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論　文

Formation of Pearl-chain Adhesion of Dielectric Particles in Electrostatic Field

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In this paper, the adhesion of polarized dielectric particles in the form of pearl-chains onto material surfaces was investigated experimentally. Al_2O_3 powder, having an average particle size 0.5μm, was used as the coating material and dispersed sufficiently before sprayed into the space between electrodes. In a non-uniform field without corona discharge, the pearl-chain adhesion was realized on a stainless steel mesh surface and a porous alumina substrate. It was observed that pearl-chains grew from the protrusions in the surfaces. Because the protrusions subjected to external electric field created regions of high field intensity, it became the seeds for forming pearl-chains. In a corona discharge field, the adhesion result on the mesh showed that the particle charging process blocks the formation of pearl-chains because the particles repulsed each other due to the excess charges on particle surfaces. It was found that after sintered at 1300℃ for two hours, the pearl-chains formed on the alumina substrate remained, and were stable against ultrasonication in water. Consequently, sintering can be used as a method for increasing the mechanical strength of the formed pearl-chains and fixing them onto material surfaces. The results obtained in this paper are expected for practical applications, for example, fabricating membranes with catalytically active components.

1. Introduction

The pearl-chain agglomeration, or called particle chain agglomeration, is a phenomenon that closely spaced particles subjected to an electric or magnetic field attract each other and align parallel to the imposed electric field. The basic interpretation of the phenomenon is attributed to G. Zebel, who treated the formation of pearl-chain with a fine-particle aerosol of spherical magnetic and electrical dipoles theoretically, and assumed an external force field imparts to the dipoles a parallel orientation.[1)] R. Flossmann and A. Schütz reported a method depending on coagulation and precipitation of the chain-like iron oxide particles in an electrostatic field as a result of induced dipole forces.[2)] The strong attractive particle interactions responsible for chaining exist in almost any physical situation where polarizable or magnetizable particles are subjected to electric or magnetic fields. Many researchers have been exploiting this phenomenon in many areas, such as electrofusion of biological cells, chaining in electrorheological fluids, Electrofluidized and electropacked beds, etc.[3-5)]

In some cases, it is desirable to obtain a layer composed of particle chains on material surface, for example, fabricating porous membrane. H. Yamamoto and S. Masuda reported a new method for forming a ceramic membrane.[6,7)] Ultrafine particles synthesized by thermally activated chemical vapor deposition (CVD) were deposited on a porous ceramic tube by electrostatic force, and very peculiar ceramic membranes with a three-dimensional network were obtained. In this paper, we intended to coat material surfaces by fine dielectric particles in the form of pearl-chain. The fine particles come from powder dispersion instead of CVD. The purpose is to find a simple way to control particle chains perpendicular to material surface by electrostatic force, and confirm if sintering can be used as a method for fixing the pearl-chains formed from particles suspended in gas phase on dielectric substrate.

Key words: pearl-chain, adhesion, dielectric particle, sintering

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2. Experimental setup and procedures

The experiment mainly consists two steps: realizing the pearl-chain adhesion on material surfaces and sintering the formed pearl-chains. The adhesion process was controlled by electrostatic force, and fine dielectric particles were from dispersed Al_2O_3 powder.

The experimental setup of the coating system is depicted in Fig.1. The electrode structure for creating non-uniform field was pin to plate, while DC high voltage was applied on the pin, and the plate was earthed. The opening angle of the pin, 15 degree, was used to calculate the electric field intensity between the electrodes. Al_2O_3 powder was sprayed into the space between the electrodes by nitrogen gas. For comparison, Al_2O_3 powder was coated respectively onto a copper (Cu) substrate, a piece of stainless steel mesh (400 mesh in aperture size), and a porous alumina substrate (10×10×5 mm in size), which were located on the plate electrode. Fig. 2 shows the SEM (Scanning Electron Microscope) photograph of the alumina substrate on which irregularities exist. During the experiment, the material surfaces were set in parallel with the gas stream and the electric field direction was perpendicular to the stream.

In this experiment, Scanning Electron Microscope (SEM) was used to observe the adhesion state of Al_2O_3 particles. The pearl-chains formed on the Al_2O_3 substrate were sintered in an electric furnace.

Dispersion of the Al_2O_3 powder into ambient gas is an important operation in this experiment. The fine Al_2O_3

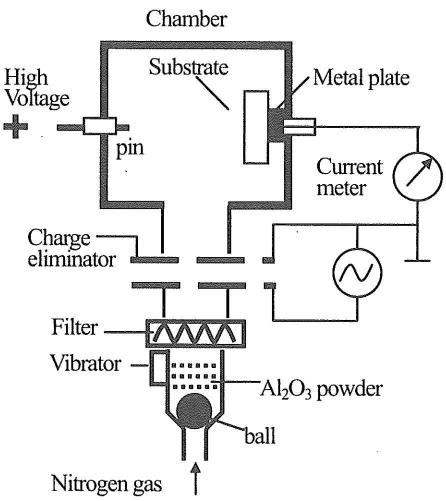
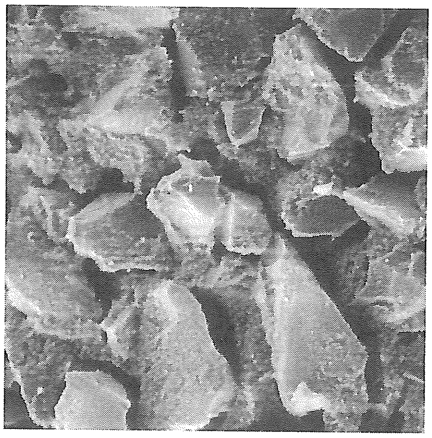


Fig. 1 Experimental setup.



45 μm

Fig. 2 SEM photograph of Al_2O_3 substrate.

particles are often in the state of particle aggregates due to the adhesive forces interacting between particles. We expect to obtain homogeneously dispersed particles, not aggregates, suspended in the gas. In order to disperse the powder completely, the following methods were employed: (1) The Al_2O_3 powder was sufficiently dried by an electric oven to decrease the liquid bridge force interacting between Al_2O_3 particles; (2) one piece of stainless steel mesh (2300 mesh in aperture size, The NILACO Co.) acting as a filter was located in front of the tube as shown in Fig. 1, and the particles were blown into the space between electrodes through the filter by nitrogen gas; (3) To decrease the electrostatic force interacting between the particles, a charge eliminator that generates positive and negative charges by high frequency corona discharge was set in the path of the particles, and the natural charges on the particles was eliminated. One problem of this dispersion system was that the filter was blocked by Al_2O_3 particle aggregates immediately. To solve this problem, a vibrator was used, as shown in Fig. 1. The dispersion result, which was obtained by collecting the dispersed powders onto a copper substrate perpendicular to the gas stream, is shown in Fig. 3. The nitrogen gas flow rate was 5 L/min. The Al_2O_3 powder was dispersed to the value as claimed , 0.5 μm in average particle size.

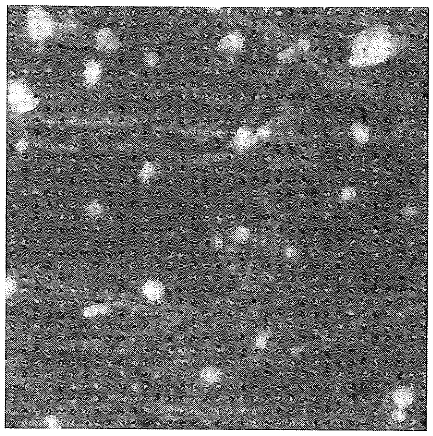
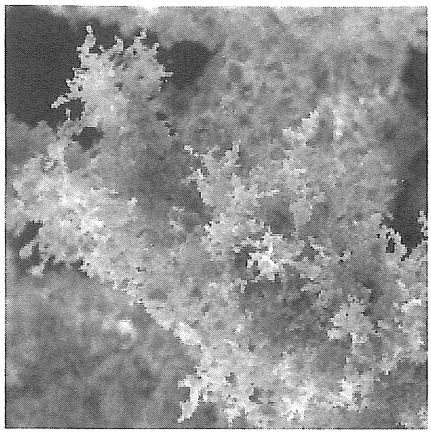


Fig. 3 The Al_2O_3 particles after dispersed.

3. Results and discussion

3.1 Comparison between the adhesion on metal mesh and metal plate

The adhesion state of Al_2O_3 particles on the stainless steel mesh is shown in Fig. 4, which was obtained under the following conditions: DC high voltage 7 kV, 2 cm of the gap between the pin and the mesh surface, the nitrogen gas flow rate 5 L/min, particle concentration 200 mg/ m^3, and the adhesion time 10 minutes. Two points should be explained here. One is that 7 kV DC high voltage imposed on the pin electrode is lower than the corona onset voltage, about 8 kV calculated, so without corona discharge took place between the electrodes. The other is that after the external electric field was removed, the shape of the formed pearl-chains remained long time and had the strength that allow us to move the substrate and observe the adhesion state by SEM. We observed that Pearl-chains grew from the protrusions in the mesh surface into space along the electric force lines. This process is schematically depicted in Fig. 5.



45 μm

Fig. 4 SEM photograph of pearl-chain adhesion on metal mesh.

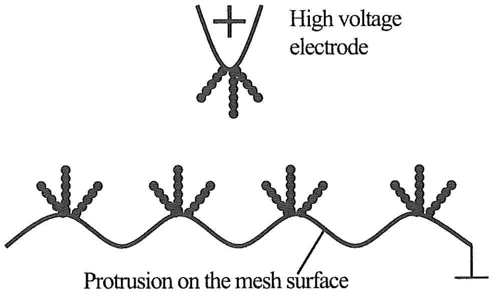


Fig. 5 Schematic of the process for forming pearl-chain adhesion on metal mesh surface.

Analytical and numerical treatments of chain forming have been published for many important cases.[8-12] According to these works, particles experience a dielectrophoresis force only when the electric field is non-uniform; a dielectric particle in an electric field becomes polarized and causes the distortion of the applied field in the vicinity of each particle; Chain formation is due to the strong attractive particle interactions, in other word, due to the dipole-dipole interactions. In this experiment, particle chains were formed from the surface protrusions where higher electric fields exist. This is because the protrusions subjected in an electric field cause the distortion of the applied field in their vicinity. So, the protrusions could be considered as the seeds for chain forming. In contrast, the adhesion state on the copper substrate, which was obtained in the same experimental conditions as that of metal mesh, is shown in Fig. 6. The substrate surface was coated uniformly, and particle aggregates could also be observed. This result suggested that roughness of material surface is important for forming chain-like adhesion.

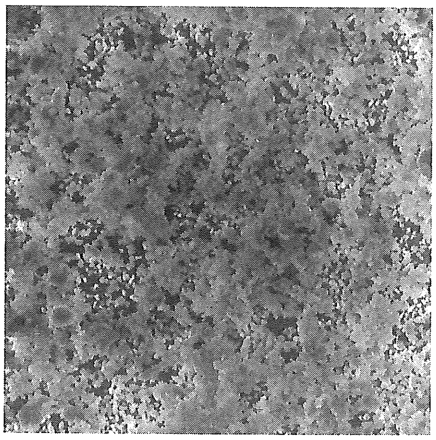


Fig. 6 The adhesion state on the copper substrate.

3.2 The adhesion on metal mesh in corona field

The situation for forming pearl-chain adhesion is different with a common powder coating process, which needs corona discharge for charging particles. In a powder coating process, it is difficult to coat protrusions on material surface because field intensification directs higher currents to these regions. In the forming process of pearl-chain adhesion, the particle charging process blocks the formation of pearl-chain adhesion, because the particles repulse each other due to the excess charges on particle surfaces. Fig. 7 shows the adhesion result on the metal mesh under corona discharge, created by applying 12 kV high voltage on the pin electrode. The other experimental conditions were same with that of Fig. 4. Fig. 8 shows the current change between the electrodes.

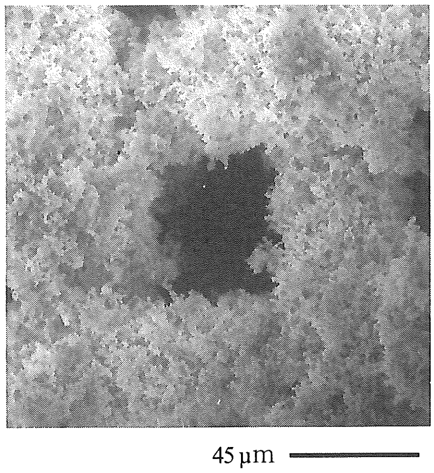


Fig. 7 The adhesion state on the mesh surface under corona discharge field.

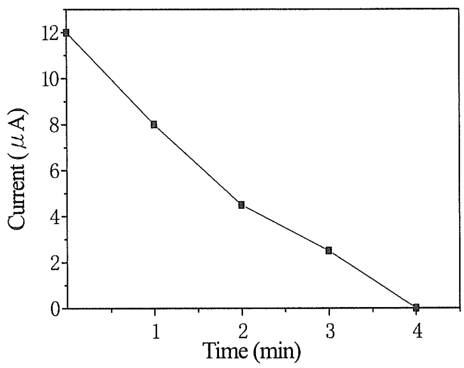


Fig. 8 Current change between the electrodes.

The adhesion like that shown in Fig. 4 was not observed, but there were still some short pearl-chains formed. In the corona field, particle charging is mainly owing to corona discharge. As shown in Fig. 8, corona discharge would disappear with the coating process. So, two processes account for the result shown in Fig. 7. One is that charged particles were attracted to the mesh surface. The other is that after the time when corona discharge disappeared, the polarized particles were attracted to the protrusions or particle aggregates on the surface where high field intensity existed. By comparing Fig. 4 with Fig. 7, to form chain-like adhesion, a non-uniform electric field without corona discharge is also necessary.

3.3 The adhesion on Al_2O_3 substrate

Dielectric particle chain formation on dielectric material surfaces is probably of greater technological significance than on metallic material surfaces, because it can be processed and applied in high temperature environment. Fig. 9 shows the micrograph of the adhesion of Al_2O_3 particles on the Al_2O_3 substrate (surface morphology shown in Fig. 2), which resembled pearl-chain. The experimental conditions were: DC high voltage 7 kV, 2 cm of the distance between the pin and the substrate surface, the nitrogen gas flow rate 5 L/min,

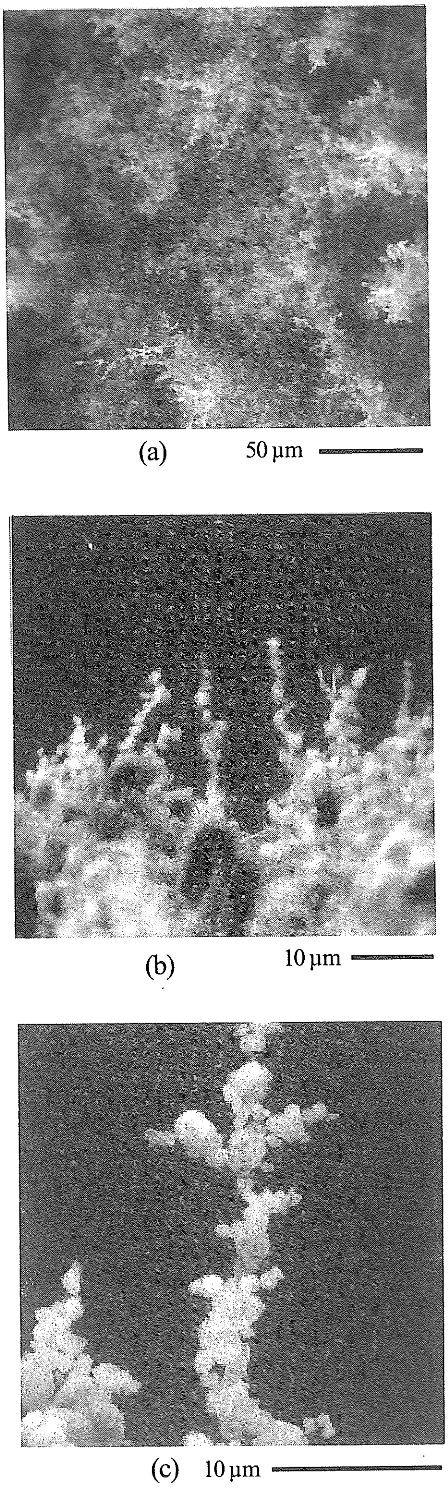


Fig. 9　SEM photograph of pearl-chains grown on Al_2O_3 substrate (a) surface morphology (b) section view (c) microstructure of pearl-chain.

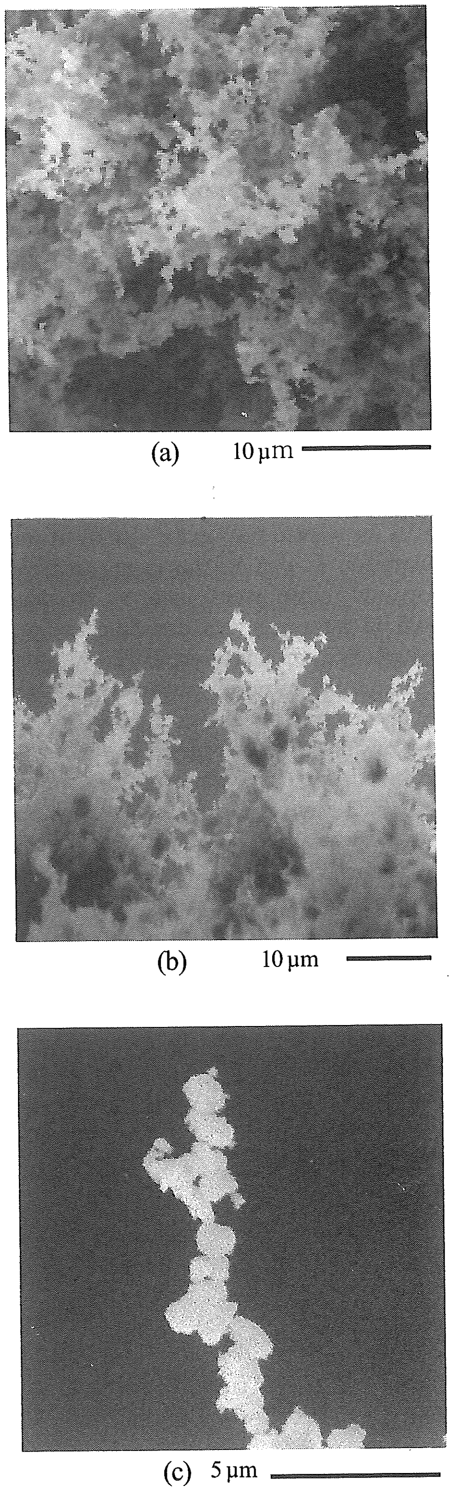


Fig. 10　SEM photograph of pearl-chain adhesion on the Al_2O_3 substrate after sintered at 1300℃ for 2 h (a) surface morphology (b) section view (b) microstructure of pearl-chain.

particle concentration 200 mg/m^3 and the adhesion time 10 minutes. As observed, a layer composed of pearl-chains was formed on the substrate, and the formed pearl-chains were longer than 10 μm as shown in Fig. 9(b). Like the adhesion on the metal mesh surface, pearl-chains grew from the protrusions in the Al_2O_3 substrate along the external electric field. This result shows that the pearl-chain adhesion could be realized on both metal and dielectric material surfaces where protrusions exist. During the process of pearl-chain forming, there was a possibility of inclination due to the disturbance of gas stream and the resulting induced moments of the particles. So a pearl-chain has many branches as shown in Fig. 9 (c).

3.4 Sintering of the formed pearl-chains

Fig. 10 shows the micrograph of pearl-chains on the Al_2O_3 substrate after sintered. During the sintering process, the temperature was kept constant at 1300℃ for 2 hours and the time of increasing temperature from room temperature to 1300℃ was 3 hours. After sintered, the structure of pearl-chain was roughly maintained as shown in Fig. 10(c), and pearl-chains became fiber-like. The layer that composed of pearl-chains was sintered tightly to the substrate. We had tested it by putting the substrate in an ultrasonic cleaner for 5 minutes. It was stable against ultrasonication in water. The above results show that sintering can be used as a method for fixing the formed pearl-chain onto material surface and raising the mechanical strength of it. It also suggests that there is possibility of applying pearl-chain in fabricating ceramic fibers.

4. Conclusions

In this paper, we have presented experimental results on coating material surfaces with pearl-chains of fine dielectric particles suspended in gas phase under the action of electrostatic field. The results indicate that roughness of material surfaces and non-uniform field without corona discharge are necessary for forming the pearl-chain adhesion. It was found that after sintered at proper temperature, the structure of the pearl-chains formed on the Al_2O_3 substrate remained, and was mechanically stable.

The coating process described in this paper may be of special interest for its use as a method for increasing contact surface area. We summarize the basic steps of the process as follows. First, disperse fine dielectric particles into ambient gas. Second, control the fine particles by electrostatic force to form pearl-chain adhesion on a rough material surface. Third, sinter the formed layer composed of pearl-chains onto the material surface. This process can become a simple way for fabricating membranes with catalytically active components.

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References

1) G. Zebel: Staub, **23** (1963) 263
2) R. Flossmann and A. Schütz: Staub. **23** (1963) 443
3) U. Zimmermann and J. Vienken: J. Membrane Biol., Vol. **67** (1982) 165
4) T. C. Halsey: Science, **258** (1992) 761
5) K. J. McLean: J. Air. Pollut. Contr. Assoc., **27** (1977) 1100
6) H. Yamamoto and S. Masuda: IEEE Trans. Ind. Appl., **27** (1991) 307
7) H. Yamamoto and S. Masuda: Ceram. Trans., **31** (1993) 305
8) M. H. Davis: Am. J. Phys., **37** (1969) 26
9) Yu. A.Godin and A. S. Zil'bergleit: Sov. Phys. Tech. Phys., **31** (1986) 632
10) Y. Chen, A. F. Sprecher and H. Gonrad: J. Appl. Phys., **70** (1991) 6796
11) T. B. Jones, R. D. Miller, K. S. Robinson and W. Y. Fowlkes: J. Electrostat., **22** (1989) 231
12) Y. Nakajima, and T. Matsuyama: J. Electrostat., **55**(2002) 203