Analysis of Movement of Spherical Particles in a Twin Roller System for Size Classification

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ABSTRACT
The movement of spherical particles in a twin roller system for size classification has been studied experimentally. The diameter of the particles used is 600 µm. The classification system consists of a feeder, a twin roller unit and containers for collecting particles classified. The two rollers can be set at a desired angle from the horizon. The rollers can be rotated at an arbitrary angular velocity. All the particles that are fed from the feeder move along the gap between the two rollers. As the gap width increases downward, the particles fall down at a point where the gap width exceeds the particle diameter and are collected in containers arranged in a row. The motion of the particles moving along the gap is observed through a high-speed camera connected with a microscope. The image analysis shows that the particles roll down with small jumping, and the rotation of the particles depends on the operating condition of the twin roller system. The particle velocity along the gap varies according to the jumping. The flight time, normal velocity, and distance can be calculated from the velocity difference of the particles before and after the contact with the rollers.

KEYWORDS
size classification, spherical particle, twin roller system, motion analysis

INTRODUCTION
In recent years, electronic devices, which are widely used for the information and communication equipment, become very small owing to the progress of the packaging technology. BGA: Ball Grid Array (Liu et al., 1995), allowed significant size reduction compared to conventional surface mount devices such as QFP: Quad Flat Package. For BGA, spherical solder particles less than 1 mm are used for the joints, which are under of the chip, and thus the board area becomes smaller. If the diameter of the solder particles is not constant, the electric connection might result in a failure. The size classification of the solder particles requires accuracy in a few micron levels; however, it is difficult to realize the required accuracy and efficiency using conventional methods such as sieving or air classification (İnoya and Tanaka, 1997). A few fine or coarse particles would be contained in the classified products. A newly developed method using a twin roller unit enables us to classify spherical particles with the accuracy within 1 µm. Individual particles move along the gap of the rollers. When the gap width is larger than the particle diameter, the particles fall down and are completely classified. Since the behavior and the
translational velocity of the particles are related to the accuracy and efficiency for the classification, the movement of the particles should be clarified. In the previous paper (Matsusaka et al., 2003), it was shown that the average velocity of the particles moving along the gap is proportional to the angular velocity of the rollers and the tangent of angle of inclination irrespective of particle diameter. Also, microscopic observation showed that the particles are not simply rolling along the gap between the rollers but moving with complicated motions.

In the present work, we pay attention to the rotation and translation with fluctuation of the particles moving in the twin roller system. In particular, the effect of the rotational direction and angular velocity of the rollers on the behavior of the particles are studied in detail.

METHODS

The experimental apparatus consists of a feeder, a twin roller unit and containers for collecting particles classified (YSW, Yutaka Co.). Figure 1 shows the main part of the classifier. The two rollers can be set at a desired angle $\theta$ from the horizon with a small angle $\alpha$ between the rollers. Individual particles that are fed from the feeder move along the gap between the rollers. To prevent the particles from adhering to the rollers, the rollers must be rotated ($\omega_1, \omega_2 \leq 13$ rad/s). As the gap width increases downward, the particles fall down at a certain point and are collected in the containers arranged in a row. The particles used for the experiments are bearing balls, which are almost perfectly spherical ($D_p = 600$ µm).

![Figure 1. A twin roller system](image-url)
The motion of the particles moving along the gap was observed through a high-speed camera (Fastcam-Max, Photron Co.) connected with a microscope (CX, Hilox Co.). The images were recorded at the intervals of 1/8000 s for 0.1 s. The magnification of the microscope was 150 times. The movement of the particles was analyzed using a software (Dipp Motion 2D, Ditect Co.). A coordinate system was adopted as shown in Figure 1, i.e., the $X$-axis and $Y$-axis were aligned, respectively, in the longitudinal and transverse directions and $Z$-axis was perpendicular to the two axes (see Figure 1). To analyze the rotation of the particles, the orientation was recalculated by converting the two-dimensional coordinate to three-dimensional coordinate, and both $X$-axis rotation and $Y$-axis rotation were investigated under various operating conditions.

Figure 2 illustrates three cases of the rotation of two of the rollers, i.e., the opposite rotation (case 1), single rotation (case 2), and the same rotation (case 3), where a clockwise rotation is defined as positive.

![Figure 2. Rotation of two rollers](image)

Operating condition

Although the gap between rollers widen downward for classification, the angle $\alpha$ does not affect the movement of the particles as long as the angle is sufficiently small; thus, we simply set them in parallel ($\alpha = 0^\circ$). The gap width between rollers was $590 \mu m$ that is slightly smaller than the particle diameter of $600 \mu m$. The angle of inclination was $12.5^\circ$, and the angular velocity of the rollers were in the range $\omega_1, \omega_2 = 0$–$13.5$ rad/s.

RESULTS AND DISCUSSION

Rotation of particles

When the two rollers rotate in opposite directions (case 1), the particles mainly rotate about the $Y$-axis. The $X$-axis rotation is, also, observed when the particles contact with one of the rollers. However, the direction of the $X$-axis rotation is changed frequently because the two rollers rotate in opposite directions, i.e., the rotational power of the roller is not sufficiently transmitted to the particles. This phenomenon is sometimes referred to as frustration. When the two rollers rotate in the same direction (case 3), the rotational power is sufficiently transmitted to the particles, thus the $X$-axis rotation becomes dominant. The angular velocity of the $X$-axis rotation is proportional to the angular velocity of the rollers, and the circumferential velocity of the particles is equal to that of the rollers. Therefore, a slip hardly occurs between the contacting surfaces. As for single
rotation (case 2), the Y-axis rotation mainly occurs.

**Velocity of particles**

Figure 3 shows the variation of the particle velocity along the \(X\)-axis, which is obtained by the image analysis. The acceleration and deceleration are repeated periodically. The acceleration corresponds to the jump of the particle and the gradient is equal to \(g \cdot \sin \theta\). The deceleration is caused by the contact friction with the wall of the rollers. For the single rotation (case 2), minimum velocities were almost zero. When the two rollers rotate in the same direction (case 3), the velocities are extremely small. Therefore, the particle velocity for the opposite rotation is higher.

![Figure 3. Variation of particle velocity along X-axis (case 1, \(\theta = 12.5^\circ\))](image)

**Particle jumping**

Figure 4 illustrates the jump of a particle in this system. The particle caught in the gap is thrown up by the two rollers; after a small flight, the particle contacts with the rollers again. The trajectory of the particle is controlled by the initial velocity and the gravity. If the particles are not so small, the drag force is negligible. \(V_x\) denotes the particle velocity along the \(X\)-axis and \(V_z\) is that along the \(Z\)-axis, and \(\Delta t\) is the flight time. The subscripts 0 and 1 refer to the start and the end of the jump, respectively. The flight time \(\Delta t\), the particle velocity \(V_{z0}\), and flight distance \(\Delta x\) are expressed as

\[V_x = gs \sin \theta\]
\[ \Delta t = \frac{1}{g \sin \theta} (V_{x1} - V_{x0}) \]  \hspace{1cm} (1) \\
\[ V_{z0} = \frac{1}{2g \tan \theta} (V_{x1} - V_{x0}) \]  \hspace{1cm} (2) \\
\[ \Delta x = \frac{1}{2g \sin \theta} (V_{x1}^2 - V_{x0}^2) \]  \hspace{1cm} (3)

Figure 5 shows the effect of the angular velocities of the two rollers \( \omega_1 \) and \( \omega_2 \) on the particle velocity \( V_{x0} \) and \( V_{x1} \). The particle velocity varies according to the operating condition. It is worth noting that the tendency of the variation of \( V_{x1} \) differs from that of \( V_{x0} \).

Figure 4. Jumping of a particle in the twin roller system

Figure 5. Particle velocities before and after contact with the rollers \( V_{x0} \) and \( V_{x1} \)
Velocity difference

Figure 6 shows velocity difference $\Delta V_x (= V_{x1} - V_{x0})$. For the single rotation ($\omega_2 = 0$), $\Delta V_x$ becomes larger. For the same rotation (at the right-hand side in Fig. 6), $\Delta V_x$ is rather small. To realize high-accuracy classification, it is desirable to keep the velocity difference smaller, which can be achieved in $\omega_1 = \omega_2$. However, as the particle velocity is small, the total efficiency is low. In addition, the risk of the fracture of the particles caught in the gap will be increased. Therefore, the operating condition should be determined taking into account the accuracy and efficiency.

![Figure 6. Velocity difference under various conditions](image)

The flight time $\Delta t$ and the particle velocity $V_{z0}$ are proportional to the velocity difference $\Delta V_x$ (see Eqs. (1) and (2)). As a reference, the scale for these values are also shown in Figure 6. The value of $\Delta t$ is as small as several ms, and $V_{z0}$ is several tens mm/s. The flight distance and height along Z-axis can also be calculated.

CONCLUSIONS

The movement of spherical particles in a twin roller system for size classification has been studied experimentally, and the following conclusions were drawn.

(1) When the two rollers rotate in opposite directions, the particles roll down with small jumping, where the particle velocity along the gap between the rollers is rather high.

(2) When the two rollers rotate in the same direction, the rotational power is sufficiently transmitted and the circumferential velocity of the particles is equal to that of the rollers; however, the particle velocity along the gap is low.

(3) For the single rotation, the velocity difference of the particles before and after the contact with
the rollers is larger. As for the same rotation, the velocity difference is small.

(4) For a high-accuracy classification, the same rotational direction is desirable because of the small velocity difference, and for a high efficiency classification, the opposite rotation is desirable. Therefore, the operating condition should be determined taking into account the accuracy and efficiency.

NOMENCLATURE

\( D_p \) particle diameter [m]

\( r \) radius of rollers

\( V_{x0}, V_{x1}, V_{z0}, V_{z1} \) Particle velocity component [m/s]

\( \Delta V_x \) velocity difference \( (= V_{x1} - V_{x0}) \) [m/s]

\( \Delta t \) flight time

\( \Delta x \) flight distance

\( \alpha \) angle between roller axes

\( \theta \) angle of inclination from horizon

\( \omega_1, \omega_2 \) angular velocity of roller

REFERENCES

