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Relationship between the Structure and the Fluidity of Powder in Vibrating State

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The relation between structure and fluidity of powder bed was examined in a vibrating state. Various graphite with several different particle size and sphere carbon were used as samples. The structure of powder in a vibrating state was studied by measuring electric resistivity. The fluidity was measured by means of a rotation viscometer.

With an increase in amplitude, electric resistance of a powder bed increases in a specific form. In a vibrating state, fluidity also changes similar to electric resistance in relation to the amplitude. The process of these changes resembles such changes as can be seen in the relation between the temperature and the specific volume in the glass transition phenomena of various substances.

In a region where acceleration due to vibration exceeds gravity, the relation between change in electric resistance R_x and fluidity ϕ of a powder bed can be expressed in the following equation:

$$\phi = a \exp\left(-b\frac{R_0}{R_x}\right)$$

where R_0 is electric resistance in fixed bed, and a and b are constants.

In the region where amplitude is reduced and acceleration falls below $1\,g$, all the particles constitute some packing structure which changes to a more stable structure with decrease in the amplitude.

I. INTRODUCTION

Fluidity of powder is affected by the mode of packing, namely, the structure in which the particles are arranged in space. However, it is difficult to know the mode of packing of powder, then it is in many cases expressed indirectly by the apparent volume or the porosity of a powder bed. In particular, it is more difficult to know the structure of powder in a moving state. On the other hand, various conduction phenomena in powder bed are directly affected by the inter-particle contact condition. Especially, as electric resistivity is easy to measure, it is utilized for the study of powder packing process.[1,2] As, however, contact resistance is considerably high in the case of general metal powder due to the existence of oxide film on the particle surface, measuring electric resistance is not easy in a state in which particles are lightly in touch with each other, yet being partly sticking to and partly separating from each other, as in the case of fluidized powder. In order to know the relationship between structure and fluidity of the powder bed in a vibrating state, the effect of the amplitude on the electric resistivity and fluidity have been experimentally studied with graphite

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and sphere carbon whose electric resistivity are small. These samples are more suitable for the above purpose than metal powder. Though there are available some reports[3,4] describing the characteristics of a fluidized bed of powder with change in its porosity as a parameter, the electric resistance is more suitable, because it is directly related to the contact condition of particles.

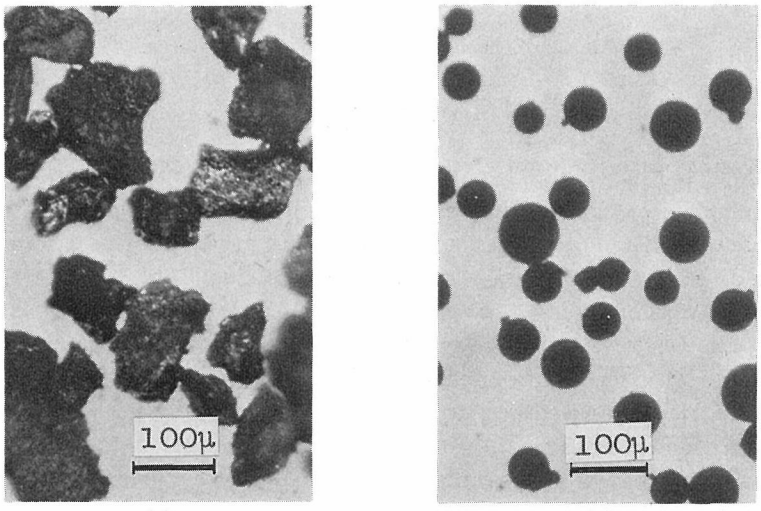
II. EXPERIMENTAL

II. 1. Sample

Graphitized coke and synthesis sphere carbon powder have been used as sample powder. Graphitized coke (GL) was pulveriged and classified through sieves, and sphere carbon powder was obtained by polymerization of divinyl benzen. Their characteristics are shown in Table 1. The bulk density shown in the table represents the value obtained when powder was packed as close as possible by vibration. The particle shape of samples is shown in Fig. 1. a, b.

Table 1. Characteristics of Sample Powder.

Sample	Particle Size, μ		Density	Bulk Density
	Range	Mean	g/cm^3	g/cm^3
II	74—105	90	2.23	0.89
III	105—149	130	2.22	1.05
IV	149—210	180	2.04	1.03
V	210—250	230	2.06	1.03
VI	250—297	280	2.07	1.02
VII	381—500	450	2.12	0.88
S	20— 90	49	1.42	0.86



(a) (b)

Fig. 1. Particle shape of samples.
(a) Graphite (b) Sphere carbon

II. 2. Apparatus

The schematic diagram of the experimental apparatus is shown in Fig. 2. The vessel fitted to the vibrator is a cylinder made of acrylic resin, 6 cm in inside diameter and 260 ml in volume, with the 2 cm^2 copper electrodes. The frequency of the applied vibration was 60 Hz and the amplitude was varied by changing input voltage at a constant rate. The amplitude was also measured with a detector provided at the bottom of the vessel and recorded together with a continuous recording of the electric resistance change of the bed which included 120 g of the sample powder. The rotation viscometer was used for the measurement of the fluidity of powder at the rate of revolutions of 0.2 R/min.

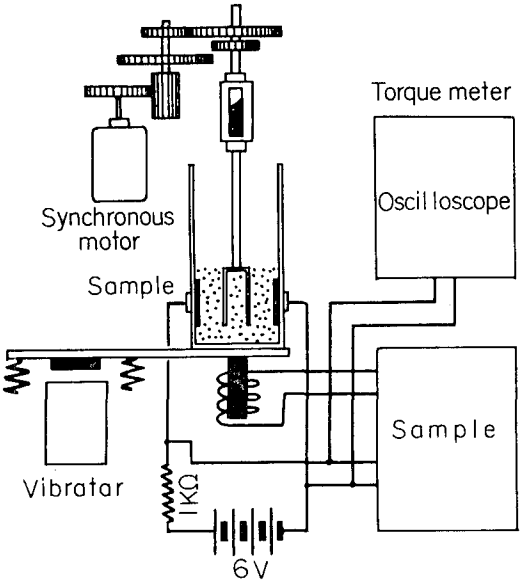


Fig. 2. Schematic diagram of the apparatus.

III. RESULTS

III. 1. Effect of amplitude on electric resistivity of powder bed

Typical plots of changes in electric resistance of the powder bed with amplitude are shown in Fig. 3. The experiments in both cases of increase and decrease of amplitude have shown always remarkable reproducibility in resistivity change, so far as the rate of change in potential applied to the vibrator is constant. However, the resistivity change was affected by the rate of change in potential in the process of decreasing amplitude. Namely, the slope BC becomes more slow and the electric resistance at the point A becomes larger with the decreasing rate as shown in Fig. 4. As such an effect can not be observed when the rate of potential change is less than 10 V/min., the experiments were usually conducted at this condition. The pattern of chane in the electric resistance with respect to the amplitude is quite similar to the relationship between temperature and specific volume as can be seen in the glass transition process of various

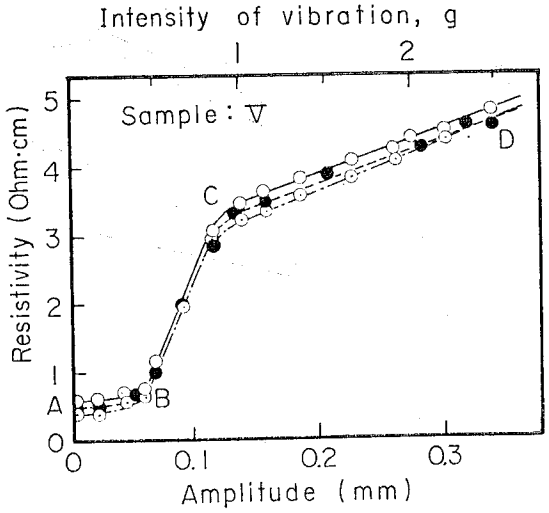


Fig. 3. Change of electric resistance with amplitude of vibration.
○, ⊙: Amplitude increase ●: Amplitude decrease.

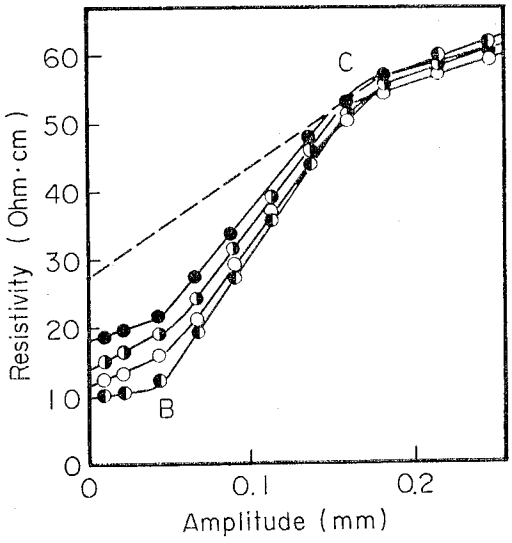


Fig. 4. Influence of decrease rate of amplitude for amplitude-resistance curve.
●: 0.13 (mm/sec), ◑: 0.03 (mm/sec), ○: 0.006 (mm/sec),
◐: 0.001 (mm/sec)

materials.

Figure 5 represents the set of the relations between amplitude and electric resistance of each sample. As shown in Fig. 6 the relationship between the mean particle weight and the slope in BC region of the suitable amplitude is linear except sphere carbon.

III. 2. Change in fluidity due to vibration

On defining the reciprocal of torque $(g\cdot cm)^{-1}$ as fluidity ϕ, changes in ϕ with amplitude were measured. Figure 7 shows the set of fluidity curves for the

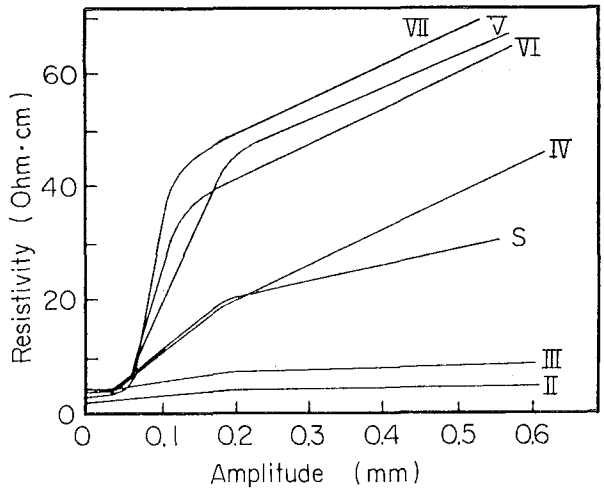


Fig. 5. Relation between the amplitude and the electric resistance of powder beds.

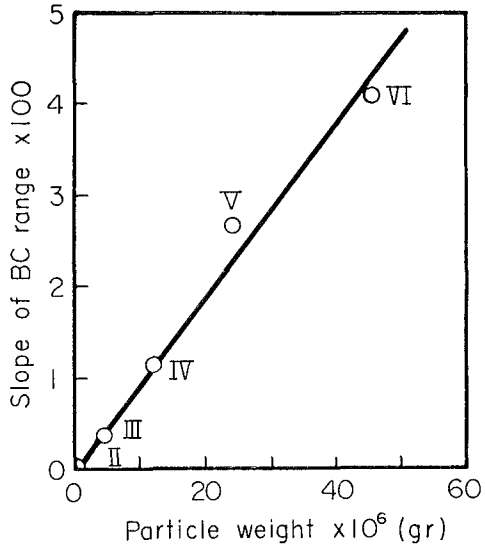


Fig. 6. Particle weight dependence of curve slope of BC range of Fig. 5.

individual samples. The fluidity curves have apparently the same general behavior with amplitude as the resistivity, except in the case of sphere carbon whose fluidity increases rapidly at low amplitude region.

IV. DISCUSSION

As both electric resistance and fluidity of a powder bed are related to the particle contact condition, their changes in regard to amplitude will be discussed assuming them to be caused both by the common behavior of particles. In order to consider the relation between electric resistance R_x and fluidity in the region CD, $\log \phi$ was plotted against R_0/R_x, where R_0 was electric resistance at the point A, namely, where the sample powder assume the most closed packing state

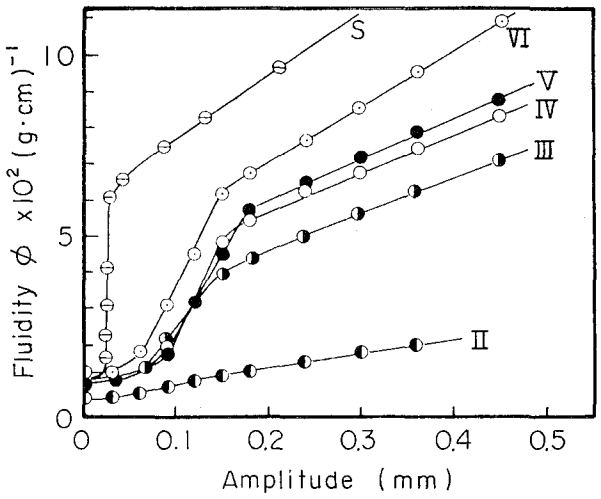


Fig. 7. Relation between the amplitude and the fluidity of powder beds.

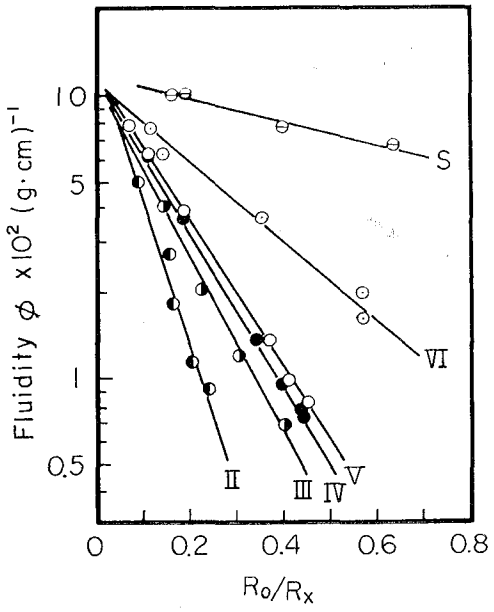


Fig. 8. Relation between R_0/R_x and fluidity ϕ.

Table 2. Values of Constant a, b.

Sample	a	b
II	13.5	5.13
III	10.0	3.03
IV	12.0	2.63
V	12.0	2.78
VI	11.0	1.45
S	12.0	0.43

$$\phi = a \exp\left(-b\frac{R_0}{R_x}\right), \tag{1}$$

where a and b are constants, whose values obtained from Fig. 8 are shown in Table 2. As the result, straight lines were obtained as shown in Fig. 8 which are well expressed in the form of equation (1). For the purpose of simplification it was assumed that electric resistance of powder bed was only related to the degree of particle interaction, namely, the number of contact points and the degree of interparticle contact. Then R_0/R_x represents the changes in particle interaction with the changes in amplitude, and will be 1 in the most closed

packing state of particles and 0 in the complete dispersion state. For graphite, the slope b of curves in Fig. 8 increases with the decrease in particle size, and is greatest for graphite VI. For sphere carbon, however, the slope b is smaller than that for graphite IV in spite of the smallest particle size. The values of a is approximately constant.

In several papers,[5,6] we have presented the analysis of particle movement in a vibrating state on the basis of dynamic behavior of particles. Such a behavior varies depending on whether the acceleration is more or less than $1\,g$. As it reaches $1\,g$ in the vicinity of the point C in this experiment, it is considered that in the region CD, particles repeat a periodic movement of free leap without rigid mutual contacts, causing the particle packing structure in a powder bed to be discontinuous everywhere. The fluidity of powder in such a condition is related to the distance that can be covered by particles until they collide each other and the distance increases with the increase in void volume. For the smaller samples in which the decrease in particle interaction due to the increase in void volume are more significant, the relatively larger values are obtained as b. The slope b is presumably influenced by interparticler attractive force. When this force becomes smaller, in sphere or coarse particles, the fluidity is little affected by the change of contact state of particles. In the case that particles are dispersed completely, they are not in touch with each other and electric resistance becomes infinite, resulting in $R_0/R_x=0$. The fluidity ϕ at that time is the constant a which is determined by the characteristics of the apparatus only, irrespective of the type of sample.

In the region BC in which amplitude is reduced and acceleration falls below $1\,g$, the individual particles move in the condition of mutual contact. In this region, corresponding the vibrating condition, all the particles constitute some packing structure which changes to a more stable structure with decrease in amplitude. In this process, the formation of a more closed packing structure accompanied by an increase in the number of contact points and in the contact force causes a decrease in the electric resistance. At the same time, it means a decrease in the fluidity ϕ. The particle packing process is affected by the particle weight and the particle interaction force.[7] Each particle takes up the minimum potential energy related to the packing structure formed at that stage and also to the behavior of other particles. Since the larger particles are little affected by interparticler cohesion force, they are ready to forming a stable structure. Consequently, the slope BC is proportional to particle weight as shown in Fig. 6. For sphere carbon, each particle is ready to roll down and form a more closed packing structure because of its spheric sphape. For this reason, it is considered that the fluidity suddenly increases at a definite value of lower amplitude as shown in Fig. 7. Further, as this process is a relaxation phenomenon in which particles form a stable structure, a sudden decrease in amplitude and a rapid progress of packing cause particles to interfere with each other, which therefore can not take stable positions and form a metastable structure leaving a large void volume. This is the phenomenon shown in Fig. 4. Accordingly, a stable packing structure has been formed at point B and the electric resistance

changes little in the region BA below that point. In the cases where the amplitude goes on increasing, the point B represents a yield value at which a stable packing structure is broken. On the other hand, in the cases where amplitude is reduced rapidly, a metastable structure is destructed even by a slight vibration and shifts to a more stable structure resulting in the resistance decreases in the region BA.

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