Development of Metallic Closed Cellular Material Containing Organic Materials and Its Mechanical Properties*

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A metallic closed cellular material containing organic materials for smart systems has been developed. Polymer powder particles coated with a nickel-phosphorus alloy layer using electroless plating were pressed into green pellets and sintered at high temperatures in a vacuum. A metallic closed cellular material containing organic materials was then fabricated. The compressive, damping and ultrasonic tests were carried out to measure the mechanical, damping and ultrasonic properties of this material, respectively. The results showed that this material had different stress-strain curves among the specimens of different cell thickness, each stress-strain curve had a long plateau region, and the sintering temperatures of the specimens affected the compressive strength of each specimen. The internal friction and ultrasonic attenuation coefficients of this material were shown to be very large. These results indicate that this metallic closed cellular material can be utilized as a material for energy-absorbing and passive-damping systems.

Key Words: Metallic Closed Cellular Material, Energy Absorption, Smart Structure, Electroless Plating, Sintering, Isostatic Pressing, Damping Property

1. Introduction

Many current research projects have been studied to develop the smart materials and smart structures. Particularly, an energy absorbing system has been required to protect persons from impact shock of accident. Additionally, passive and active damping functions are becoming increasingly important in terms of vibration control of the structures. Therefore, these materials which have high-energy absorbing capacity and damping functions are required.

Recently, cellular materials are receiving renewed attention as structural and functional materials. Cellular materials have unique mechanical, thermal, acoustic and energy absorbing properties that can be combined with their structural efficiency⁽¹⁾. Therefore, many kinds of cellular materials have been tested as energy absorbing and damping materials.

Particularly, the closed cellular materials are thought to have many favorable properties and applications. However, there is a lack of technique to produce such fine closed cellular materials except for the gas forming method⁽²⁾⁻⁽⁷⁾, the sintering of hollow powder particles^{(8),(9)} and the two-dimensional honeycomb structures⁽¹⁾. Therefore, the authors have developed a fabrication process for a metallic closed cellular material containing organic materials for the smart structure⁽¹⁰⁾.

In this study, a metallic closed cellular material containing organic materials has been fabricated and the mechanical, damping and ultrasonic properties of this material were measured. The effects of sintering temperature and thickness of the cell walls on the mechanical damping and ultrasonic properties were analyzed. The utility of this material is also discussed.

2. Conceptual Process

A fabricating process for the metallic closed cellular material⁽¹⁰⁾ is shown in Fig. 1. The process is as follows: 1) Powdered polymer particles are coat-

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ed with a metal layer using electroless plating. 2) The powder particles are pressed into pellets (green compacts) by cold isostatic pressing. 3) After sintering at high temperature in a vacuum, the closed cellular material containing organic materials is then fabricated.

3. Experiments

3.1 Preparing the metallic closed cellular material

A thermal plastic polymer, polystyrene, particles with a 10 μm diameter (Japan Synthetic Rubber Co., Ltd.) were selected for this study. These polystyrene particles were coated with 0.19 – 0.53 μm thick nickel-phosphorus (Ni-P) alloy layers using electroless plating. This alloy includes about 2.5% phosphorus. These particles were then pressed into pellets (green compacts) with about a 8 mm diameter and 8 mm length, 8 mm diameter and 12 mm length and 16 mm diameter and 8 mm length by isostatic pressing at 200 MPa and 90°C. After this, these green compacts were sintered for 1 h at 800°C and 850°C in a vacuum condition produced by diffusion pump (about 10^{-3} Pa).

3.2 Characterization

The microstructure of the powder particles, the green compacts before sintering, the cross-sections after sintering and fracture surface were observed

using a scanning electron microscope (SEM). To observe the cross-section of this material, the specimen was cut and the cross-section surface was polished using emery paper (#600) and then 0.05 μm Al_2O_3 powders.

To measure the mechanical properties, compressive tests were performed at room temperature. After that, the material inside cell walls is analyzed by the laser-Raman spectroscopy. The vibration tests were performed on the sheet specimen in order to estimate the internal friction of this material. In addition, ultrasonic measurements were carried out to estimate the attenuation coefficient of this material. The vibration tests carried out with the elastometer (Nihon Techno-Plus Co., Ltd, TE-HT) using 4 mm wide, 10 mm long and 1 mm thick specimens and the ultrasonic measurements were carried out with a 6.4 mm diameter probe generating a longitudinal wave of 10 MHz at room temperature using 16 mm diameter specimens.

4. Results

4.1 Micro-structural observation

Figure 2 shows an SEM image of the polystyrene powder particles coated with 0.47 μm thick Ni-P alloy layers and Fig. 3 shows an SEM image of the green compact after cold isostatic pressing. The polystyrene particles were deformed to polyhedrons by isostatic pressing. An SEM image of the cross-section of this material after sintering for 1 h at 850°C is shown in Fig. 4. In this figure, the cell walls of the Ni-P alloy are observed as bright parts and the material inside the cell walls is observed as the darker parts. The result of the laser-Raman spectroscopy analysis shows the material inside cell walls is carbonized.

4.2 Compressive test

Compressive tests were carried out at room temperature. Typical examples of the compressive test

Fig. 1 Flow diagram of metallic closed cellular material fabricating process

Fig. 2 SEM image of polystyrene particles coated with Ni-P alloy layer

Fig. 3 SEM image of green compact after isostatic pressing

Fig. 4 Cross-section of the metallic closed cellular material

results are shown in Figs. 5(a), (b) and (c). Figure 5(a) shows stress-strain curves of the specimens fabricated from the polystyrene particles coated with $0.19\text{ }\mu\text{m}$ thickness of Ni-P alloy layers, Fig. 5(b) shows stress-strain curves of the specimens fabricated from the polystyrene particles coated with $0.26\text{ }\mu\text{m}$ thick Ni-P alloy layers, and Fig. 5(c) shows the stress-strain curves of the specimen fabricated from the particles coated with $0.47\text{ }\mu\text{m}$ thickness of Ni-P alloy layers. These specimens were sintered at 800°C (broken lines) or 850°C (solid lines) for 1 h in a vacuum. The stress-strain curve shows a linear elastic region, a long plateau region where the stress gradually increases and a wavy region where the stress repeatedly decreases and increases. The specimen sintered at 850°C has a higher strength than that of specimens sintered at 800°C .

The fracture surfaces of these specimens were observed by an SEM. The fracture surfaces in the specimens are almost parallel to the loading direction and the cells at the fracture surface were broken.

(a)

(b)

(c)

Fig. 5 Compressive stress-strain curves for metallic closed cellular materials sintered at 800°C and 850°C from polystyrene particles with (a) $0.19\text{ }\mu\text{m}$ Ni-P alloy layer, (b) $0.26\text{ }\mu\text{m}$ Ni-P alloy layer and (c) $0.47\text{ }\mu\text{m}$ Ni-P alloy layer

4.3 Damping tests

The internal friction was measured by the half-width method using an elastometer (Nihon Techno-Plus Co., Ltd., TE-HT). The internal frictions of this closed cellular materials made from the polystyrene particles coated with the 0.53 μm thick Ni-P alloy layer and sintered at 830°C and 850°C are 5.3×10^{-3} and 4.4×10^{-3} , respectively.

4.4 Ultrasonic measurement

The ultrasonic attenuation coefficient of the 16 mm diameter specimen sintered at 800°C was measured by using a 6.4 mm diameter probe generating a longitudinal wave of 10 MHz at room temperature. The ultrasonic attenuation coefficient (about 3.8–4.8 dB/cm) is higher than that of pure aluminum (0.1–2.5 dB/cm), but lower than that of polystyrene (15.2 dB/cm).

5. Discussion

5.1 Metallic closed cellular material

A metallic closed cellular material has been fabricated in this study. The density of this material is from 2.2 g/cm³ to 2.6 g/cm³, which is smaller than that of an aluminum alloy. As Figs. 3 and 4 show, the polystyrene particles were deformed to polyhedrons by the isostatic pressing and the Ni-P alloy layers were joined together. Figure 4 also shows that cell walls of an Ni-P alloy are observed as the bright parts and the material inside the cell walls is observed as darker parts. The amount of emitted secondary electrons per a primary electron of the polymer or organic material is smaller than that of the metals. The results of the Laser-Raman spectroscopy analysis shows the remained materials inside cell walls are carbonized. Therefore, the material inside the cell walls is thought to be carbonized polystyrene. This result indicates that the organic material remains inside of the cell walls after heat treatment and this metallic closed cellular material containing the organic material can be produced using this technique.

5.2 Energy absorption

As shown in Figs. 5, each stress-strain curve has a linear elastic region, a long plateau region and a wavy region. It seems that the presence of the plateau region in the compressive stress-strain curve is an evidence of the high energy absorption. Therefore, this metallic closed cellular material seems to have a high-energy absorbing capacity. These results show that this material can be utilized as an energy absorbing material.

After the linear elastic region in the stress-strain curves, a few cracks were observed on the specimen's surface in the direction parallel to the stress axis. Unfortunately, observation of the cross-section of the

specimens before testing showed a few defects (Fig. 6). It should be thought that these defects were caused during sintering of the Green compact, which has some defects. It is postulated that the fracture initiates from the defect in this material. Therefore, if this metallic closed cellular material has only few defects, the plateau area of the stress-strain curve will continue longer during the compressive test. It should be considered that the specimen sintered at 850°C has fewer defects than specimens sintered at 800°C. Therefore, the compressive stress of the specimens sintered at 850°C is higher than that of the specimens sintered at 800°C.

Comparing among Figs. 5(a), (b) and (c), as the thickness of the coated Ni-P alloy increases, the compressive stress during the plateau region increases. It should be considered that the compressive strength depends on the thickness of the cell walls. These results show that compressive stress during the plateau region and the energy absorption of this material can be controlled by changing the thickness of coating layer of the particles.

5.3 Young's modulus

Young's modulus of this material was measured using the data in the upper part of the linear elastic region for each specimen in Figs. 5. The relationship between the Young's modulus and thickness of the cell walls of this material is shown in Fig. 7. The relationship between Young's modulus and sintering temperature is also shown in this figure. As the thickness of cell walls increases, the Young's modulus of the specimens increases. Therefore, it should be considered that Young's modulus of the specimen depends on the thickness of the cell walls of the specimen. Additionally, as the sintering temperature increases, the Young's modulus of the specimen decreases.

It should be considered that thickness of the cell

Fig. 6 SEM image of the cross section of the specimen

Fig. 7 Relationship between thickness of the cell walls and Young's Modulus of the closed cellular materials

walls of this material can be controlled by changing the conditions of the electroless plating. Therefore, it seems that the Young's modulus of this material can be controlled by changing the thickness of the cell walls and the sintering temperature.

5.4 Damping property

The internal frictions of this material (about 5.3×10^{-3} and 4.4×10^{-3}) are higher than that of the most of metallic structural materials⁽¹¹⁾. The measurement results show that as the sintering temperature increases, the damping constant of this material decreases. It should be considered that it is possible to control the damping property of this material by changing the sintering temperature. These results suggest that this material can be utilized as a passive damping material.

5.5 Ultrasonic attenuation coefficient

The attenuation coefficient of this material (about 3.8 - 4.8 dB/cm) is higher than that of metallic materials (for example, the attenuation coefficient of pure aluminum is about 0.1 - 2.5 dB/cm), but smaller than that of polystyrene (15.2 dB/cm). These results suggest that this material can be utilized as a sound proofing material.

6. Conclusion

A metallic closed cellular material containing

organic materials has been developed. This metallic closed cellular material is light and has a high-energy absorption, large internal friction and large ultrasonic attenuation coefficient. In addition, Young's modulus of this material depends on the thickness of the cell walls of the specimen and sintering temperature. The obtained results emphasize that this metallic closed cellular material can be utilized as an energy absorbing material and passive damping material.

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