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Properties of Functionally Graded Materials Manufactured by Progressive Lamination Method for Applications

段階添加法で作製された傾斜機能材料の特性と応用

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Abstract　In the 20th century, people get a space flight and developed a space shuttle. Functionally graded materials (FGMs) shall have covered the outside of the shuttle to relax the thermal stress. The authors have been proposed a new manufacturing process of FGMs with a filtration technique, a mechanical compression technique and a sintering technique. In this paper, the manufacturing method of FGMs by the progressive lamination method was reported. The results show that thick FGMs with functionally graded characteristics were manufactured. Several kinds of raw materials were used for industrial applications. The characteristics of manufactured FGMs for industrial applications were experimentally investigated. For the air purification, TiO_2 based FGM can reduce the NO_x by TiO_2 photocatalytic effect. For the electrical insulator, the $BaTiO_3$ based FGMs have excellent characteristics, since the dielectric loss and the dielectric constant of FGM can be controlled by the progressive lamination method. It can be concluded that thick FGMs that manufactured by the progressive lamination method have a possibility to use for industrial applications.

1. Introduction

In the latter half of 20th century, functionally graded materials (FGMs)[1)] have been developed for cover of the outside of the shuttle to relax the thermal stress. More recently, it has been requested to produce highly functional materials, since the FGMs offer a wide range of applications in many fields of engineering, such as electrical engineering (heat emitting plates, sensors, magnetic shields etc.), mechanical engineering (engines, turbines, tools, erosion and heat resistant sealing etc.), nuclear technology (ultra high temperature plasma containers for nuclear fusion etc.), chemical processes (erosion resistant materials for chemical plants etc.) and biotechnology (artificial bones and teeth etc.). The FGMs are a type of material possessing special physical properties and having no interfaces between each component. Therefore, many methods of producing FGMs have been proposed. However, most methods can only produce thin FGMs. In order to supply FGMs for industrial applications, it is also necessary to produce thick materials. Therefore, the authors have proposed a manufacturing process of FGMs with a filtration, a mechanical compression and a sintering for the industrial production of thick FGMs.[2-6)]

The purpose of this study is to establish the manufacturing method of FGMs and to apply for industrial applications. In this paper, the manufacturing method of FGMs by the progressive lamination method was reported. And the characteristics of manufactured FGMs for industrial applications were also reported.

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2. Functionally Graded Materials

A simple model illustrating the differences between FGM and more conventional materials is shown in Fig. 1: (a) a compound flat material, (b) a connected material and (c) a functionally graded material. The compound flat material has a flat characteristic, and the connected material has a boundary on the interface of two materials. FGMs have excellent characteristics which differ from those of the compound flat and connected materials. Therefore, the FGMs are drawing attention in terms of their application in industrial fields. Since the FGMs have dual properties of the two raw materials that are mixed together, and the component distribution is graded continuously. For example, one of the FGMs that consist of metal and ceramic has the characteristic of thermal conductivity and metallic strength in metal side and resistivity to high temperatures in ceramic side.

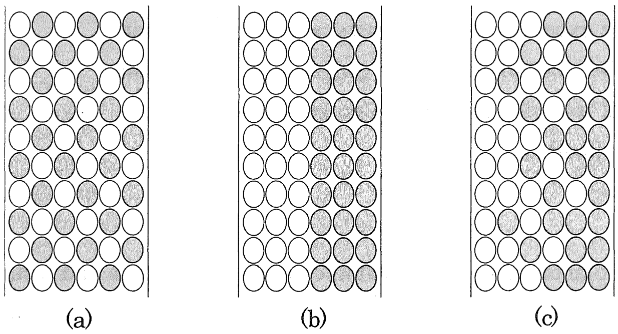

Figure 1: Component distribution of materials.
(a) Compound flat material,
(b) Connected material,
(c) Functionally graded material.

3. Manufacturing FGMs by Progressive lamination method

The manufacturing process of FGMs with a filtration, a mechanical compression and a sintering has been proposed.[2] Thick FGMs were manufactured by the progressive lamination method using a solid-liquid separation technique, that is, wet filtration using a vacuum pump, pressing using consolidation tester and sintering using furnace in a reduction atmosphere, as shown in Fig.2 and Fig.3. The apparatus was consisting of an upper and a lower cylinder, a piston and two perforated plates and made of bronze. The upper cylinder had an internal diameter of 60 mm, an external diameter of 130 mm and a length of 95 mm. The lower cylinder was 40 mm in length, with an outlet port for the extraction of filtered water. The piston was 60 mm in diameter with a port in its upper portion for the extraction of air. The two perforated plates were 5 mm in thickness. The cylinder plate had a diameter of 66 mm, the piston plate a diameter of 52 mm.

For raw materials of Korean kaolin and titanium dioxides (TiO_2), the manufacturing process is shown as an example.[3] Korean kaolin and TiO_2 of uniform granular diameter are mixed in distilled water. The slurry is put into a cylinder having a diameter of 60 mm and then vacuum filtered. When the first layer cake has been formed, next mixed slurry is put into the cylinder and thus successive layers are added. After the final layer cake is formed, the FGMs of filter cake are compressed at applied pressure of 1.0 MPa for 24 hours. The FGMs are then dried naturally, and sintered to firmness in a reducing furnace. The sintering temperatures are 400-1200 degrees Celsius. The TiO_2 used for the present materials was 1st grade TiO_2 of rutile and anatase crystalline form. Korean kaolin is a clay primarily consisting of kaolin ore, having the chemical formula $Al_2Si_2O_5(OH)_4$.

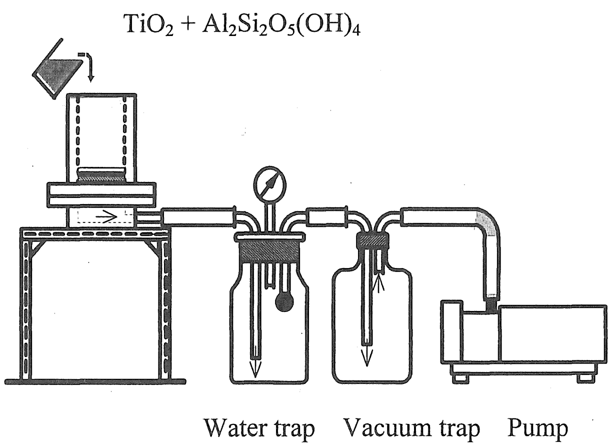

Figure 2: Schematic diagram of experimental apparatus to manufacture the FGMs by progressive lamination method.

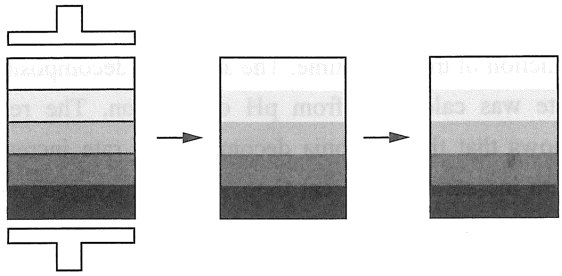

Figure 3: Illustrating the progressive lamination method.

4. Results and Discussions

A typical photograph of the cross section of Fe-PSZ (Partial Stabilized Zirconium) FGMs manufactured by the progressive lamination method is shown in Fig.4. The FGMs have eleven layers with a thickness of 10mm. Boundaries of layers disappeared and functionally graded characteristics were observed.[4) The material distribution is graded from upper layer to lower layer.

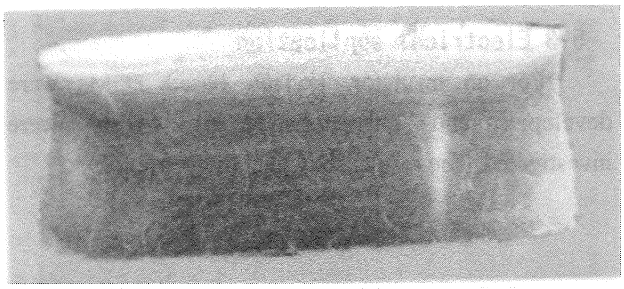

Figure 4: Photograph of cross section of Fe-PSZ FGM.

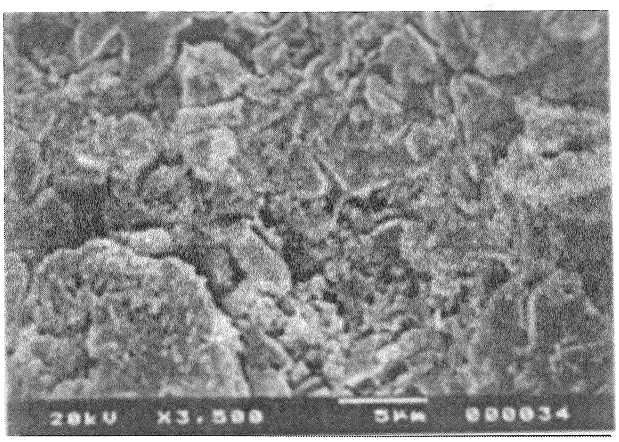

Figure 5: SEM image of magnetite - kaolin FGM.

Figure 5 shows other example of a scanning electron microscope (SEM) image of magnetite-kaolin FGMs. From the SEM image, grains of magnetite and kaolin exist together in each layer of compound materials were observed. However, the grain separation occurred locally. And some voids caused by steam were also observed.

5. Applications of FGMs

5-1 Laser processing for application

For industrial applications, the FGMs also require reprocessing, including cutting and drilling. It is generally difficult to reprocess FGMs, because the component distribution is graded continuously. Figure 6 shows a cross section of magnetite - kaolin FGM after excimer laser processing.[5) The depth of the laser processing has a tendency to be affected by material difference as well as by the increase in the number of laser pulses. The laser processing velocity of the kaolin layer was faster than that of the magnetite layer. This is due to the difference in mass associated with the type of material.

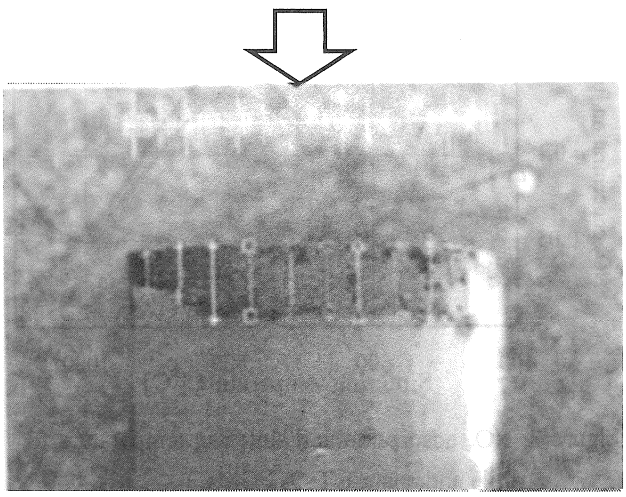

Figure 6: Photograph of laser processed FGM.
Laser fluence: 1.0kJ/cm^2, Repetition frequency: 20Hz.

5·2 Environmental application

The photocatalysis of titanium dioxides (TiO_2) was used for preserving the living environment from the atmospheric pollution. TiO_2 is a material with excellent photocatalytic properties. However, as this photocatalytic function has a powerful decomposing effect on chemical combinations, it is difficult to connect TiO_2 with other materials. To overcome this problem, several types of FGMs with TiO_2 as a component were manufactured.[3)]

After manufacture the TiO_2 based FGMs were placed in a Pyrex container (dimension 9.2 x 9.2 x 4.6 cm^3) filled with a simulated NO_x gas (8.5 ppm NO_2 or 10.1 ppm NO). They were then subjected to irradiate from a 10 W black light lamp (wavelength: 365 nm) for 2 hours. NO_x was oxidized and trapped on the surface of the material.

The TiO_2 based FGMs have excellent photocatalytic capability at sintering temperature of 800 degrees Celsius,[6)] as shown in Fig.7. The results also show that the anatase type TiO_2 FGM is more effective than the rutile type TiO_2 FGM in NO_x removing performance. For the air purification, TiO_2 based FGM can reduce the NO_x by TiO_2 photocatalytic effect.

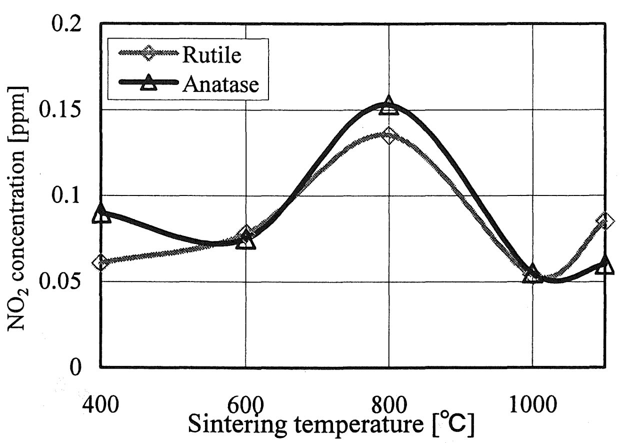

Figure 7: NO_x adsorption and sintering temperature for rutile and anatase TiO_2 FGMs.

This TiO_2 FGM can use not only for air purification but also for water purification. The characteristic of FGM for treatment of ammonia compounds in water was experimentally investigated. The FGM put on the bottom of container that filled with 100ml solution (200ppm NH_4OH). They were then subjected to irradiate from a 10 W black light lamp. Figure 8 shows ammonia decomposition rate as a function of treatment time. The ammonia decomposition rate was calculated from pH of solution. The result shows that the ammonia decomposition rate increases with increasing treatment time. Approximately 60 min. is required for treatment of 80% ammonia compound by present system.

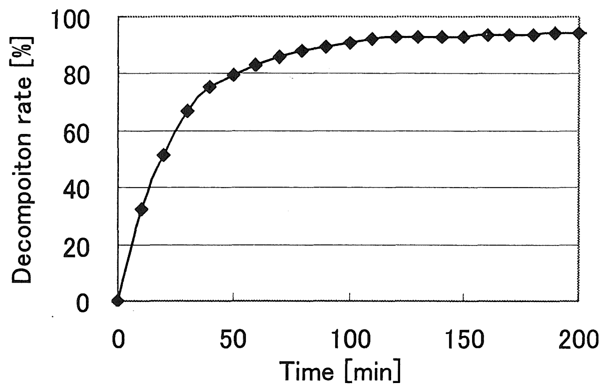

Figure 8: Ammonia decomposition rate as a function of treatment time.

5·3 Electrical application

For an insulator, $BaTiO_3$ based FGMs were developed and characteristics of FGMs were investigated. The results show that dielectric loss

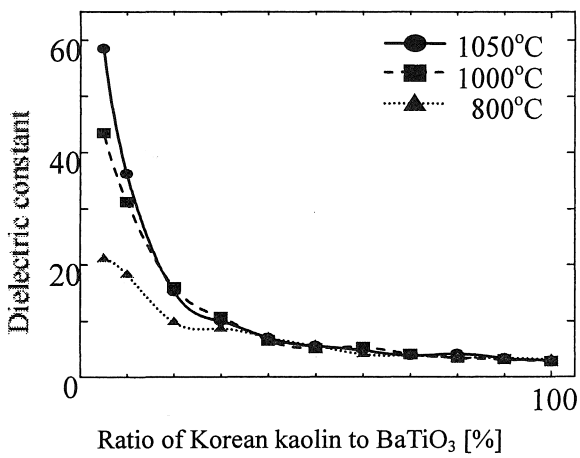

Figure 9: Dielectric constant as a function of ratio of Korean kaolin to $BaTiO_3$ for various sintering temperatures.

decreases with increasing sintering temperature as shown in Fig.9. Stabilities of the dielectric loss and the dielectric constant for frequencies were observed at higher sintering temperature. The results also show that the dielectric constant decreases with increasing the ratio of Korean kaolin to $BaTiO_3$.[7] Based on these results, it can be controlled the dielectric loss and the dielectric constant of FGM. It can be concluded that the $BaTiO_3$ based FGMs have a possibility to used for the insulator.

6. Concluding remarks

The manufacturing method of FGMs by the progressive lamination method was reported. The results show that the thick FGMs with functionally graded characteristics were manufactured. This manufacturing method can applies to several kinds of raw materials for industrial applications.

The characteristics of manufactured FGMs for industrial applications were experimentally investigated. For the air and water purification, TiO_2 based FGM can reduce the NO_x and ammonia by TiO_2 photocatalytic effect, respectively. For the electrical insulator, the $BaTiO_3$ based FGMs have excellent characteristics, since the dielectric loss and the dielectric constant of FGM can be controlled by the progressive lamination method. It can be concluded that thick FGMs that manufactured by the progressive lamination method have a possibility to use for industrial applications.

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