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Transport phenomena of circular particles and fibers in axially rotating drum

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Abstract

Several processing techniques have been proposed for the fabrication of functionally graded materials (FGMs), whose composition and microstructure, i.e., the chemical and physical properties vary in the specific direction. The mechanical property of FGMs is affected by dispersed particle size, its volume fraction, and particle orientation. In order to clarify its property, it is important to disclose the particle motion during the fabrication process. In this study, circular particle and fiber motion during fabrication of Functionally Graded Materials is studied using the cold model centrifugal casting. Consideration is given to the timewise variation of the radial circular-disk and fiber motion in the axially rotating cold water drum. The velocity measurement is carried out by means of the Particle Tracking Velocimetry (PTV) method and the measured value is compared with that estimated by the theoretical prediction. It is found that (i) as the disk moves toward the rotating wall, its motion is perpendicular to the wall, (ii) the measured velocity is in good agreement with compared with the theoretical one (BBO equation), (iii) in contrast, translation and rotation of the fiber occur in the interior region and each fiber is oriented in the several directions, and (iv) these motions of the fiber are suppressed and one side of the fiber tips is attracted toward the drum wall as time progresses.

Keywords: Multiphase flows, Micro- and nano- scale flows, Flow visualization and imaging
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1. Introduction

Several processing techniques have been explored for the fabrication of functionally graded materials (FGMs) [1], which allow their elements of structures and/or compositions to suit for various conditions of applications during their design processes. Their splendid characteristics are dominated by the wide gradation of physical and/or chemical properties, which can be controlled at different composition ratios. One of FGMs processing methods is a centrifugal solid-particle method [2]. In this method, since centrifugal force is applied

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during casting and the processing temperature is lower than the liquid temperature of the master alloy, a solid phase remains to be dispersed in a liquid matrix.

The centrifugal solid-particle method employs a casting mold filled with molten metal and solid particles. In general, Al/SiC, Al/Shirasu and Al/Al_3Ti are used as particles. The mold is rotated around the axis in high-speed. By using dissimilar centrifugal forces applied to particles with different densities and sizes, they are distributed in the rotating mold in order. To the authors' knowledge, there is no information on the circular disks and fibers transport phenomena in the mold, in which a carbon fiber is employed as a particle.

The present study is to investigate the disk and fiber transport phenomena in Functionally Graded Materials fabricated by the centrifugal solid-particle method. A cold model centrifugal casting is employed to visualize the actual circular disk and fiber motions in an axially rotating drum. In particular, consideration is given to the disk motion in the drum using PTV (Particle Tracking Velocimetry) and a comparison of measured value with the theoretical one estimated by BBO (Basset-Boussinesq-Ossen) equation.

2. Experimental apparatus and experimental method

Figure 1 shows the experimental apparatus, which consists of a cylindrical drum, a CCD camera, a pulley and an electric motor. A voltage adjustment device is adopted to control the torque and rotational speed. The drum with 200mm in inner diameter and 400mm in length is made of acryl in order to visualize the motion of disk particles. Here, a half of the drum is the visualization portion for accommodating the CCD camera and the other one is filled with a particle-fluid mixture. The ends of the drum are supported by ball bearings, one of which is linked with a pulley and the motor. The shaft fixed onto the drum is driven with the aid of the motor. Two counter-weights are placed on the inner surface of the drum to balance out the weight of the CCD camera so as to ensure a smooth rotation. A light sheet (1mm in thickness) of Argon laser is employed to visualize the circular disk (PET:ρ=1.36X10^3 kg/m^3 and 3mm in diameter) motion in the glycerin (μ_f=856X10^{-6} m^2/s, ρ=1.26X10^3 kg/m^3). Based the digital image including the disk or fiber motions, these velocities are obtained by means of the PTV method. The particle-fluid mixture consists of the circular disk or fiber as particles and the glycerin as a working fluid. By setting a low volume fraction of fibers in the fluid, visualization of the particle motions is achieved. Rotating speed of the drum is fixed throughout the experiments and its level is determined using the parameter G, which is referred as to G number, as mentioned in the following.

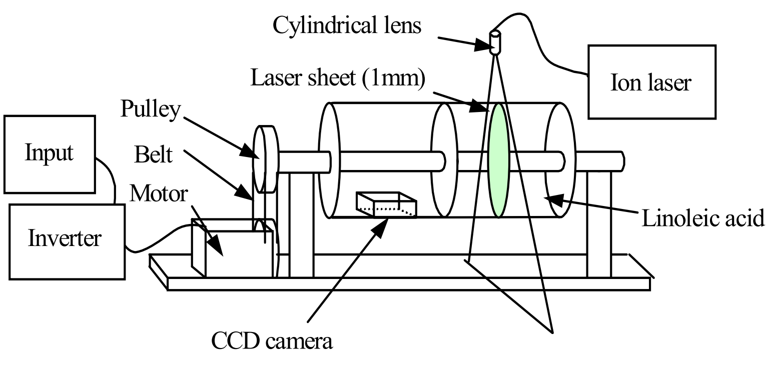
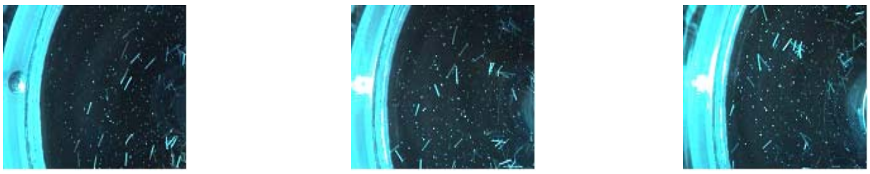


Fig. 1: A schematic of the experimental apparatus.

3. Results and Discussion

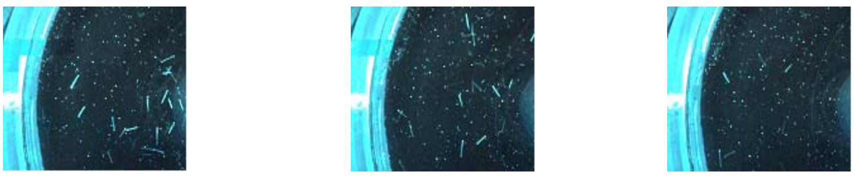
3.1 Fiber motion in the rotating durum

Figures 2 and 3 depict the photographs of fiber translation and rotation in the drum rotated at different rotating speeds of 400 and 640 rpm, respectively. Each frame is taken at a time interval of 3 sec. Slender white parts in the drum are fibers. Note that since a volume fraction of fibers in the fluid is substantial lower, each fiber moves independently and does not interact in the drum. It is observed that the fiber motion is classified into two patterns, that is, one pattern is located in the inner region of the drum and the other pattern is located in the vicinity of the drum wall. In other words, translation and rotation of the fiber occur in the interior region and each fiber is oriented in any directions. In contrast, both motions of the fiber are suppressed near the drum wall and the fiber tip is attracted toward the drum wall as time progresses. These fiber behaviors in the drum become clearer for the higher rotating speed, as seen in Fig. 3. Each fiber is oriented in the arbitrary directions in the region away from the drum wall. As time progresses, the fiber is attracted toward the drum wall by the centrifugal force in the rotating drum. At this time, the moment acted at both tips of the fiber is different because the centrifugal force in the rotating drum increases along the radial direction, as found from the definition of the G number. Thus one side of the fiber accelerates in the drum wall and finally attaches normal to it. After that, the fiber lies gradually on the wall by the moment acted at the other side of the fiber tip, because the standing position of the fiber is unstable. Notice that such fiber motion in the radial direction is different in the case that a volume fraction of fibers in the fluid is substantially larger.



(a) 0 sec. (b) 3 sec. (c) 6 sec.

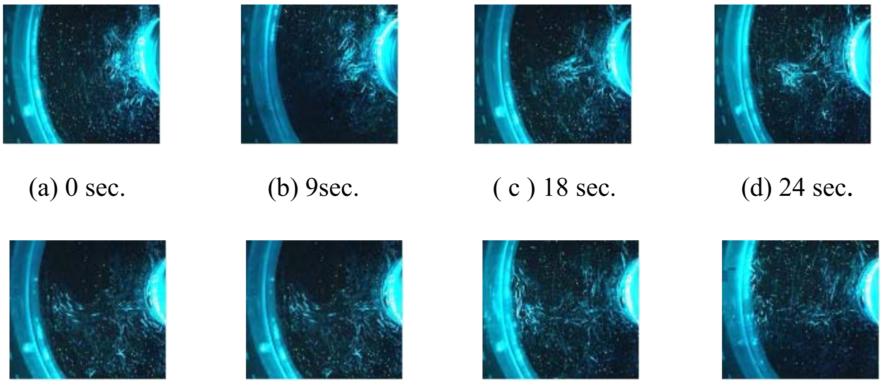
Fig. 2: Timewise variation of Fiber motion in the rotating drum at 400 rpm.



(a) 0 sec. (b) 3 sec. (c) 6 sec.

Fig. 3: Timewise variation of Fiber motion in the rotating drum at 640 rpm.

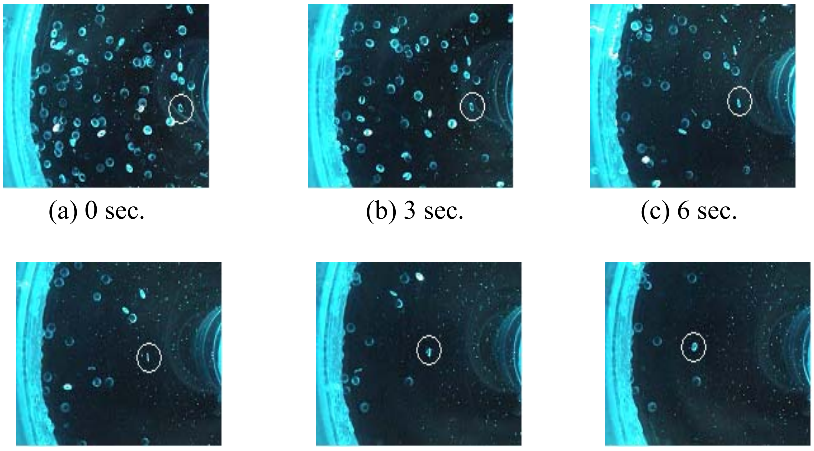
Figure 4, for 320rpm, depicts the timewise variation of the fiber motions in a time interval of 9 sec. One observes that each fiber cannot move independently and interact in the drum. It is observed that a lump of fiber appears in the inner region of the drum and moves toward the wall by the centrifugal force, and the movement of the lump causes the fluid flow, resulting in the dispersion of the fibers. This dispersion is ascribed to the added mass of the fluid surrounding a lump of fiber that moves in the fluid.



(a) 0 sec. (b) 9sec. (c) 18 sec. (d) 24 sec.

(e) 36 sec. (f) 45 sec. (g) 54 sec. (h) 63 sec.

Fig. 4: Timewise variation of fiber motion in the rotating drum at 320 rpm.



(a) 0 sec. (b) 3 sec. (c) 6 sec.

(d) 9 sec. (e) 12 sec. (f) 15 sec.

Fig. 5: Timewise variation of circular disk motion in the rotating drum at 950 rpm.

3.2 Disk motion in the rotating durum

Figure 5 illustrates the time history of the circular disk in the drum rotating at rotational speed of 950rpm. Circular disks are detected as white color in the images. Consecutive images are obtained at a time interval of 3sec. Note that as the motor torque accelerates the drum rotation, i.e., at the spin-up process, the shear stress yields on the inner surface of the rotating drum because of an inertial force (Fig. 5(a)). As time progresses, this shear stress attenuates, because the drum rotating speed becomes steady state, as seen in the process of Fig. 5(a) to Fig. 5(b). One observes that circular disk, at t=0 s., are oriented in the several directions, as seen in Fig. 5(a). As these particles move toward the drum wall, circular disk edge is oriented in the centrifugal direction. Finally, these particles attach the drum and the particles on the drum wall array parallel to it. Such particle morphology in material structure, for example, can be detected in Al/Al_3Ti FGMs. In other words, Al_3Ti in Al/Al_3Ti FGM particles in the vicinity of the drum wall are arrayed parallel to its wall, while the disk particles in the inner region are oriented along the centrifugal direction. Using a series of images in Fig. 5, the velocity profile of circular-disk particles in the rotating drum is illustrated in Fig. 6. One observes that the particles in the vicinity of the drum wall move perpendicular to its wall and these velocities are gradually increased along the radial direction. On the contrary, the velocity vectors in the inner region of the drum are oriented in the several directions, because the bubble motion is taken as disk particle motion. Therefore, only the particles selected in the vicinity of the drum wall are employed in the present analysis.

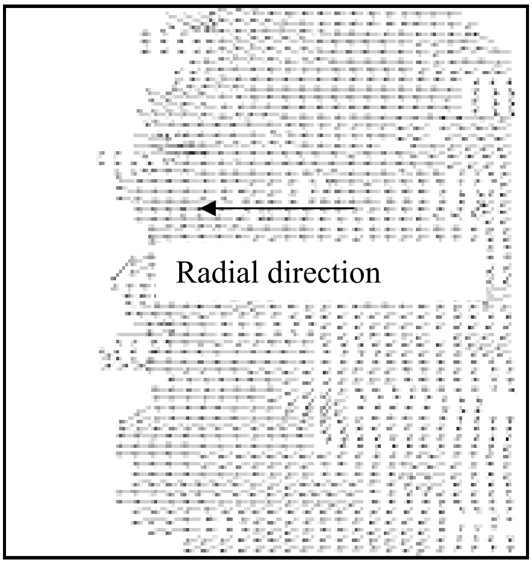


Fig. 6: Velocity distribution of disks in the rotating drum.

The timewise variation of rotation and orientation motions of the circular disk in the rotating drum is shown in Fig. 7 as composite image. Note that the upper region of the figure corresponds to the center of the drum and the lower one is the drum wall. One observes that the circular disk is oriented in the several directions in the region far from the drum wall and as time progresses the disk is oriented toward the wall by the centrifugal force. At this time, the moment acted at the disk edge is different because the centrifugal force in the rotating drum increases along the radial direction, as mentioned in the following section. Thus one side of the disk accelerates in the radial direction of the rotating drum and finally attaches normal to it, as shown in the lower part of Fig. 7. After that, the disk edge lies gradually on the wall by the moment acted at the other side of the edge, because the standing position of the circular disk is unstable.

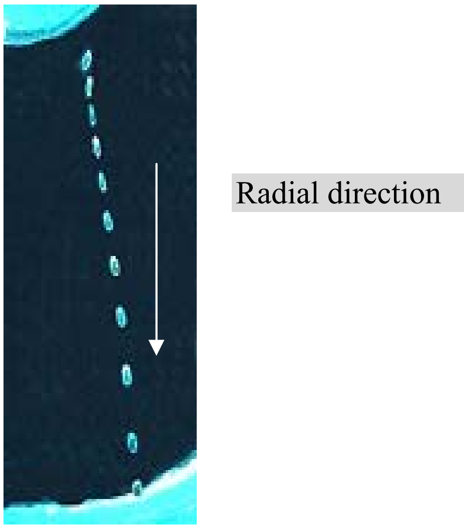


Fig. 7: Motion of circular disk in the rotating drum.

3.3 Analysis of disk-particle and fiber behaviors

In order to predict a particle motion, BBO (Basset-Boussinesq-Ossen) equation is employed as:

$$m_p \frac{d u_p}{dt} = 3\pi\mu_f d_p (u_f - u_p) + \frac{\rho_f}{\rho_p} m_p \frac{D u_f}{Dt} + \frac{1}{2}\frac{\rho_f}{\rho_p} m_p \left(\frac{d u_f}{dt} - \frac{d u_p}{dt}\right)$$
$$+ \frac{3}{2} d_p^3 \sqrt{\pi\mu_f \rho_p} \int_0^t \left(\frac{d u_f}{d\tau} - \frac{d u_p}{d\tau}\right) \frac{d\tau}{\sqrt{t-\tau}} + G(m_m - m_f) g \tag{1}$$

Here, the first term in the right hand side of Eq. (1) represents the force acting on the particle due to a stationary viscous flow and implies the viscous force acting on a sphere particle if its drag coefficient CD is expressed as CD=24/Re. The second term is the pressure gradient in the surrounding fluid. The third term is the added mass of the fluid surrounding the particle that moves in the fluid. The fourth term is the Basset force that constitutes an instantaneous flow resistance. The fifth term is an external force. If the single disk particle moving in the fluid is considered, the second, third and forth terms of the right hand side of Eq. (1) are neglected. This is because the following assumptions are imposed in the formulation of the problem: (i) fluid properties are constant, (ii) the force of gravity is much smaller than the centrifugal force, (iii) the density of the fluid is less than that of the solid particle, (iv) the rotational motion of the disk is sufficiently slow, and (v) the volume fraction of the particles in the drum is negligible. Here, the last term in the right side of Eq. (1) implies an external force, which is gravity and centrifugal forces in this experiment. Since the gravity is much smaller than the cetrifugal force, its effect is neglected. G in this term, which is called G number, is the ratio of the centrifugal force to the gravity.

$$G(t)=\frac{4\pi^2}{g}r_p(t)n^2 \tag{2}$$

where r(t) is the radial distance from the center of the drum. Note that G number of the disk particle varies along the radial direction. In the present analysis, a circular disk is regarded as an oblate ellipsoid. Under these assumptions, Eq. (1) is reduced as

$$\left(0.0863m_f+m_p\right)\frac{d^2r_p}{dt^2}+11.71a\mu_f\frac{dr_p}{dt}-4\pi^2n^2\left(m_p-m_f\right)r_p=0 \tag{3}$$

Equation (3) is solved under initial conditions as

$$r_p(0)=r_0\ ,\quad \frac{dr_p(0)}{dt}=v_0\ ,\quad t=0. \tag{4}$$

Here, r_0, which is the radial distance from the center of the drum and initial particle velocity v_0 are constant.

Submitting properties of disk particle and glycerin and n=950rpm into Eq. (4), Eq. (5) is obtained.

$$r_p(t)=r_0e^{0.1183t} \tag{5}$$

Equation (5) is differentiated with respect to time, t, resulting in the particle velocity as

$$\frac{dr_p(t)}{dt}=0.1183r_0e^{0.1183t} \tag{6}$$

Equations (5) and (6) are combined.

$$\frac{dr_p(t)}{dt}=0.1183r_p(t) \tag{7}$$

Note that Eq. (7) is independent of the initial condition and implies that the disk particle velocity in the axially rotating drum is given as a function of the radial distance from the center of the drum. The similar equation is obtained using the other thermal properties and rotation speed. The measured velocities of circular disk are illustrated in Fig. 8 in the form of velocity versus radial distance from the center of the drum. Theoretical value which corresponds to Eq. (7), is superimposed with a solid straight line in Fig. 8 for comparison. The experimental results are predicted in some degree by Eq. (7). In other words, the particle velocity increases lineally along the radial direction.

An attempt is made to analytical approach of fiber movement. As mentioned previously, In general, the Basset-Boussinesq-Oseen (BBO) equation, i.e., Eq. (1) is used to predict the particle motion. The third term is the added mass of the fluid surrounding the particle that moves in the fluid, as mentioned previously. However, when a lump of fiber yields in the drum as seen in Fig. 4, the third term is not omitted in the governing equation to be solved. It is postulated therefore that the added mass of the fluid surrounding a lump of fiber causes the fluid flow due to the fiber movement, resulting in the dispersion of the fibers.

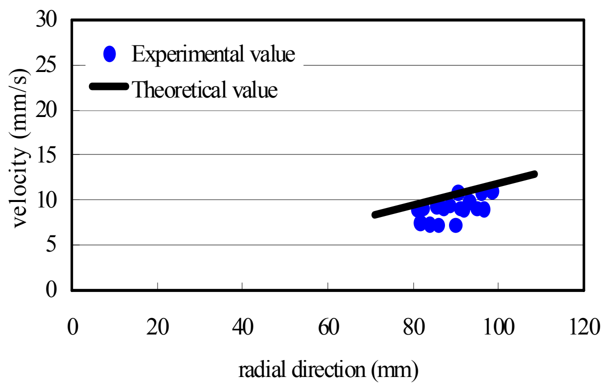


Fig. 8: Comparison of the measured particle velocity with the theoretical value.

4. Summary

Experimental study has been conducted to investigate the fiber and disk transport phenomena in a rotating drum using the cold model centrifugal casting. In particular, the disk velocity in the rotating drum has been theoretically studied using the BBO equation. The results obtained are summarized as follows:

(1) The visualization method employed is effective to observe the transport phenomenon of fibers in the cylindrical drum and to capture the fiber motions.
(2) When a volume fraction of fibers in the rotating mold, i.e., drum is substantially larger, each fiber cannot move independently and interact in the drum. Thus, the added mass of the fluid surrounding the fiber that moves in the fluid plays an important role in the fiber motion.
(3) The velocity profile of the disk in the rotating drum is obtained by PTV (Particle Tracking Velcimetry) method.

(4) The particle velocity increases lineally along the radial direction whose characteristics are dependent on particle geometry, rotating speed, and physical property. The velocity of the disk is predicted by the BBO equation.

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