ_2,ϕ_3 phase angle at the contact of a ball with the container, float and shaft, respectively
φ_n phase angle in the nth wave number
ω rolling angular speed of a ball at each contact
$\omega_{b,i}$ spin angular speed of the ith ball
ω_{br}, ω_{bz} r and z components of ball-spin angular speed, respectively
Ω_b circulation speed of the ball
Ω_f angular speed of the float
Ω_s angular speed of the shaft

the ball interaction resulted in an 8° oscillation in the ball-spin angle as the balls travel around the container during the grinding process. However, this model was only suitable for a steady-state solution for the motion of the ball and the float. Using the equation for the grinding tracks developed by the authors [6,7], grinding tracks formed due to the ball interactions still concentrate within a small ring area under steady-state conditions. Hence, it is obvious that the dynamic model provides the possibility to randomize ball motions in the grinding cell and hence to equalize material removal from the entirety of a given ball's surface.

In light of the aforementioned research, it is clear that the support system for the balls and the float plays an important role in the ball motion and in the surface generation mechanism of the ball. It is therefore necessary to combine a dynamic model of the support system of balls with the previous model [8]. Moreover, as the balls travel between the shaft and the float in a magnetic fluid grinding cell, the geometrical imperfections promote dynamic changes in the contact load and friction forces. Consequently, the balls are continually subjected to accelerations and decelerations. To further understand its effect, the geometrical imperfections on the surfaces of the ball and container are used as the major variables in this study. Furthermore, the ball interaction on the ball motion and the grinding tracks is different from other parameters. Therefore, the effects of the ball interaction on the ball motion and the distribution of the grinding tracks are also investigated in this study.

2. Theoretical analysis

2.1. Dynamic model of geometrical imperfections

Since the balls are placed on a float, the imperfections on their surfaces will cause the float to move up and down, resulting in variation in the grinding load. Therefore, it is necessary to combine a dynamic model of the support system of balls with the previous model [8].

In a magnetic fluid grinding system, the chamber is filled with a magnetic fluid, which provides magnetic buoyancy to the float. This magnetic fluid support system can be modeled by a mass m_f, a spring with stiffness k_f, and a damper with damping coefficient c_f. Hence, the contact load W_f of a ball from a float can be expressed as

$$W_f = L_0 - N_f \tag{1}$$

where L_0 is the preload and the force variation N_f due to the vibration is given as

$$N_f = m_f\ddot{z}_f + c_f\dot{z}_f + k_f z_f \tag{2}$$

Here, the axial displacement from the rest position of the float center (i.e. the z-direction) is denoted by z_f.

During the grinding process, the geometrical imperfections on the ball always have a marked effect on the ball motion. It is clear that in each individual ball, the surface profiles are different. However, since they are produced by the same machining process, it can be expected that the surfaces have certain features in common. Because any form of shape error can always be decomposed into a series of sinusoidal waveforms in terms of a Fourier series, the shape error $\delta(t)$ from the perfect ball can be written as

$$\delta(t) = \Delta_n \sin(n\omega t + \varphi_n) \tag{3}$$

The parameter Δ_n is the amplitude of the shape error in the nth wave number, while the phase angle of φ_n is distributed over the interval $[0, 2\pi]$. The angular speed ω is the rolling speed of the ball at each contact. Fig. 1 is helpful in describing the effect of the shape error, while the dotted circle indicates the nominal circle of a ball