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MODEL SIMULATION OF VIBRATORY BALL MILLING OF METAL POWDERS

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ABSTRACT

The impact action of milling balls during ball milling of metal powders has a special relation to mechanical alloying. The motion of milling balls during vibratory milling of metal powders was analyzed by computer simulation using one-, two- and three-dimensional models. The average impact velocity of balls and frequency of ball-collisions were estimated as a function of ball charge fraction. It was found that with increase in ball charge the average normal component of the impact velocity decreases. The result of the simulation was verified by the experimental results on vibratory ball milling of a mixture of copper and graphite powders.

INTRODUCTION

Ball milling is widely used for mechanical alloying of elemental metal powders. The process of mechanical alloying which includes the formation of composite particles, formation of alloy phase and eventual amorphization is seriously affected by milling conditions such as milling intensity[1], milling ball size[2,3] and type of ball milling[4]. All these milling conditions have a close relation to the impact energy of milling balls. It is therefore necessary to clarify the effect of the impact energy of balls on the process of mechanical alloying. However, it is very difficult to measure the impact energy of balls during milling because that the impact energy of balls ranges widely and that a great number of collisions occur for a very short time.

Model simulation is an effective method of estimating quantities difficult to measure. In this study, the motion of individual milling balls during vibratory milling of metal powders was analyzed by computer simulation using one-, two- and three-dimensional models. The impact velocity of individual ball-collisions and the frequency of collisions were estimated as a function of ball charge. The results of the simulation were verified from the viewpoint of work-hardening of milled powder particles during vibratory milling of a mixture of copper and graphite powders.

MODEL SIMULATION

Figure 1 shows a laboratory ball mill which was used in our milling experiment. Two cylindrical stainless steel vials charged with steel balls were fixed on a vibrating equipment. Vibration with a small gyratory motion which is driven by rotation of unbalanced weights was given to the mill vials. A radius of gyration was 2.5 mm and its frequency was 25 Hz. In order to simulate the motion of milling balls in this laboratory mill, three mathematical models which are shown in Fig.2[5] were used. Fig.2a) shows a one-dimensional model. The one-dimensional model consists of a cylindrical steel vial charged with steel balls whose diameter is the same as the inner diameter of the vial. No friction between the balls and the vial was assumed. This assumption assures smooth one-dimensional motion of the balls. A harmonic vibration with an amplitude of 2.5 mm and a frequency of 25 Hz was given to the vial in its longitudinal direction. A two-dimensional model consists of a cylindrical steel vial charged with steel balls whose diameter is the same as the inner length of the vial, as shown in Fig.2b). No friction between two parallel side walls of the vial and the balls would assure smooth two-dimensional motion of the balls. The inner diameter of this vial is the same as the experimental vials. Three-dimensional model consists of steel balls and a cylindrical steel vial having the same size as the experimental vials, as shown in Fig.2c). The same vibration as in the experiment was given to the two- and three-dimensional models.

In these models, milling of metal powder particles was modeled under the following assumptions:

(1) Consumption of impact energy of milling balls due to micro-compaction of the metal powder particles can be regarded as the energy consumption due to an imaginary viscosity given to the milling balls and the vials.

(2) Elasticity of the powder particles is ignored.

These assumptions enable the motion of elastic balls during vibratory milling of metal powders to be substituted by the motion of viscoelastic balls in a vibrating viscoelastic vial. A simple Kelvin model[6], as shown in Fig.3, was used to approximate the viscoelastic bodies. A spring represents the elasticity of the milling ball and of the vial. A dashpot represents the imaginary viscosity given to the milling balls and the vials.

When two viscoelastic bodies come in contact, the elastic repulsion force, f_e [N] acting on their contact surface is given by eqn.(1) according to Hertz's contact theory[7]:

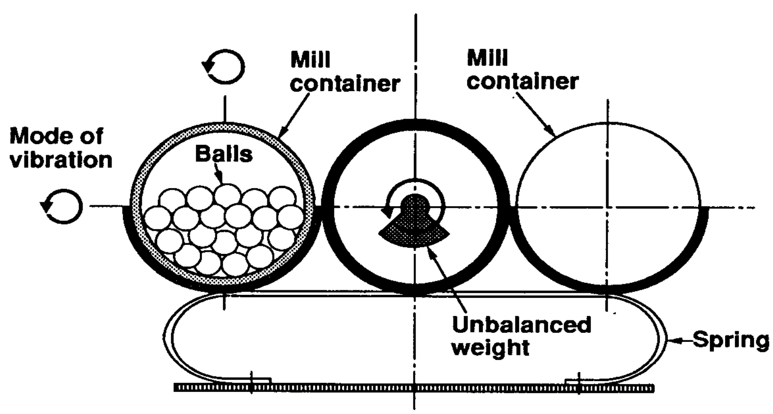

Fig.1 Vibratory ball mill

MODEL SIMULATION OF VIBRATORY BALL MILLING OF METAL POWDERS 91

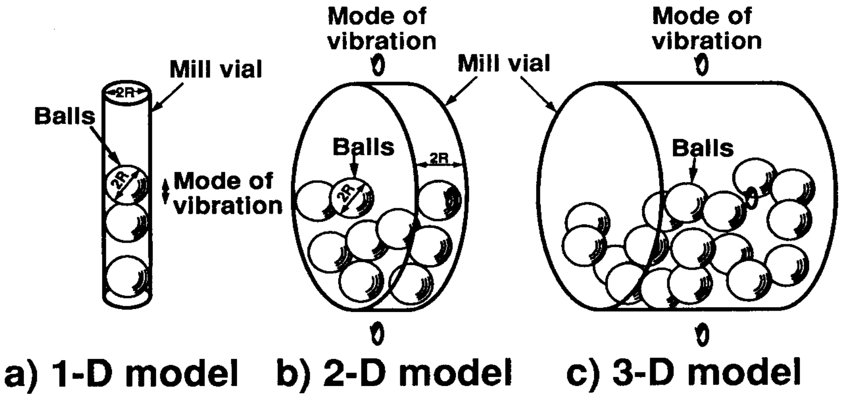

Fig.2 Mathematical models of vibratory ball mill

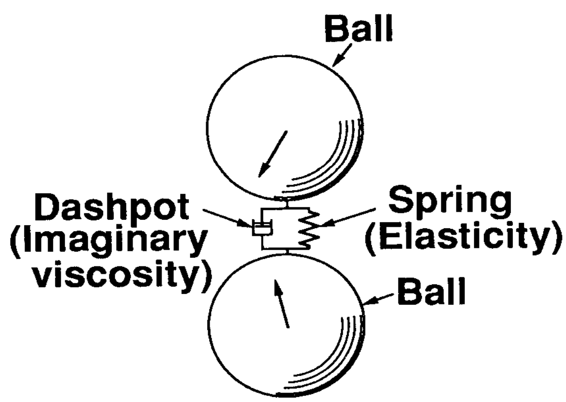

Fig.3 Viscoelastic collision model (Kelvin model)

$$f_e = K D^{3/2} \tag{1}$$

where **D** [m] is an amount of approach due to the deformation of the bodies in the loading direction and **K** is a coefficient given by

$$K = \frac{2}{3}\left(\frac{R_1 R_2}{R_1 + R_2}\right)^{1/2}\left(\frac{Y_1}{1-v_1^2} + \frac{Y_2}{1-v_2^2}\right) \tag{2}$$

In eqn.(2), R_1 and R_2 [m] are radii of curvature of the bodies, Y_1 and Y_2 [Pa], Young's moduli, and v_1 and v_1, Poisson's ratios. By analogy of eqn.(1) with Hooke's law applied to the spring, coefficient **K** may be regarded as an elastic coefficient and the quantity $D^{3/2}$ as the elastic displacement of the spring. The viscous resistance f_v [N] by the dashpot was assumed to be proportional to the deformation rate of the spring, $dD^{3/2}/dt$ [$m^{3/2}/s$], as follows;

$$f_v = C_r(dD^{3/2}/dt) \quad (3)$$

where C_r [$kg/m^{1/2}s$] is regarded as a coefficient of viscosity. Since the imaginary viscosity was introduced into the models to approximate the energy consumption by the metal powder particles compressed between colliding bodies, f_v was set to be zero when the deformation rate $dD^{3/2}/dt$ becomes negative.

In the two-dimensional model, frictional force acting in the tangential direction of contact surfaces of the milling balls was taken into account. The frictional force f_f [N] is given by eqn.(4),

$$f_f = \mu(f_e + f_v) \quad (4)$$

where μ is a coefficient of friction.

It was assumed that the motion of the gravitational center of the ball is determined by the gravitational force, elastic repulsion force and viscous resistance, and that the frictional force determines the rotation of the balls. These assumptions give the equations of motion of the individual balls as follows;

$$M_I \frac{d^2 x_I}{dt^2} = \sum_{J=0}^{n} \left(f_{ex_{I,J}} + f_{vx_{I,J}}\right) \quad (5)$$

$$M_I \frac{d^2 y_I}{dt^2} = \sum_{J=0}^{n} \left(f_{ey_{I,J}} + f_{vy_{I,J}}\right) \quad (6)$$

$$M_I \frac{d^2 z_I}{dt^2} = \sum_{J=0}^{n} \left(f_{ez_{I,J}} + f_{vz_{I,J}}\right) - M_I g \quad (7)$$

$$J_I \frac{dw_I}{dt} = \sum_{J=0}^{n} (f_{f_{I,J}}) R_I \quad (8)$$

where M_I [kg] denotes the mass of the I-th ball, J_I [kg m^2], the moment of inertia, R_I [m], the radius, w_I [rad/s], the rotational speed (angular velocity), and x_I, y_I and z_I [m], the coordinates of the gravitational center, $f_{exI,J}$, $f_{eyI,J}$ and $f_{ezI,J}$ [N], the components of the elastic force acting on the contact surface between the I-th ball and the J-th (J=0 means the vial), $f_{vxI,J}$, $f_{vyI,J}$ and $f_{vzI,J}$ [N], those of the viscous resistance and $f_{fI,J}$ [N], the frictional force, and g, the gravitational acceleration. The frictional force acting on the I-th ball was set to be positive when the force accelerates the counterclockwise rotation of the I-th ball.

In the one-dimensional model, eqn.(7) was used to analyze the translational motion of the gravitational centers of the individual balls. In the two-dimensional model, eqns.(5) and (7) were used to analyze the translation of the gravitational centers and eqn.(8) was used to analyze the rotation around the gravitational centers. In the three-dimensional model, the translation of the gravitational centers was analyzed by eqns.(5), (6) and (7) and the rotation was ignored. The major algorithm of the model simulation was given in the previous paper[8].

In this simulation, the coefficient **Cr** in eqn.(3) has no clear physical meaning but plays a decisive role in the energy consumption[8]. The value of **Cr** corresponds to the ability of energy absorption of the metal powder particles. Therefore, the model simulation was performed by using various values of **Cr**.

RESULT OF THE SIMULATION

A result of the one-dimensional model simulation is shown in Fig.4 in which the average impact velocity of 12.7-mm balls is plotted against ball charge fraction, for various **Cr** values; (a)**Cr**= 2200, (b)11000 and (c)25000 $kg/m^{1/2}s$. For each of the **Cr** values with the impact velocity of 2.0 m/s for instance, (a)20%, (b)50% and (c)80% of the impact energy are estimated to be consumed, respectively. The average impact velocity has a tendency to decrease with increase in ball charge.

Impact frequency of 12.7-mm balls in the vial which was calculated by the one-dimensional simulation at various ball charge is shown in Fig.5. The impact frequency rapidly decreases with decreasing ball charge in a ball charge fraction ranging from 0.4 to 0.85. and becomes very low in a range under 0.4.

In the two-dimensional model, the frictional force acting in the tangential direction of the contact surfaces was taken into account, because the shearing force, as well as the impact compressive force, acts on the powder particles between balls. It should be noted here that the impact compression of the powder particles is related to the normal component of the impact velocity and the tangential component of the impact velocity relates to the shearing of the particles. The two components of the impact velocity of 12.7-mm balls were calculated by the two-dimensional simulation for various ball charge fractions, and is shown in Fig.6(**Cr**=11000 $kg/m^{1/2}s$). The average tangential component of the impact velocity increases with increasing ball charge, while the average normal component decreases.

Figure 7 shows a result of the three-dimensional simulation in which the average normal impact velocity of 25.4-mm balls is plotted against the ball charge fraction. The average normal impact velocity decreases with increasing ball charge in a quite similar way to the one- and two-dimensional simulation.

EXPERIMENT

In order to verify the results of the simulation, a milling experiment was performed on a mixture of electrolytic copper and 5 vol.% graphite powders by using the laboratory mill(see Fig.1). The graphite powder was used as a marker for the observation of welding and kneading action of copper particles. The milling was done at four volume fractions of ball charge(0.2, 0.4, 0.6 and 0.85) with a constant volume fraction of powder against the volume of void in the ball bed. Vickers hardness of milled powder particles were measured.

EXPERIMENTAL RESULTS[8] AND DISCUSSION

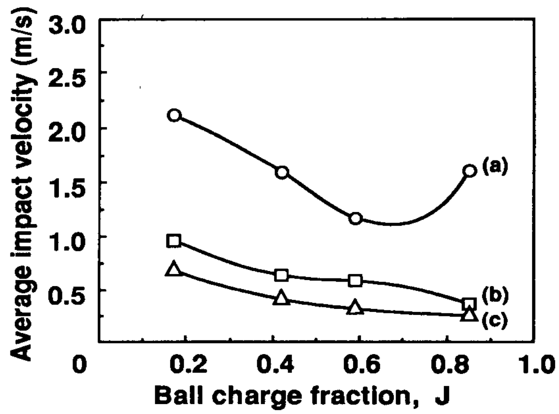

Fig.4 Impact velocity of balls as a function of ball charge fraction which was calculated by one-dimensional simulation by use of (a) Cr= 2200, (b) Cr= 11000 and (c) Cr= 25000 kg/m$^{1/2}$s

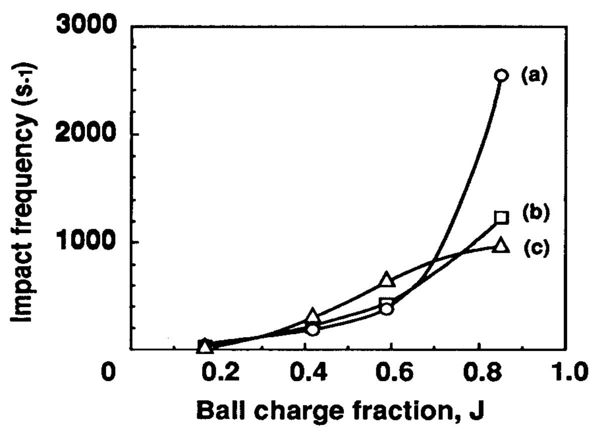

Fig.5 Impact frequency of balls as a function of ball charge fraction which was calculated by one-dimensional simulation by use of (a) Cr= 2200, (b) Cr= 11000 and (c) Cr= 25000 kg/m$^{1/2}$s

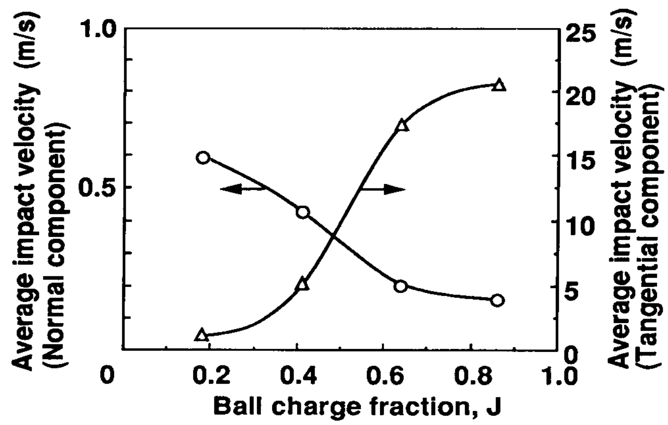

Fig.6 Changes in both average normal and average tangential components of impact velocity with ball charge fraction

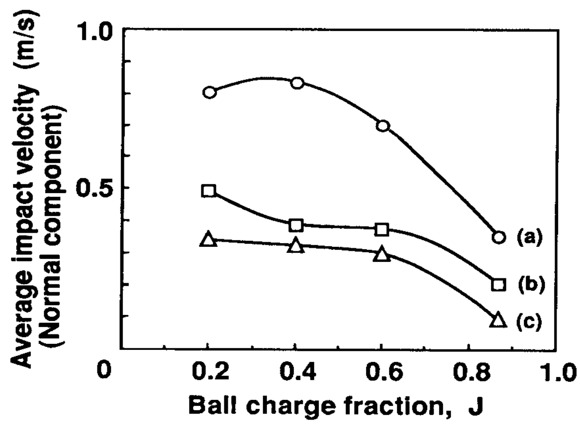

Fig.7 Impact velocity of balls as a function of ball charge fraction which was calculated by three-dimensional simulation by use of (a) Cr= 11000, (b) Cr= 41500 and (c) Cr= 135000 $kg/m^{1/2}s$

Figure 8 shows the hardness of the powder particles milled for 28.8 ks (8 hours) at four fractions of ball charge. The hardness tends to decrease with increasing ball charge in the fraction ranging from 0.4 to 0.85. By comparing this figure with the simulation results shown in Figs.4, 6 and 7, it is easily realized that the saturate hardness of the particles increases with an increase in compressive force acting on the particles which relates to the normal component of the impact velocity. The lower hardness at the ball charge fraction of 0.2 should be due to too small impact frequency in spite of the larger normal component of the impact velocity.

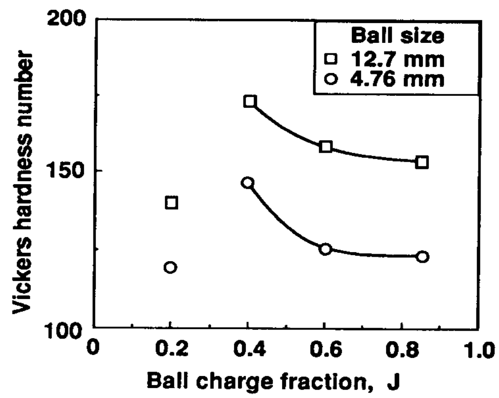

Fig.8 Effect of ball charge fraction on Vickers hardness of Cu-C powder particles milled for 28.8 ks

SUMMARY

Impact frequency and the normal and tangential components of the average impact velocity of the milling balls in vibratory ball milling were analyzed by one-, two- and three-dimensional model simulation. It has been found that the impact frequency increases with increasing ball charge, whereas the average normal component of the impact velocity decreases and the tangential component increases. The results of the simulation have been verified on the basis of the experiment of the vibratory ball milling of copper and graphite powders.

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