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Effect of molding temperature on fluidity and injection moldability of oven-dry steam-treated bamboo powder

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ABSTRACT

The thermal fluidity and injection moldability of oven-dry steam-treated bamboo powder were investigated with control of the temperature. Thermal analysis, such as differential thermal analysis and thermogravimetry, indicated that the steamed powder underwent degradation at lower temperatures, and the weight loss of the steamed powder was larger than that for the untreated powder. Thermal flow tests of the steamed powder at several temperatures revealed the flow rate was high at 180 and 200 °C. Injection molding was attempted while controlling the temperature of the injection part and metal mold. It was possible to obtain products with a surface similar to plastic via injection molding and the range of metal mold temperature that resulted in a successfully molded product increased with the injection temperature. The four-point bending strength and Rockwell superficial hardness of the product increased with the mold temperature at each injection temperature. Both characteristics were high when the injection temperature was 180 °C, and the highest values obtained were 36 MPa and HR15w 78. Observation of the fracture part of the molded product confirmed that the fiber strength of the product molded at an injection temperature of 180 °C was maintained, while that molded at an injection temperature of 200 °C was not.

1. Introduction

There is a demand for the effective and sustainable use of woody biomass materials. However, applications for woody biomass materials are limited due to a lack of effective processing methods for woody biomass materials in industry. Woody biomass materials are generally processed by machining or simple plastic forming; however, molding processes that use a metal mold are difficult for these materials due to a lack of fluidity. Therefore, the mass production of arbitrary shaped products from woody biomass materials is difficult.

Recent research and development on molding processes for woody materials has included research on injection molding processes for wood-plastic composites (WPC). Injection molding using WPC is possible due to the fluidity of plastic. For example, Stark et al. (2004) reported that a WPC with 50% ponderosa pine wood powder was successfully injection molded. In addition, Nagaya (2014) reported an automobile interior material fabricated from WPC pellets with 60% kenaf fiber by injection molding. However, Akashi and Ohnuma (1975) reported that the fluidity of the WPC was significantly decreased when the woody biomass content surpassed 60%. Therefore, injection molding is difficult when using a WPC with over 60% woody biomass due to the poor fluidity. However, WPC with a high wood content over 60% is desirable in terms of the effective use of woody materials, and the fluidity of the woody biomass should be improved to obtain injection mold products with a high wood content.

Research on the fluidity of woody materials has also been conducted. Yamashita et al. (2007) performed fluidity tests on bamboo culm using a capillary rheometer, and confirmed that bamboo that contains water can flow under heat and pressure due to softening and the decomposition of lignin and hemicellulose. By exploiting this property of woody material, Miki et al. (2004b) fabricated a complex shaped product by injection molding only wood powder saturated with water. However, the fluidity of the dry woody material was low, so that molding was reported to be difficult by both research groups. The water inside the material has a negative effect on the molding process because much water vapor and pyrolysis gas are produced when the material is heated. Therefore, woody biomass with good fluidity in the dry state is desirable for use in injection molding.

To improve the fluidity of woody biomass in a dry state, it was reported that preparation by saturation with water vapor at high temperature is effective because the woody biomass components

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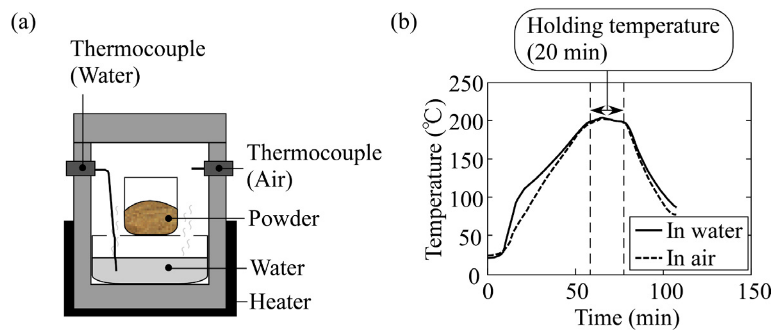

Fig. 1. Steaming method. (a) Schematic diagram of the small pressure vessel and (b) temperature variation during steaming.

Table 1
Particle size distribution of the bamboo powder.

Particle size (μm)	0–38	38–53	53–75	75–150	150–300
Ratio (wt%)	8.8	5.7	5.9	31.3	48.3

are decomposed by the hydrolysis reaction prior to the molding processes. Takahashi et al. (2010b) reported that the thermal flow temperature of beech wood powder decreased when prepared by steaming, and the wood powder in the oven-dry state started to flow at 170–180 °C. However, the effect of steam treatment varies according to wood species, because the difference in chemical components. Shimizu and Ishihara (1990) reported that the xylan content of bamboo is higher than that of other woody materials. Tjeerdsma and Militz (2005) reported that xylan has an acetyl group that can form acetic acid, which activates the acid hydrolysis reaction. Therefore, it is considered that bamboo can be more easily treated by steaming than other woody materials. Kajikawa and Iizuka (2013) conducted an injection test with steamed bamboo powder as a fundamental study to determine the applicability of the steamed woody biomass for injection molding, and confirmed that the injectability of the powder was improved by steam treatment. Therefore, it is possible that only dry woody biomass or a WPC with a high content of woody biomass can be injection molded by using steamed woody biomass.

In this study, the possibility of injection molding using only oven-dry bamboo powder that was steam-treated was investigated, and the mechanical properties of the molded product were evaluated. The thermal properties of the steamed powder were also evaluated to determine the temperature for injection molding. Therefore, differential thermal analysis (DTA) and thermogravimetry (TG) were conducted as a preliminary evaluation. In addition, the fluidity was investigated by thermal flow testing using a capillary rheometer. Injection molding was attempted while controlling the injection and metal mold temperatures based on the thermal properties of the steamed bamboo powder. Four-point bending and Rockwell hardness measurements of the molded products were then conducted to evaluate the mechanical properties.

2. Material and methods

2.1. Material preparation

Moso bamboo powder was used as the woody biomass material. Bamboo culms were planed using an automatic feed planer to obtain bamboo shavings. The bamboo shavings obtained were then milled in a pin mill to produce bamboo powder. The powder was passed through a ϕ300 μm screen to obtain the powder used in the present study. Table 1 shows the particle size distribution of the powder, which was mainly in the range of 75–300 μm.

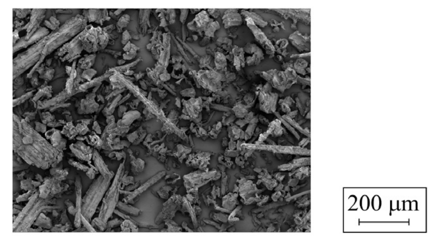

Fig. 2. SEM micrograph of the steamed bamboo powder.

A small pressure vessel was used to steam the bamboo powder, as shown in Fig. 1(a). The powder was treated with saturated water vapor by heating the vessel containing the powder and water. The moisture content of the powder was adjusted to 200% before steaming. Fig. 1(b) shows the temperature variation in the vessel during steaming. The temperature was held at 200 °C for 20 min. After the steam treatment, the powder was brought to an air-dry state by drying at 30 °C. The powder was then dried at 105 °C to achieve an oven-dry state for the experiments. Fig. 2 shows a scanning electron microscopy (SEM) micrograph of the steamed bamboo powder. The powder consisted of fiber-like particles with a large aspect ratio and round particles.

2.2. Differential thermal analysis and thermogravimetry

TG/DTA (TG/DTA 6200, Seiko Instruments Inc.) measurements were conducted to observe chemical changes in the bamboo components up to a temperature of 250 °C. The bamboo powder was placed in an Al pan, while an empty Al pan was used as a reference. Drying was conducted at 105 °C for 30 min by purging with dry air to ensure that the powder was oven dry in the apparatus. The temperature was then increased to 250 °C at a constant rate of 10 °C/min.

2.3. Thermal flow test

The thermal flow test was conducted to investigate the fluidity of the steamed powder. A capillary rheometer (CFT-500D, Shimadzu) was used for the flow test, as shown in Fig. 3(a). Firstly, a cylinder was heated to the test temperature, T_f. 1.5 g of powder was placed in the cylinder and a piston was then inserted into the cylinder. The powder was then preheated for 6 min. The piston was temporarily compressed to vent gas for 3 min after the preheating was started. The piston was then compressed at 49 MPa and the material was extruded from the die. Test temperatures T_f,