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Structural analysis of mesoporous ZrO_2 and TiO_2 nanofiber mats prepared by electrospinning methods

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Ag particles loaded mesoporous zirconia oxide (ZrO_2) and titanium oxide (TiO_2) nanofibers were prepared by electrospinning methods followed by calcination at 500-600°C. The crystal structure of the Ag particles were investigated by X-ray diffraction (XRD) and scanning electron microscopy (SEM). The fiber diameters for the ZrO_2 and TiO_2 mats were in the range of 60-160 nm and 50-450 nm, respectively. X-ray line broadening analysis showed that they were composed of smaller sized crystallites. Nitrogen-adsorption studies revealed that the ZrO_2 and TiO_2 fibers have both mesoporous and macroporous structures, which were originated from the aggregation of smaller crystallites than the fiber diameters and the interspaces formed by randomly oriented nanofibers. The deposition of Ag on the fibers followed by calcination at 500°C changed the distribution of the mesopore sizes.

Key words: ZrO_2 , TiO_2 , mesoporous materials, electrospinning method

1. Introduction

Zirconium dioxide (ZrO_2) and titanium dioxide (TiO_2) are widely used in the catalysts for supporting materials because they are chemically and physically stable and have generally high surface areas. These materials are generally prepared by liquid-phase and gas-phase synthesis processes^{1,2}. As for the catalyst supports, mesoporous materials which have the pores whose diameters are in the range of 2-50 nm because they generally have large surface areas and intrinsic properties caused by the porous structures. Over the decades, mesoporous materials have been developed using liquid-phase preparation methods using surfactants as the template molecules³. The preparation of mesoporous ZrO_2 and TiO_2 has been reported by several groups and the efficacy of these materials for catalytic reactions has been discussed^{4,5}. In addition, much attention has been recently focused on the metal oxides that have macroporous structures because the catalyst

properties also depended on the shape and morphologies of the catalysts. For instance, the control of the catalyst shape and structures improved the oxidation of diesel soot emitted from the diesel engines. Therefore, the fabrication of metal oxides having macropores is one of the important targets in the research area of catalysis science.

The electrospinning phenomenon was firstly observed by Rayleigh in 1897. Since then, this has been utilized for fabricating polymeric and inorganic fibrous materials⁶⁻⁸, due to their convenient and versatile method. In particular, electrospun ceramic fibers are often in the spotlight due to the outstanding characteristics such as high surface area and hierarchical pore^{9,10}. Additionally, they are widely used in a wide variety of applications, for example, as filtration membranes¹¹, delivery of bioactive agents¹², batteries or solar cells^{13,14}, proton exchange membrane fuel cells¹⁵ and catalytic reaction¹⁶.

We herein report that the ZrO_2 and TiO_2 nanofibers which have both mesoporous and macroporous structures have been successfully prepared by the electrospinning method. The characteristic porous and crystallographic structure of ZrO_2 and TiO_2 nanofibers are

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investigated by scanning electron microscopy (SEM), N₂ adsorption desorption isotherm, Barrett-Joyner-Halenda (BJH) pore size distribution and X-ray diffraction (XRD) analyses. We also investigated the effect of Ag loading on the porous structures of ZrO₂ and TiO₂ fibers because supported silver catalysts draw much attention due to their potential application for solid-solid heterogeneous catalytic reactions such as catalytic soot oxidation and catalytic sterilization.

2. Experimental

2.1. Chemicals and preparation of ZrO₂ and TiO₂ nano-fibrous support and catalysts

Zirconium oxychloride (ZrOCl₂·8H₂O) and Titanium isopropoxide were purchased from Kishida Chemical. Silver nitrate (AgNO₃, 99.8%) and N, N-dimethylformamide (DMF, 99.5%) were obtained from Wako Pure Chem Ind Ltd. Polyvinylpyrrolidone (PVP, MW=1.3×10⁶) were obtained from Sigma–Aldrich Japan.

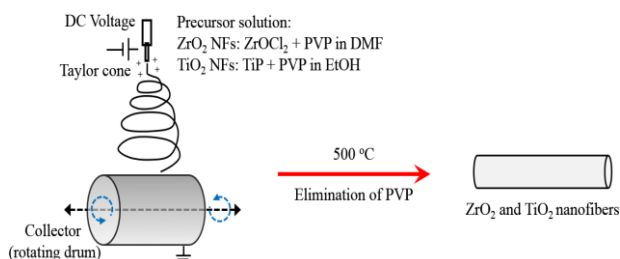


Fig. 1. Schematic illustration of ZrO₂ and TiO₂ nanofibers synthesis sequence.

Figure 1 shows the schematic illustration of ZrO₂ and TiO₂ nanofibers synthesis sequence. To prepare ZrO₂ nanofiber, we used a general electrospinning method followed by a heat treatment. 3g of ZrOCl₂·8H₂O and 1g of PVP were dissolved in 9g DMF. Then, this precursor mixture was vigorously stirred at room temperature for 6 h. The prepared precursor solution was electrospun onto a rotating drum with a distance between the drum surface and spinneret tip of 12 cm. High voltage of 18 kV was applied at the stainless steel needle (27 G, inner diameter = 0.21 mm) and feeding rate was maintained at 0.5 mL h⁻¹. The electrospun Zr/PVP nanofibers were calcined at 600°C for 3 hrs under the air atmosphere to perfectly eliminate PVP.

For the synthesis of TiO₂ fibers, 0.73 g of PVP and 0.35 g Acetic acid were dissolved in 7

g EtOH. Then, 1.8 g Titanium isopropoxide was added to the prepared solution, and this mixture vigorously stirred at room temperature for 30 min. The electrospinning of TiO₂ fiber was performed with the prepared precursor solution at a voltage of 14 kV and distance between the collector (rotating drum) and syringe needle (30 G, inner diameter = 0.15 mm) of 15 cm. During electro-spinning, a feeding rate and humidity were kept at 0.6 mL hr⁻¹ and 30 % RH, respectively. To remove the polymer substance (PVP) and form the pure TiO₂ fiber, the electrospun TiO₂/PVP fibers were calcined at 500°C for 6 hrs in air atmosphere.

5 wt% silver was loaded on the calcined ZrO₂ and TiO₂ fibers by the following procedures; (1) calculated amount of AgNO₃ (5 wt% Ag) was dissolved in 100 mL of pure water; (2) 0.1 g of fibers were added to solution; (3) to evaporate water and decompose the metal salts, they were stirred at 250°C for 3 h; (4) finally the sample was calcined at 500°C for 5 h.

2.2. Characterization

The morphologies of ZrO₂ and TiO₂ nanofibers were observed by the scanning electron microscopy (SEM; JEOL). X-ray diffraction was performed by means of RINT 2000 (RIGAKU) recorded from 25 to 100 ° with scan speed of 10 min⁻¹. The Brunauer-Emmett-Teller (BET) surface area and pore diameter were analyzed by nitrogen sorption at 77 K (BELSORP II; BEL). To discuss the chemical condition on the surface of the catalyst, X-ray photoelectron spectroscopy (XPS; Thermo VG Scientific, UK) was conducted using a monochromated Al X-ray source (Al Kα line at 1486.6 eV) at X-ray power of 36 W under a vacuum (7.8 × 10⁻⁹ mbar).

3. Results and discussion

3.1. Structural properties of ZrO₂ nanofibers

The shapes and morphological structures were investigated using a scanning electron microscopy (SEM). Figure 2 displays SEM images and fiber diameter distribution of electrospun ZrO₂ nanofibers. The ZrO₂ nanofibers exhibited an average diameter of 105 nm (selected 200 samples) with range of about 60 to 160 nm and a rough surface morphology, as shown in Fig. 2a. Figure 2c also shows that the ZrO₂ nanofiber mats have the porous structures, which were composed of the

randomly oriented ZrO₂ fibers. The interspace sizes are in the range of 1-20 μm.

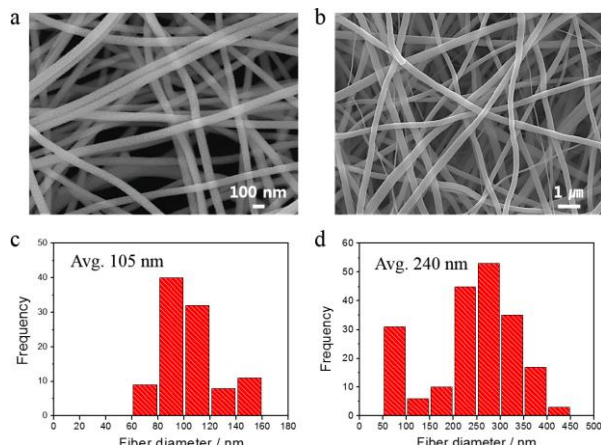


Fig. 2. SEM images of electrospun nanofibers (a) ZrO₂ and (b) TiO₂ and fiber diameter distribution of (c) ZrO₂ and (d) TiO₂ nanofibers.

Figure 3a exhibits the XRD patterns of ZrO₂, which confirms the crystal structure. The major diffraction peaks corresponding to (11̄), (111), (002), (110), (21̄), (220), (131), (311) and (400) of crystalline monoclinic structure (JCPDS No. 74-0815) and (101), (110), (112), (211), (202) and (220) of crystalline tetragonal phase (JCPDS No. 79-0815) were clearly

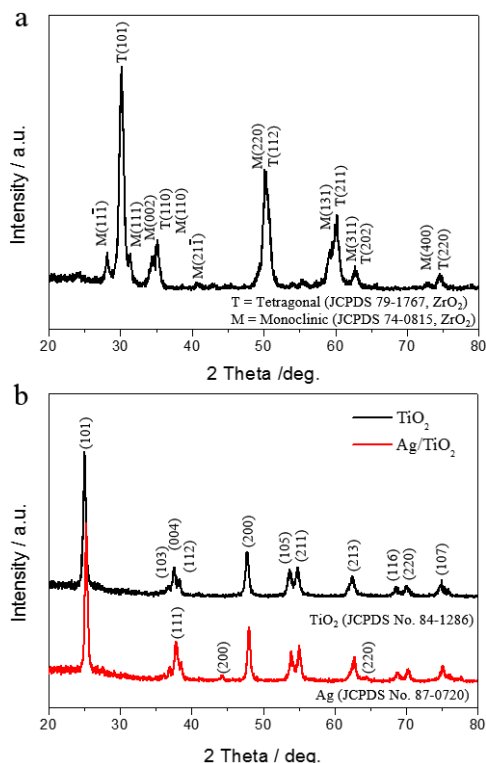


Fig. 3. XRD patterns of (a) ZrO₂ and (b) TiO₂ and Ag supported TiO₂ nanofiber.

observed, respectively. According to peak band width, line-broadening analyses were carried out to estimate the crystalline sizes of the ZrO₂ fibers using the Scherrer equation (1).

$$D = 0.94\lambda / (\beta/2 \cos \theta) \quad (1)$$

Where D is the crystallite size, λ is the X-ray wavelength of 1.54056 Å, β/2 is the full width at half maximum (FWHM) of (101) peak and θ is the Bragg angle. The average size of the ZrO₂ crystallites thus determined were 12 nm, which was much smaller than that of the ZrO₂ fibers determined by the SEM images. This findings indicates that the fibers were composed of the aggregated crystallites of monoclinic and tetragonal phases.

The pore structure of ZrO₂ and Ag/ZrO₂ nanofibers was investigated by nitrogen adsorption studies. Figure 4 shows the nitrogen adsorption-desorption isotherms obtained at 77 K (Fig. 4a and b). ZrO₂ and Ag/ZrO₂ nanofibers showed type III isotherms and H3 hysteresis loops, which are the characteristics of N₂ adsorption-desorption on mesoporous materials. Moreover, pore size distribution measured from Barrett, Joyner and Halenda (BJH) method exhibited the maximum peaks in range of 4.63 – 7.98 nm, further confirming that the ZrO₂ fibers have mesoporous structures (see Fig. 5a).

Figure 4 also shows the N₂ adsorption-desorption isotherms for Ag deposited ZrO₂ (Ag/ZrO₂) nanofibers. The material has also exhibit the hysteresis loop in the relative pressure range of 0.6-0.9. The pore size distribution obtained by the BJH method shows that the Ag/ZrO₂ nanofibers have the pores in the range of 2-20 nm with a maximum at 10 nm. Thus, the pore sizes distribution was slightly changed after deposition of AgNO₃ on the ZrO₂ fibers followed by the calcination.

BET surface areas of ZrO₂ and Ag/ZrO₂ nanofibers were calculated to be 15.5, and 9.5 m² g⁻¹, respectively. Because the Ag loading was 5wt%, the decrement of the BET surface area by Ag deposition cannot be explained in terms of the decrement of the ZrO₂ content. It is likely that the sintering of ZrO₂ in the calcination process gave rise to the decrease in ZrO₂ surface area.

3. 2. Structural properties of TiO₂ fibers

Figure 2 shows the SEM images of the TiO₂ nanofibers prepared by the electrospinning method. After calcination at 500°C, the

diameter of TiO₂ nanofiber ranged from about 50 to 450 nm (average diameter of 240 nm) and exhibited a rough surface morphology (Fig. 2b and d). The sizes are much larger than those for ZrO₂ fibers. The difference is presumably due to the combustion of polyimide substance (PVP) at high temperature. Figure 2 also shows that the TiO₂ nanofiber mats have the porous structures, which were composed of the randomly oriented TiO₂ fibers, as in the case of ZrO₂ fibers.

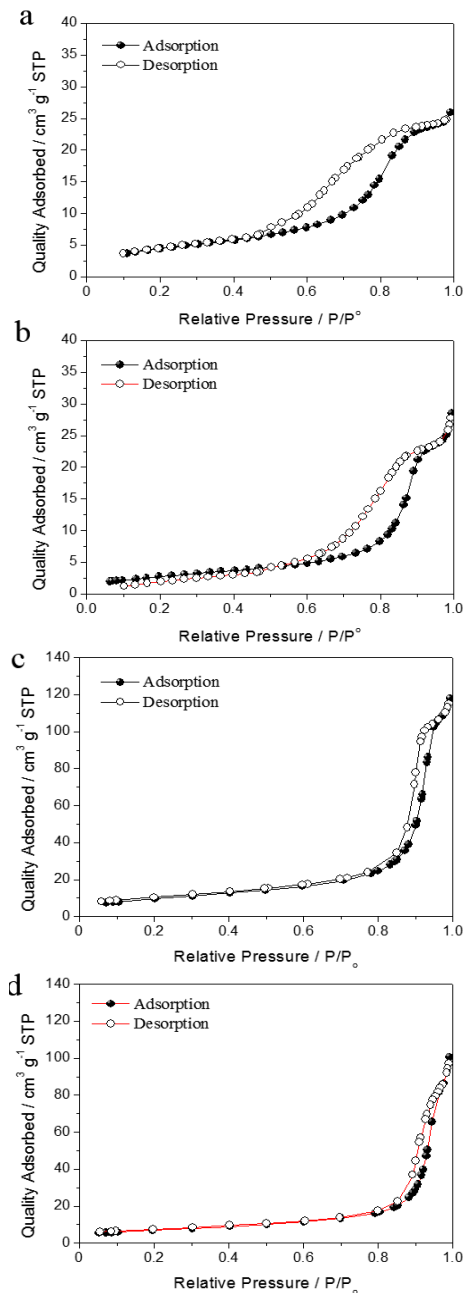


Fig. 4. N₂ adsorption-desorption isotherm of (a) ZrO₂, (b) Ag/ZrO₂, (c) TiO₂ and (d) Ag/TiO₂ nanofibers.

The crystalline structure of the TiO₂ was investigated using of X-ray diffraction (XRD) analysis and the XRD patterns TiO₂ fiber in the range of 20 to 80° is presented in Fig. 3b. The diffraction peaks (black line) showed (101), (103), (004), (112), (200), (105), (211), (213), (116), (220) and (107) planes, indicating the formation of anatase phase of titanium oxide (JCPDS No. 84-1286). The crystallite size was calculated using the Scherrer equation (1). The crystallite size of TiO₂ was 19.5 nm. This value was much smaller than that of TiO₂ fiber diameters, indicating that the fibers were composed of the crystallites of anatase phases.

Figures 4 and 5 show the N₂ adsorption-desorption isotherms and the BJH pore size distributions obtained from the desorption branch of the isotherms for TiO₂ fibers. The N₂ adsorption-desorption isotherm also confirmed that TiO₂ and Ag/TiO₂ fibers also showed type III isotherms and H3 hysteresis loops, corresponding to a mesoporous structure, as shown in Fig. 4c and d. One major pore-size peak was observed for the TiO₂ fibers at about 10.5 nm with range from 2 to 12 nm, indicating the presence of mesopores (see Fig. 5b). The pore size distribution was not so much affected by Ag deposition, whereas the pore volume was lowered due to the pore blocking by the Ag deposition and lowered amount of TiO₂ fibers contained in the catalyst. Thus, the

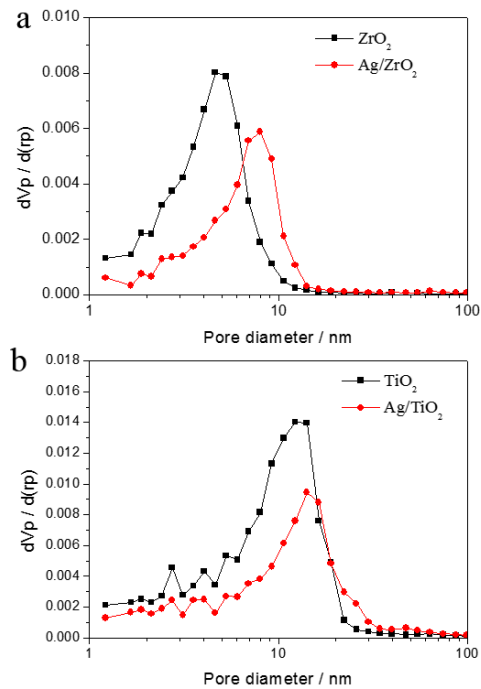


Fig. 5. BJH pore size distributions of (a) ZrO₂ and Ag/ZrO₂ and (c) TiO₂ and (d) Ag/TiO₂ nanofibers.

calcination of TiO₂ in the presence of AgNO₃ did not change the pore sizes, although the volume of mesopore decreased. This is in marked contrast with the results for Ag/ZrO₂.

According to the N₂ adsorption isotherms, the surface areas of the fibers were determined by the BET method. The surface areas of TiO₂ and Ag/TiO₂ fibers were calculated at 34.4 m² g⁻¹ and 24.1 m² g⁻¹, respectively. Therefore, the surface area of the fiber catalyst also decreased by the Ag deposition, which were located in the mesopores of the TiO₂ fibers blocking the pores and reduced the amount of fibers contained in the catalyst.

3.3 Comparison of ZrO₂ and TiO₂ nanofibers

As described above, the ZrO₂ and TiO₂ fiber materials prepared by the electrospinning method have both mesopores. The mesopores in the range of 2-10 nm with the maximum of 5 nm were located on the ZrO₂ fibers, whereas those in the range of 5-20 nm with the maximum of 10 nm were formed in the TiO₂ fibers. Because the mesopores were originated from the aggregation of the crystallites of ZrO₂ and TiO₂, the difference in the mesopore sizes were due to the sizes of these crystallites. As the crystallites consisting the fibers increased, the interstitial spaces, the mesopores of the fibers, which were formed by the aggregation of the crystallites increased. These findings also imply that the changes in crystalline sizes can control the mesoporous structures.

The ZrO₂ and TiO₂ fibers showed different average diameters of 105 and 240 nm, respectively. This difference can be attributed to the difference in the electrospinning parameters such as precursor solution concentration, feeding rate, spinneret inner size and applied voltage for the formation of low lever diameter (100-300 nm), which control the structures of fiber materials. On the other hand, the macroporous structures of ZrO₂ and TiO₂ fiber materials, which were originated from the interspaces formed by the nanofibers were not so much different for these two fibers. It is likely, however, that the interspace sizes can be controlled by changing the density of the nanofibers, which is also affected by the preparation conditions for fiber materials.

It is noteworthy that the post-treatment of the fiber materials changed the porous structures of the ZrO₂ fibers. When the Ag particles were deposited on the ZrO₂ fibers, the pore sizes of Ag/ZrO₂ nanofibers apparently

increased. One of the explanations for this behavior is that the calcination of ZrO₂ in the presence of AgNO₃ promoted the sintering and coarsening of the ZrO₂ crystallites, leading to the increase in mesopores formed by the aggregation of the crystallites.

4. Summary and Conclusion

In this paper, we showed that the ZrO₂ and TiO₂ fiber materials were successfully prepared by the electrospinning method, followed by calcination at 600 and 500°C, respectively. Both the ZrO₂ and TiO₂ fibers have the mesoporous and macroporous structures. The former structures were originated from the aggregation of crystallites. The latter structures were due to the interspace of the fibers. These fiber materials are good candidates for catalytic processes in which the adsorption, diffusion, and the morphology strongly affect the catalytic performances.

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