Possibility of Extrusion of Wood Powders*

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Extrusion tests of mixed wood powders of cryptomeria with the Japanese cypress are carried out at various temperatures in order to confirm the possibility of near net shape forming of wood powders. Effects of extrusion temperature, extrusion ratio, moisture content and particle size of the mixed wood powders on the flow characteristics, bending strength, hardness and bulk density of extruded products are discussed. The experimental results show that the fluidity of the mixed powders and the bending strength and bulk density of extruded products increase with increasing temperature and moisture content of powders. However, when the extrusion temperature is too high, the bending strength and bulk density of extruded products tend to decrease due to bubbles generated in the extruded product.

Key Words: Wood Powders, Extrusion, Temperature, Moisture Content, Bending Strength, Bulk Density

1. Introduction

Wood-based materials are good resources for the environment, because they are finally resolved into carbon dioxide and water in the disposal stage. Problems, however, arise regarding productivity and workability: it takes long years for a tree to grow to a useable size, and the processing of wood materials is more difficult than that of metal and plastic materials.

To overcome these problems, the compaction or solidification technique of crashed wood chips was developed, which enabled the production of new wood-based materials such as plywood, fiber-board and particle-board. However, since an adhesive or bond made from petroleum is used in the production process of these materials, an environmental pollution problem remains when they are disposed of or incinerated.

To overcome this problem, the compaction of wood chips⁽¹⁾ and wood powders⁽²⁾ should be done

without using a petroleum adhesive. In an attempt to achieve the compaction of wood powders without any adhesive and binder, the authors had already investigated the effect of compaction conditions on the strength and bulk density of products, and the possibility and problems of the compaction of wood powders have already been discussed⁽³⁾. The experimental results showed that if appropriate compaction conditions were adopted, the wood powders could be compacted successfully; the strength and bulk density of the compacted product were higher than those of natural wood.

In the compaction of wood powders, not only the strength and bulk density of the product but also complication in shape can be obtained. This is another important factor which is closely related to the flow characteristics of the wood powders. Especially, for near net shape forming like injection molding, hot pressing and hot isostatic pressing, it is necessary to know the fluidity of the wood powders at elevated temperatures. However, there have been few studies on the flow characteristics of wood powders under various conditions.

From this point of view, in the present paper, the backward extrusion^{(4),(5)} is employed as a simple method to evaluate the fluidity of the wood powders, and the effects of the extrusion temperature, extru-

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sion ratio, and the moisture content and particle size of the wood powders on the flow characteristics, the bending strength, hardness and bulk density of extruded products and its tendency are experimentally investigated. The possibility and problems of the extrusion of wood powders are also discussed.

2. Wood Powders and an Experimental Method

2.1 Wood powders

Mixed powders of cryptomeria and Japanese cypress were used in the experiment. The wood powders were produced from wood chips and smashed by a vibrating ball mill. The powders produced were sieved and classified into three particle sizes; $\sim 90 \mu\text{m}$, $106 - 150 \mu\text{m}$, $180 - 250 \mu\text{m}$ by metal wire cloth. The SEM photographs of the wood powders are shown in Fig. 1.

In general, the mechanical properties of wood materials are remarkably affected by the water existing on the cell wall and in voids such as the bore of the cell. In this experiment, the existence of the water was expressed as the moisture content (M.C.), and was calculated from Eq. (1).

$$\text{M.C.} = \frac{W - W_0}{W} \times 100(\%) \quad (1)$$

Where, W and W_0 are the weight of wood powders with and without moisture.

W_0 was defined as the weight of wood powders which were dried by a blast drier at a temperature of about 110°C for 2 hours. These drying conditions were determined on the basis of JIS Z 2102 (Japanese Industrial Standard). Wood powders with different moisture contents were prepared by keeping the dried wood powders in several desiccators for ten days,

each desiccator is controlled so as to keep the humidity at a desired value.

2.2 Compaction process

The experimental method is schematically shown in Fig. 2. The backward extrusion is used as a compaction process. Dimensions of the container and die used for the extrusion are listed in Table 1. Wood powders of about 2 g are filled in the container and compressed by the die. Lubricants are not used at all throughout the experiment. The compaction device was heated at various temperatures for five minutes by an infrared furnace, while the compaction load was kept constant. During this compaction and heating process, the wood powders are extruded through the die. The length of the extruded product depends on the extrusion conditions and this length is used as a measure to evaluate the fluidity of the wood powders.

2.3 Measurement of mechanical properties of extruded products

Average bulk density, bending strength and micro-Vickers hardness of the extruded product were

Table 1 Diameter of extrusion tools

	Outside diameter / mm	Inside diameter / mm		
Container (height 65mm)	111	$d_2 = 20$		
Die (length 50mm)	d_2	d_1		
	20	1	※ 3	※ 5
Extrusion ratio $\alpha = (d_2/d_1)^2$		400	44	16

※ Die exit is plugged in the experiment.

Fig. 1 SEM observations of wood powders (d : Particle size)

Fig. 2 Compaction process of wood powders

measured as mechanical properties of the products. The average bulk density ρ and bending strength $\sigma_{\max}$ of extruded products were calculated from Eqs. (2) and (3).

$$\rho = \frac{4G}{\pi d^2 L} \quad (2)$$

$$\sigma_{\max} = \frac{8FL}{\pi d^3} \quad (3)$$

Where, d , L and G are diameter, length and weight of the extruded product, respectively, and F is maximum bending load.

3. Flow Characteristics of Wood Powders

3.1 Evaluation of fluidity of wood powders by extruded length

Figure 3 gives a typical example showing the effect of temperature on the length of extruded products which are obtained under a constant extrusion pressure. This difference in the extruded length could be observed when using only a die with a large extrusion ratio of $\alpha=400$. It is seen from Fig. 3 that the length of extruded product increases with increasing temperature because the fluidity of wood powders improve as the temperature rises. This means that the extruded length at a constant extrusion pressure can be used as a measure to evaluate the fluidity of the wood powders^{(3),(4)}.

Figure 4 shows the effects of the extrusion temperature and the moisture content (M.C.) of wood powders on the extruded length. Regardless of the moisture content, the extruded length increases with increasing temperature. For a given extrusion temperature, the extruded length increases as the moisture content increases. This is because the softening temperature of lignin (a component of wood) decreases due to the water in the wood powders, and this leads to the improved fluidity of the wood powders. However, for moisture content larger than

Fig. 3 Effect of temperature on extruded length ($P=178$ MPa M.C.: 0% $d: \sim 90 \mu\text{m}$)

about 10%, the difference in the extruded length is hardly observed. Furthermore, for an extrusion temperature lower than 100°C , wood powders did not flow into the die at all, even if the moisture content was increased.

Figure 5 shows the effect of particle size of wood powders on the extruded length. For the moisture content of 0%, the temperature required to extrude wood powder to arbitrary length rises as particle size increases. While, for moisture contents of 11% with large particle size of $180-250 \mu\text{m}$, the temperature decreases much more than that for dry powders. However, for moisture content of 5% and particle size of $106-150 \mu\text{m}$, the reduction of extrusion temperature is less than the former case. Regardless of the particle size, the extruded length increases with increasing moisture content.

For the dry wood powders with large particle size, required extrusion temperature was over 200°C . This high temperature leads to burning of extruded

Fig. 4 Effects of temperature and moisture content on extruded length

Fig. 5 Effects of temperature, moisture content and particle size on extruded length

products. Therefore, in the extrusion of wood powders, the moisture content is one of the most important factors, especially in the case of near net shape forming of complicated shape parts.

3.2 Conditions to achieve successful extrusion

In the near net shape forming such as injection molding, the filled state of the wood powders in the mold is essential to obtain a product with good dimensional accuracy. To examine the effect of extrusion conditions on the filled state of powders in the die, extrusion tests⁽⁵⁾ were carried out using dies with extrusion ratios of 44 and 16.

The main factors affecting the filled state are extrusion pressure, temperature and moisture content of wood powders. The relationships among these factors that achieve successful extrusion are summarized in Fig. 6.

The extrusion can be successfully achieved in the regions shown by the oblique lines. It is seen from Fig. 6 that when the moisture content is large, successful extrusion can be carried out at a lower temperature. And, when the temperature is kept high, the extrusion can be carried out at a lower pressure. However, for the temperature region higher than 220°C, it was impossible to get good extruded products due to the burning of the wood powders (● in Fig. 6). In contrast, for the temperature region lower than 100°C, it was also impossible to achieve extrusion due to the lower fluidity of the wood powders, even if the extrusion pressure and the moisture content were increased.

Examples of successful products are shown in Fig. 7, which are extruded at the pressure of $P=178$ MPa, temperature of 200°C and moisture content of 0%. It was confirmed that the result shown in Fig. 6 does not depend on extrusion ratios of 44 and 16.

Fig. 6 Relationship between extrusion pressure, temperature and moisture content

4. Effects of Extrusion Conditions on Mechanical Properties of Extruded Products

The experimental results describe the case of $\alpha=16$, since the tendency there was the same as for $\alpha=44$. In addition, measurement of mechanical properties was difficult for $\alpha=400$.

4.1 Effects of extrusion pressure and temperature on bulk density of products

Figure 8 shows the effect of extrusion pressure on the bulk density of products. It is seen that the bulk density of extruded products increases with increasing extrusion pressure. However, the rate of increase in the density decreases with increasing extrusion pressure. For the extrusion pressure larger than 150 MPa, the bulk density reaches almost a constant value of $1.4 \text{ g}\cdot\text{cm}^{-3}$.

Figure 9 shows the effect of extrusion temperature on the bulk density of extruded products. The

$P=178\text{MPa}$ $T=200^\circ\text{C}$ M.C.: 0% $d: 90 \mu\text{m}$

Fig. 7 Extruded products of wood powders

Fig. 8 Effect of extrusion pressure on bulk density

Fig. 9 Effect of extrusion temperature on bulk density

density increases as the extrusion temperature increases and reaches a maximum value at the temperatures of 180°C to 200°C. The fluidity of wood powders decreases as the particle size increases. Therefore, for powders with larger particle size and lower moisture content, the temperature at which the density becomes maximum exceeds 200°C. When the temperature becomes too high, the density of products tends to decrease. This seems to be caused by the thermal decomposition of each component of wood powders.

4.2 Effect of extrusion temperature on bending strength of products

Figure 10 shows the effects of temperature, particle size and moisture content of wood powders on the bending strength of extruded products. It is seen that the bending strength tends to increase with increasing temperature and reaches a maximum value at temperatures of 170°C to 200°C. This tendency is similar to the variation of density with temperature, shown in Fig. 9.

For powders with particle size smaller than 90 μm and moisture content less than 8%, the bending strength of products becomes maximum at the temperature of 195±5°C. While, for the moisture content of 43%, the bending strength becomes maximum at 175±5°C. In this case, free water is contained in the powder, and therefore the bending strength of extruded product is lower than those for powders with less moisture content. The decrease in the bending strength of a product at a temperature higher than 200°C is caused by the thermal decomposition of wood powders. From these results, it can be concluded that an optimum extrusion temperature exists for each particle size and moisture content of wood powders.

4.3 Vickers hardness distribution

Figure 11 shows Vickers hardness distributions of

Fig. 10 Effect of extrusion temperature on bending strength

Fig. 11 Effects of temperature and moisture content on Vickers hardness

extruded products under various conditions. It is seen that the Vickers hardness is different depending on the extrusion temperature and moisture content of wood powders. Although there are some scatters in the measured values, the Vickers hardness tends to decrease at the tip of the product because of insufficient back pressure at the tip portion. It should be emphasized that the Vickers hardness of a product made by the extrusion of wood powders is about 25, which is close to that of annealed aluminum ($H_v \approx 30$).

5. SEM Observations of Surface and Fracture Surface of Products

Figure 12 shows the effect of extrusion temperature on the product surface and the fracture surface after the bending test. For case (a), the extrusion temperature of 180°C, a crack was observed on the surface of extruded product. However, for case (b), when the temperature was increased to 200°C, the size

Fig. 12 SEM observations (Effect of temperature on surface and fracture surface of products after bending test)

of cracks was reduced and the number also decreased. For case (c), when the temperature is further increased to 220°C, the trace of bubbles are observed on the surface of the extruded product. While, on the fracture surface, differences are hardly observed between (a) and (b) in which wood powders are joined strongly to each other. However, in case (c), large cracks exist on the fracture surface, and it is thought that these cracks caused the decrease in the density and the bending strength of extruded products as shown in Figs. 9 and 10.

Figure 13 shows the effect of moisture content of wood powders on the surface of extruded products. It is seen that the surface of the product becomes smooth as the moisture content increases, as shown in case (d). However, in case (e), moisture content of 43%, a trace of bubbles was observed on the product surface. On the fracture surface, the contour of each powder can not be observed, because the powders are joined together. This seems to be a reason why the bending strength of extruded product becomes maximum with a moisture content of about 10%.

As was described previously, the fluidity of wood powders becomes worse as particle size increases. Therefore, in order to enable the extrusion of the wood powders with large particle size, the extrusion temperature or the moisture content should be in-

Fig. 13 SEM observations (Effects of moisture content of wood powders)

Fig. 14 SEM observations (Effects of particle size and moisture content)

creased. Figure 14 shows the surface condition of the extruded product using wood powders with large particle size of 180–250 μm. In case (f), large particle size and no moisture content (i.e. dry condition), extrusion can be done, but the trace of bubbles appeared on the surface of the extruded product because of high temperature. In case (g), on the other hand, extrusion of wood powders with large particle size can be successfully achieved by combining the temperature of 200°C and the moisture content of 11%. The surface state and joining condition of the extruded products was very good.

6. Conclusions

The extrusion of wood powders has been successfully achieved without using any adhesives and binders made from petroleum. The effects of temperature, moisture content and particle size of wood

powders on the flow characteristics were mainly investigated. The experimental results show that the density and bending strength of extruded products increase with increasing temperature. However, the excessive heating beyond 200°C decreases these values due to the occurrence of bubbles or the burning of wood powders. The density and bending strength can be increased even at a low temperature if the moisture content of the wood powders is increased. This is attributed to the decrease in the softening temperature of lignin. The optimum moisture content is about 10%. The fluidity of wood powders becomes worse as the particle size increases. Therefore, in order to enable the extrusion of the wood powders with large particle size, the extrusion temperature or the moisture content should be increased.

The backward extrusion technique proposed by the present investigation can be used as a method to evaluate the fluidity of wood powders. And also, the results obtained will be useful as basic data for near net shape forming, such as injection molding of wood powders.

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