Effect of process for producing Al₂O₃ particles on deposition efficiency in aerosol deposition method

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The aerosol deposition method (ADM) is a technique to form dense films by impacting solid particles on a substrate. Dense ceramic films with thicknesses of over several μm can be formed directly on substrates even at room temperature by the ADM. In this study, to improve the deposition efficiency of the ADM, the effect of the process for producing Al₂O₃ particles on the deposition efficiency was investigated. Two types of commercially available α-Al₂O₃ particles produced by sintering Al(OH)₃ (sintered particle) and chemical vapor deposition (CVD particle) were used. The average deposition efficiency of the sintered particles ranged from 0.067 to 0.088% and was much higher than that of the CVD particles, which ranged from 0.005 to 0.012%. When the sintered particles were used, the AD films grew about 30 μm. In contrast, when the CVD particles were used, the AD films didn’t grow over several μm. The morphologies of the AD films suggested that the deformed volume of the sintered particles was larger than that of the CVD particles. The specific fracture energy of each particle was estimated from a compression test. The average specific fracture energy of the sintered particles was 7.3 × 10⁴ J/m³, which was about 32% of that of the CVD particles (2.3 × 10² J/m³). Comparing this specific fracture energy with the specific kinetic energy, which was estimated to range from 4.4 × 10⁸ to 1.8 × 10³ J/m³, there is a possibility that the sintered particles showed higher deposition efficiency because they could deform by their kinetic energy and easily form activated surface promoting the bonding between the ceramic particles. We conclude that the specific fracture energy of the particle depends on the process for producing it and could be the crucial property to focus on to improve the deposition efficiency.

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1. Introduction

The aerosol deposition method (ADM) has recently been attracting attention as a new method for formation of ceramic films because it can form dense ceramic films (AD films) directly on a substrate even at room temperature. By impacting solid ceramic particles with a diameter of around 1 μm on a substrate, many kinds of ceramic films, such as Al₂O₃, PZT, AlN, and MgB₂, ceramic films, can be obtained. This novel phenomenon is referred to as room temperature impact consolidation (RTIC). One advantage of the ADM is the ability to directly form dense ceramic films with thicknesses typically of several μm on a substrate without heating. In the case of the thermal spray, which is the conventional industrial method for formation of ceramic films, the films are porous and oxidation or phase transformation of the films is caused by heating the ceramic particles over the melting point. On the other hand, one disadvantage is the low deposition rate. For example, the deposition rate of Al₂O₃ was reported to range from 1 to 3 μm/min for a deposition area of 10 mm × 10 mm. This deposition rate is inferior to the typical deposition rate of the thermal spray, which is over 10³ μm/min for the same deposition area.

To increase the deposition rate of the ADM, the deposition efficiency has to be improved. In the ADM, it is known that not all impacted particles can be deposited. We inferred that the deposition efficiency of the ADM is lower than that of the thermal spray. Regarding the deposition efficiency, the following fact could provide valuable information. In the case of forming dense ZrO₂ films by the ADM, it has been reported that dry-milled particles were superior to chemically prepared wet-type ones. When dry-milled ZrO₂ particles were used, the film was successfully formed with a wide range of particle sizes ranging from 0.73 to 10.2 μm. In contrast, when wet-type ZrO₂ particles were used, the film could be formed only with a narrow range of particle sizes ranging from 2.1 to 3.5 μm. This result regarding the difference in the starting particles suggests that the deposition efficiency depends on the properties of the particles that reflect the process for producing them. Then, we thought that developing ceramic particles suitable for the ADM might improve the deposition efficiency dramatically. However, general guidelines for developing ceramic particles for the ADM have not been discussed yet. To establish the guidelines, it is necessary to clarify the bonding mechanism between ceramic particles.

10 Previous reports revealed some important characteristics of the ADM regarding the bonding mechanism. The laminar structure of an AD film composed of a mixture of Al₂O₃ and PZT was observed along the substrate in the cross-sectional transmission electron microscopy (TEM) image. The structure indicated that RTIC was caused by the deformation of ceramic particles during the ADM process. It was also suggested that the deformation of ceramic particles resulted in the formation of new and activated surface which promoted the bonding between the ceramic particles. Although the bonding mechanism has not been completely understood yet, it seems to be related to the deformation behavior of ceramic particles. We presume that promoting the deformation of ceramic particles could favorably affect the deposition efficiency and parameters related to the deformation behavior of...
ceramic particles could be the crucial properties to focus on to improve the deposition efficiency.

In this study, we dealt with the deposition of $\text{Al}_2\text{O}_3$ particles, which was the typical material for the ADM,12,13 and the effect of the process for producing $\text{Al}_2\text{O}_3$ particles on the deposition efficiency was investigated. And the difference in the deposition efficiency was discussed in terms of the deformation behavior of the $\text{Al}_2\text{O}_3$ particle.

2. Experimental procedure

2.1 ADM apparatus

Figure 1 schematically illustrates an ADM apparatus. This apparatus consisted of two chambers: an aerosol chamber and a deposition chamber. The aerosol chamber generated aerosol by vibration that mixed ceramic particles with carrier gas. A substrate was attached to the X-Y stage in the deposition chamber, and the vacuum in the deposition chamber was created by a mechanical booster pump and an oil rotary vacuum pump. The aerosol was delivered to the deposition chamber as a result of the pressure difference between the deposition chamber and the aerosol chamber. The ceramic particles in the aerosol accelerated through a nozzle and impacted on the substrate. The nozzle had a rectangle exit with dimensions of $10 \text{ mm} \times 0.4 \text{ mm}$.

2.2 Materials used

In this study, two types of commercially available $\alpha$-$\text{Al}_2\text{O}_3$ powder were used, and the processes for producing the particles were different. One was composed of $\alpha$-$\text{Al}_2\text{O}_3$ particles produced by sintering $\text{Al(OH)}_3$ (sintered particles). The other type was composed of $\alpha$-$\text{Al}_2\text{O}_3$ particles produced by chemical vapor deposition (CVD) (CVD particles). Furthermore, to separate the deposition efficiency from that of the process for producing $\text{Al}_2\text{O}_3$ particles, 3 kinds of $\text{Al}_2\text{O}_3$ particles were used as substrates. The distance from the nozzle exit to the substrate was 8 mm.

In preparation of starting particles, we paid attention to pretreatment of particles. It has been reported that the agglomeration of particles interfered with the film formation because it could serve as a cushion for absorbing the kinetic energy.7,15) So, it was necessary to reduce the agglomeration of particles to investigate the effect of the process for producing $\text{Al}_2\text{O}_3$ particles. Therefore, in this study, the $\text{Al}_2\text{O}_3$ particles were heat-treated at 600°C for 1 h to eliminate moisture before deposition, because it has been indicated that eliminating moisture contents contained in particles by heat-treatment was effective to reducing agglomeration of particles.15) The condition of the heat-treatment in this study was determined by several preliminary experiments.

Other experimental parameters are as follows. Tough-pitch copper plates with dimensions of $50 \text{ mm} \times 40 \text{ mm} \times 3 \text{ mm}$ were used as substrates. The distance from the nozzle exit to the substrate was 8 mm. The carrier gas was $\text{N}_2$, and the gas consumption was 1.8 L/min. Neither the substrates nor the carrier gas were heated. The pressures in the aerosol chamber and the deposition chamber were 12.8 and 0.060 kPa, respectively. The traverse speed of the nozzle motion along the substrate was 1.0 mm/s, and the traverse was repeated 60 times with the traverse distance of 10 mm. The experimental parameters used in this study are summarized in Table 1.

Figure 5 shows the size distributions of the starting particles (S3) and the particles ejected from the nozzle, which were captured by plastic bags set at the X-Y stage. Although the
fraction of the particles with diameters of over 4 \( \mu m \) slightly decreased, it was found that the size distribution as a whole was retained after ejected from the nozzle under the experimental condition shown in Table 1. Therefore, we think that considering the size distribution of the starting particles is reasonable to discuss the deposition efficiency in the following sections.

### 2.3 Characterization of starting particles and AD films

The properties of the starting particles and the AD films were evaluated as follows. The microstructures of the starting particles and the AD films were observed with a scanning election microscopy (SEM) (S-4800, Hitachi High-Technologies Corporation). The thicknesses of the AD films were measured with a surface roughness measuring instrument (Surfcomder SE3300, Kosaka Laboratory Ltd.). The crystal structures of the AD films and the particles were measured with X-ray diffraction (XRD) (MXP18VAHF, Bruker AXS K.K.) using Cu K\( \alpha \) radiation at 40 kV and 100 mA with a scanning step of 0.0200 deg and scanning speed of 5.00 deg/min. And the crystallite size was calculated by Scherrer’s equation as described in Eq. (1) using the XRD pattern, where \( t \) is the crystallite size, \( B \) is the width of the Bragg peak, \( \lambda \) is the wavelength of the X-ray (0.154 nm), and \( \theta_B \) is the Bragg angle.

\[
t = \frac{\lambda}{B \cos \theta_B}
\]

To evaluate the deformation behavior of the starting particles, we focused on the fracture energy of the particles. The fracture energy of a particle was estimated using a force-displacement curve derived from a compression test of a particle (MCT-W500, Shimadzu Corporation).

### 2.4 Deposition efficiency

The deposition efficiency (DE) was measured as follows. Before deposition, the weight of \( \text{Al}_2\text{O}_3 \) particles in the aerosol chamber (\( W_{p0} \)) was measured. After deposition, the weight of \( \text{Al}_2\text{O}_3 \) particles in the aerosol chamber (\( W_{p1} \)) was measured. The weight of \( \text{Al}_2\text{O}_3 \) AD film (\( W_f \)) was calculated from the thickness, deposition area, and density. The density used in this calculation was 3.7 g/cm\(^3\), which was 95\% of the density of the bulk \( \text{Al}_2\text{O}_3 \). Then, the deposition efficiency was determined by Eq. (2).

**Table 1. Experimental parameters**

| Ceramic particle | \( \alpha-\text{Al}_2\text{O}_3 \) |
|------------------|-------------------------------|
| Substrate       | Cu                            |
| Substrate temp. (°C) | 22 (R.T.)                   |
| Carrier gas     | \( \text{N}_2 \)             |
| Gas consumption (L/min) | 1.8                        |
| Distance between substrate and nozzle (mm) | 8                          |
| Pressure in aerosol chamber (kPa) | 12.8                  |
| Pressure in deposition chamber (kPa) | 0.060               |
| Traverse speed (mm/s) | 1.0                        |
| Number of traverse (times) | 60                        |
| Traverse distance (mm) | 10                        |

**Fig. 4.** Morphologies of \( \alpha-\text{Al}_2\text{O}_3 \) particles with different production processes and size distributions. (a) S1 (AL-160SG-3). (b) C1 (AA-05). (c) S2 (AES-23). (d) C2 (AA-1.5). (e) S3 (AMS-5020F). (f) C3 (AA-3).

**Fig. 5.** Size distributions of starting particles and particles ejected from nozzle.

**Fig. 6.** Schematic illustration of compression test apparatus.
the deposition efficiency by only 0.5%
that the deposition efficiency determined by this measurement included error by only 0.5% at most.

3. Results and discussion

3.1 Deposition efficiency of sintered particles and CVD particles

Figure 7 shows the deposition efficiency of sintered particles (S1, S2, and S3) and CVD ones (C1, C2, and C3). The error bars show the maximum and minimum values obtained by 3 experiments conducted under the same experimental condition. The average deposition efficiency of the sintered particles ranged from 0.067 to 0.088% and was much higher than that of the CVD particles, which ranged from 0.005 to 0.012%. Since the size distributions of S1 and C1 were almost same as shown in Figs. 2 and 3, it is inferred that the difference in the deposition efficiency between S1 and C1 was mainly caused by the difference in particle properties, which can be ascribed to the process for producing particles. Furthermore, Fig. 7 shows that the deposition efficiency of the sintered particles was superior to that of the CVD particles even when the size distribution of the starting particles was changed. These results clearly suggest that the process for producing particles can affect the deposition efficiency more significantly than the size distribution of the starting particles and the difference in the deposition efficiency between the sintered particles and the CVD ones is mainly caused by the process for producing them.

Figure 8 shows the cross-sectional SEM image of the AD film using the sintered particles of S3. A dense and crack-free film with a thickness of about 30 μm was observed. The shape of the starting particle could not be seen in the microstructure. The deposition rate was 2.8 μm/min for a deposition area of 10 mm × 10 mm. This microstructure and deposition rate agreed well with those of Al2O3 AD films previously reported.51

Figure 9 shows a cross-sectional SEM image of the AD film using the CVD particles of C3. In contrast to when the sintered particles were used, the AD film did not grow over several μm, and the impacted particles seemed to be just implanted into the substrate.

The morphologies of the AD films were compared at higher magnification. Figure 10 shows the cross-sectional SEM image of the interface between the AD film and the substrate. The roughness of the interface, which was defined as the distance between the bottom line and the top line of the interface as shown in Fig. 10, was 0.7 μm when the sintered particles were used. And, when the CVD particles were used, the roughness of the interface was 1.5 μm. Because the particle sizes of both S3 and C3 were around 3.57 μm, the morphologies suggest that deformed volume of the sintered particles was larger than that of the CVD particles. It is inferred from the morphologies that the difference in the process for producing particles resulted in that in the deformation behavior of the particles.

To closely investigate the deformation of the particles, the crystallite sizes of starting particles, AD films, and scattered particles in the deposition chamber after the impact into a substrate were compared. The XRD patterns of them confirmed that the crystal structure of α-Al2O3 was retained in the AD films and the scattered particles. The crystallite sizes in the followings were the average of crystallite sizes calculated using (012), (104), and (116) peaks of α-Al2O3. In the case of the sintered particles of S3, the crystallite size of starting particles was 48 nm, and that of AD
film was 13 nm. The reduction of crystallite size was observed as previously reported. This result indicates that the deposited sintered particles did deform during the impact and the deformation corresponded to 73% reduction of the crystallite size. In contrast, the crystallite size of the scattered particles was 40 nm. The crystallite size was reduced about 17%, but much larger than that of the AD film. It suggests that the deformation of particles corresponding to 17% reduction of the crystallite size was insufficient to form dense AD films.

3.2 Fracture energy of sintered particles and CVD particles

We presumed that the difference in the deposition efficiency and the morphologies of AD films between sintered particles and CVD ones had something to do with the deformation behavior of the particles, so we conducted the compression test of the particle. Figures 11 and 12 show the typical force-displacement curves of a sintered particle of S3 and a CVD particle of C3, respectively. When the force was lower than the critical value ($F_c$), the displacement increased nearly linearly as the force increased, indicating that the deformation was elastic. When the force reached $F_c$, the displacement abruptly increased, indicating that the particle was destroyed. The fracture strength and the fracture energy of the particle were estimated using these force-displacement curves.

The fracture strength ($S_t$) of the particle was estimated by applying the Hiramatsu method as described in Eq. (3), where $F_c$ is the critical force mentioned above and $d$ is the particle diameter that was measured with an optical microscope before each compression test.

$$S_t = 2.8 \frac{F_c}{\pi d^2} \quad (3)$$

The specific fracture energy of the particle ($E_d$) was estimated using the accumulated elastic energy until the destruction of the particle as described in Eq. (4), where $F$ is the applied force, $x$ is the displacement, $x_c$ is the displacement when the critical force is applied, and $V$ is the particle volume. In this study, to take into account the effect of the particle size on the accumulated elastic energy, the elastic energy was normalized by the particle volume, which was approximated to that of a sphere as described in Eq. (5).

$$E_d = \int_0^{x_c} \frac{F dx}{V} \quad (4)$$

$$V = \frac{4}{3} \pi \left(\frac{d}{2}\right)^3 \quad (5)$$

This compression test was conducted to a static particle, so the fracture energy of the particle determined by this test is not exactly coincident with the fracture energy under the actual deposition condition, in which particles move toward a substrate at 150–300 m/s. However, the stress propagates in a particle at the sound velocity, which is over 9000 m/s in the case of Al$_2$O$_3$, and it is much higher than the particle velocity. Therefore, we think that considering the fracture energy of the particles determined by the compression test is reasonable to discuss the deposition mechanism to some extent.

Figure 13 shows the fracture strength of the sintered particles of S3 and CVD particles of C3. The error bars show the maximum and minimum values among the data of 7 particles. The average fracture strength of the sintered particles was 752 MPa, and that of the CVD particles was 1935 MPa. The fracture strength of the sintered particles was about 39% of that of the CVD particles. Figure 14 shows the specific fracture energy of the particles, which was derived from the same force-displace-
The error bars show the maximum and minimum values among the data of 7 particles. The average fracture energy of the sintered particles was $7.3 \times 10^7 \text{J/m}^3$, which was about 32% of that of the CVD particle ($2.3 \times 10^8 \text{J/m}^3$). These results show that both the fracture strength and the fracture energy of the particle depend on the process for producing the particle. When a particle impacts on a substrate in the ADM, the fracture energy of the particle can be supplied by the kinetic energy of the particle. Assuming that the size, density, and impact velocity of these particles were the same, the kinetic energy of the particle after being ejected from the nozzle was also the same. The typical particle velocity of the ADM was reported to be 150–300 m/s.\(^{31}\)

The specific kinetic energy of the particle was estimated by Eq. (6), where $E_k$ is the specific kinetic energy, $m$ is the mass, $v$ is the velocity, $V$ is the volume, and $\rho$ is the density.

$$E_k = \frac{m v^2}{2} = \frac{\rho V v^2}{2} \tag{6}$$

The estimated specific kinetic energy of the particle ranged from $4.4 \times 10^7$ to $1.8 \times 10^8 \text{J/m}^3$. Comparing the specific fracture energy with this kinetic energy, we inferred that the fracture energy of the sintered particles was low enough to be sufficiently supplied by the kinetic energy and the particles could deform during impact. In contrast, in the case of the CVD particles, the fracture energy was higher than the kinetic energy, so the particle could not deform during impact.

It is thought that the deformation of the particle results in the formation of clean and activated surface around it. Generally, clean and activated surface has higher energy than stable surface and easily forms bonding between the activated surfaces. For example, it is known that activating surface by removing contaminates on surface using a fast atom beam in vacuum condition can be applied to bonding of metals, and semiconductors at room temperature.\(^{15\text{16}}\) Also, in the case of the ultrasonic welding between ceramics and metals, it has been suggested that clean surface appears by deformation during the process and plays an important role to the bonding between ceramics and metals.\(^{20}\) In the case of the ADM, there is a possibility that the sintered particles showed higher deposition efficiency because they could deform by their kinetic energy and easily form activated surface around them promoting the bonding between the ceramic particles. In contrast, the CVD particles couldn’t deform by their kinetic energy and the activated surface hardly appeared. As a result, the particles were just implanted into the substrate, and the film growth did not occur. Figure 15 shows the difference in the deposition mechanism between sintered particles and CVD ones inferred form the results obtained in this study.

It is inferred that the fracture energy of the particle has something to do with the defects that could work as the starting points of a fracture, such as cracks.\(^{21}\) In the case of the sintered particles, it is assumed that these defects could be induced near the grain boundaries during the sintering process because of the anisotropy of the thermal expansion coefficient. It has been also reported that when alumina specimen showed elastic deformation during shock loading, the failure was along the grain boundaries.\(^{22}\) In contrast, the CVD particle was produced as a single crystal, so it is assumed that its microstructure was hardly affected by the anisotropy of the thermal expansion coefficient during the production process. As a result, the CVD process resulted in fewer defects inside the particle. However, further investigations are required to investigate the defects and methods for controlling them.

In this study, we found that the fracture energy of the particle could be the crucial property to improve the deposition efficiency and help us to establish the guidelines for designing ceramic particles for the ADM. However, the deposition efficiency using the sintered particles was about 0.10% at most. This fact suggests that we are missing other important factors regarding RTIC. In the compression test of this study, the force was loaded until the particle was completely destroyed. However, this ideal loading condition might hardly ever occur in the actual impact of the particle in the ADM because the gas flow or other surrounding particles interfere with the impact of the particle. There is a possibility that this interference limits the deposition efficiency to only 0.10%. To verify the possibility and dramatically improve the deposition efficiency of the ADM, more studies are needed.

4. Conclusion

To improve the deposition efficiency of the ADM, the effect of the process for producing Al$_2$O$_3$ particles on the deposition efficiency was investigated. The following main conclusions were drawn:

1. The average deposition efficiency of the sintered particles ranged from 0.067 to 0.088% and was much higher than that of the CVD particles, which ranged from 0.005 to 0.012%. The deposition efficiency of the sintered particles was superior to that of the CVD particles.

2. When the sintered particles were used, the AD films grew about 30 µm. In contrast, when the CVD particles were used, the AD films didn’t grow over several µm. The morphologies of the AD films suggested that the deformed volume of the sintered particles was larger than that of the CVD particles.

3. The average specific fracture energy of the sintered particles was $7.3 \times 10^7 \text{J/m}^3$, which was about 32% of that of the CVD particles ($2.3 \times 10^8 \text{J/m}^3$).

4. The typical kinetic energy of the particle was estimated to range from $4.4 \times 10^7$ to $1.8 \times 10^8 \text{J/m}^3$. Comparing the specific fracture energy with the kinetic energy, there is a possibility that the sintered particles showed higher deposition efficiency because they could deform by their kinetic energy and easily form activated surface around them promoting the bonding between the
ceramic particles. In contrast, the CVD particles couldn’t deform by their kinetic energy and the activated surface hardly appeared. We conclude that the specific fracture energy of the particle depends on the process for producing it and could be the crucial property to focus on to improve the deposition efficiency.

References
1) J. Akedo, J. Therm. Spray Technol., 17, 181–198 (2008).
2) W.-H. Yoon, J. Ryu, J.-J. Choi, B.-D. Hahn, J. H. Choi, B.-K. Lee, J.-H. Cho and D.-S. Park, J. Am. Ceram. Soc., 93, 2125–2127 (2010).
3) Y.-H. Kim, H.-J. Kim, J.-H. Koh, J.-G. Ha, Y.-H. Yun and S.-M. Nam, Ceram. Int., 37, 1859–1864 (2011).
4) M. Suzuki, Y. Nishihara, Y. Uesu and J. Akedo, Jpn. J. Appl. Phys., 51, 09LA17 (2012).
5) J. Akedo and M. Lebedev, Jpn. J. Appl. Phys., 38, 5397–5401 (1999).
6) J. Akedo and M. Lebedev, Jpn. J. Appl. Phys., 41, 6980–6984 (2002).
7) S.-M. Nam, N. Mori, H. Kakemoto, S. Wada, J. Akedo and T. Tsurumi, Jpn. J. Appl. Phys., 43, 5414–5418 (2004).
8) J. Akedo, J. Am. Ceram. Soc., 89, 1834–1839 (2006).
9) Y. Kaga, H. Kikuchi and J. Watanabe, J. Ceram. Soc. Japan, 111, 73–76 (2003) [in Japanese].
10) E. Fuchita, E. Tokizaki, E. Ozawa and Y. Sakka, J. Ceram. Soc. Japan, 118, 948–951 (2010).
11) E. Fuchita, E. Tokizaki and Y. Sakka, J. Ceram. Soc. Japan, 118, 767–770 (2010).
12) K. Tsujimichi, K. Mori, A. Yoshida, J. Iwasawa, H. Hatono, M. Kiyohara, M. Lebedev and J. Akedo, Ceram. Eng. Sci. Proc., 24, 121–125 (2003).
13) D.-W. Lee, H.-J. Kim, Y.-H. Kim, Y.-H. Yun and S.-M. Nam, J. Am. Ceram. Soc., 94, 3131–3138 (2011).
14) S. Fujitaka, Y. Tamura, H. Maki, N. Azuma and Y. Takeuchi, Sumitomokagaku Giyutushi, 2007-I, 24–32 (2007) [in Japanese].
15) S.-W. Oh, J. Akedo, J.-H. Park and Y. Kawakami, Jpn. J. Appl. Phys., 45, 7465–7470 (2006).
16) Y. Hiramatsu, Y. Oka and H. Kiyama, J. Min. Metall. Inst. Jpn., 81, 1024 (1965) [in Japanese].
17) S. Wakayama, T. Koji and H. Nishimura, Transactions of the Japan Society of Mechanical Engineers, Series A, 57, 504–511 (1991) [in Japanese].
18) H. Takagi, R. Maeda, N. Hosoda and T. Suga, Jpn. J. Appl. Phys., 38, L1559–L1561 (1999).
19) H. Takagi, K. Kikuchi, R. Maeda, T. R. Chung and T. Suga, Appl. Phys. Lett., 68, 2222–2224 (1996).
20) S. Matsuoka, Transactions of the Japan Society of Mechanical Engineers, Series C, 55, 2481–2486 (1989) [in Japanese].
21) A. A. Griffith, Philos. Trans. R. Soc. Lond. A221, 163–197 (1920).
22) M. W. Chen, J. W. McCauley, D. P. Dandekar and N. K. Bourne, Nat. Mater., 5, 614–618 (2006).