Impact performance of jute fabric reinforced polylactic acid composites

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Abstract

In recent years, due to the increasing importance of environmental issues, biodegradable polymers, especially polylactic acid (PLA), have attracted attention. However, their applications are limited because the impact resistance and heat resistance of PLA are lower than those of the petroleum-derived resin. The impact resistance of PLA has been the subject of research and development in injection-moulding; it can be achieved by combining PLA with short natural fibres. However, the impact resistance of PLA does not rise sufficiently as a result, thus reinforcement of PLA with continuous fibres is expected. A FRTP high speed compression moulding method using the electromagnetic induction heating system, in which it is possible to control the temperature of the mould surface, is proposed and high speed forming of FRTP using continuous fibre becomes possible. However, the impact resistance of PLA reinforced with jute continuous fibres has not been studied yet. In this study, jute continuous fibre reinforced PLA was moulded by the FRTP high speed compression moulding method, using an electromagnetic induction heating system. The effect of nucleating agents and the annealing process on their impact properties were investigated. Since this system allows control of the temperature of the mould surface, it is able to perform an annealing process during the moulding process. In this study, jute continuous fibres and PLA with a nucleating agent were used to develop high impact resistance FRTP. The impact performance of JFRTP is discussed.

Keywords: green-composite, jute fibre reinforced thermoplastics (JFRTP) natural fibre, jute fibre, PLA, non-woven fabric, electromagnetic induction.

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1 Introduction

Fibre reinforced plastics (FRPs) have been widely used in many applications, such as railway vehicles, automobile and airplanes, due to their excellence in formability and good mechanical properties [1–5]. Conventional fibre reinforced plastics cannot be biodegradable and they have the problem of being combustible [6]. In recent years, a green-composite, the natural fibre reinforced biodegradable polymer, has attracted attention [7]. For reinforcement of the green composite, natural fibres, such as bamboo fibre, ramie, flax, kenaf and jute, are used. Among these natural fibres, jute is one of the superior materials due to its low cost, large amount of production and high specific strength, and has thus gained a lot of attention [8–11]. Polylactic acid (PLA) is usually used as the matrix of the green-composite, because of its high strength, rigidity, melting point and productivity in comparison with other biodegradable resins. However, PLA has not been widely used in automotive applications due to its low impact resistance [12]. The impact resistance of PLA has been the subject of research and development; the improvement of impact resistance can be achieved by the natural fibre reinforcement. Particularly, it is preferable to use the continuous fibre as a reinforcement fibre. Moreover, there is a method of improving various characteristics with the rising of crystallinity degree of PLA by the nucleating agent and annealing process. However, the forming method that can effectively carry out the annealing process to natural fabric reinforced PLA has not been established. The annealing process of PLA has not been applied to natural continuous fibre reinforced PLA; this is due to the difficulty in controlling mould temperature during the annealing process. The authors have developed a high-speed compression moulding process of fibre reinforced thermoplastics (IH system) by means of an electromagnetic induction heating system (Cage System®) [13]. This system allows heating and cooling of the mould surface instantaneously and the mould surface can be arbitrarily controlled, so this system can be used for the annealing process. The nucleating agent is added to this PLA to enhance crystallization and the annealing process is introduced to the moulding process. However, the influence of the annealing process on impact resistance has not been studied yet. In this study, jute continuous fibre and PLA with a nucleating agent were used to develop high impact resistance FRP. The impact performance of JFRTP is discussed.

2 Materials and experimental procedure

2.1 Material

Jute plain fabric (0°/90°, fig. 1) with a weight per unit area of 370 g/m^2 was used in this study. Polylactic acid (Cargill Dow LLC) with a nucleating agent (C-PLA) was used as the matrix. It was melt-blown to a non-woven fabric (Kuraray Co. Ltd, fig. 2) with a weight per unit area of 50 g/m^2. In this study, the fibre volume fraction of the specimens was set at 50%. The thickness of the specimens

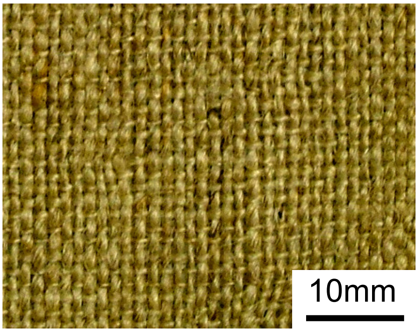

Figure 1: Jute plain fabric.

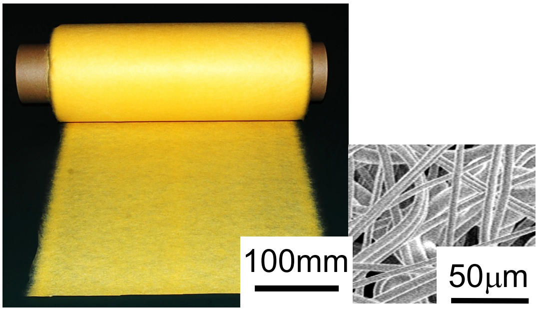

Figure 2: C-PLA non-woven fabrics.

was set at 2.8 mm. To compare the impact properties of the JFRTP composite and the matrix resin, a C-PLA specimen was moulded with an injection moulding machine (ET-40v, Toyo Machinery & Metal Co. Ltd).

2.2 Mould process

Specimens were moulded by the high-speed compression moulding method (to be referred to as the IH system) using an electromagnetic induction heating system (Roctool Co. Cage System®). Fig. 3 shows the mould for the IH system [14]. When an electrical current runs through an inductor, a magnetic field is generated. This magnetic field penetrates the mould placed inside the inductor, and creates induced currents on the mould surface. Since the current flow concentrates within the mould surface by the shin effect, only the mould surface is heated by the Joule effect. The mould surface is cooled by cooling water flowing through pipes located directly under the mould surface. The traditional hot press method heats up the mould completely, while the IH system heats up only the mould surface. As a result, the thermal capacity decreases and the IH system allows cooling of the mould surface instantly. The heating process is complete in only 40 s from 50°C to 190°C. If an electrical current supplied by the coil is adjusted properly, the temperature of the mould surface can be controlled easily. Moreover, the annealing process can be carried out easily, and the overall moulding time, including the annealing process, is shortened.

2.3 Moulding condition

The moulding conditions of the specimens are listed in table 1. The moulding temperature was set at 190°C and the moulding pressure was set at 3 MPa. The temperature of the mould surface was heated up to 190°C and maintained for 60 s, then cooled down to 50°C for the J/C0 specimen. For the J/C60, J/C120 and J/C600 specimens, the annealing process with the crystallinity temperature at 100°C was introduced after the moulding process. Fig. 4 shows an example of the temperature history of the mould surface during the moulding and annealing process.

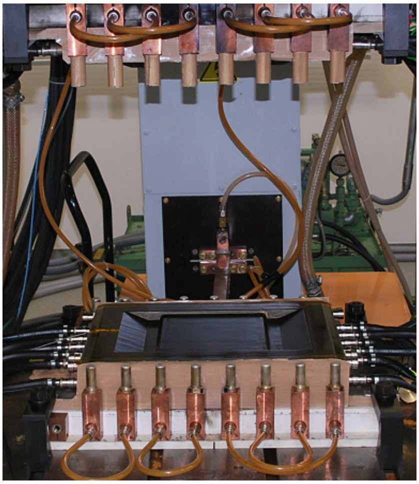

Figure 3: Mould for the IH system (Cage system® Roctool Co.).

Table 1: Moulding conditions.

Specimens	Moulding pressure (MPa)	Temperature (ºC)	Holding Time (s)	Annealing temperature (ºC)	Annealing time(s)
J/C0	3	190	60	100	0
J/C60					60
J/C120					120
J/C600					600

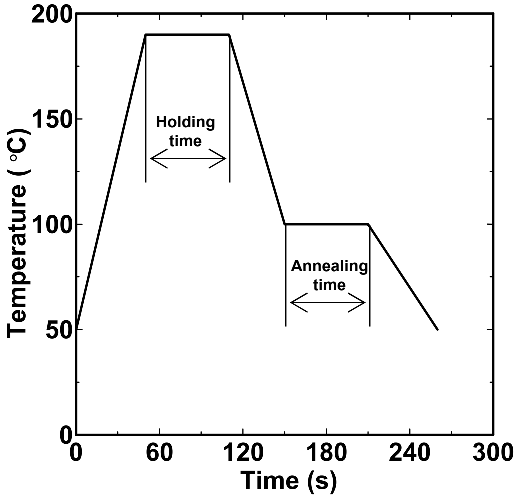

Figure 4: Temperature history of the mould surface.

3 Mechanical testing

3.1 Impact tests

A Charpy impact test was conducted with a pendulum of 4.9 J energy. The test specimens were cut out from the moulded parts using the water jet technique. The length and width of the specimens were 70 mm and 10 mm, respectively. The support span of the specimens was set at 40 mm and unnotched specimens were used.

The crystallinity degree of the PLA was measured by a Differential Scanning Calorimeter (DSC-60, Shimadzu Co.). The dynamic measurements were made at a constant heating rate of 10°C /min to 200°C. The crystallinity degree of PLA was calculated by the following equation

$$Xc(\%) = \frac{\Delta_H}{94} \times 100 \quad (1)$$

Cross sections and fractured surfaces of the specimens were observed by SEM (JSM-6390LT, JEOL Ltd.) in order to investigate the resin impregnation and fracture morphology. The void content of the specimens was measured by X-ray μCT (SMX-160CTS, Shimadzu Co.).

3.2 Three-point bending tests

Three-point bending tests were conducted by a universal material testing machine INSTRON 5566, following the recommended testing procedures as described in JIS-K7017. The test specimens were cut out from the moulded parts using the water jet technique. The length and width of the specimens were

60 mm and 15 mm, respectively. The support span of the specimens was set at 40 mm. The load was applied to the specimens at a displacement rate of 0.02 mm/s (1 mm/min).

4 Results and discussion

4.1 Impact performance

Fig. 5 shows the results of the impact tests for jute/C-PLA composites and C-PLA. Since the impact resistance of the J/C0 composite is higher than the impact resistance of C-PLA, the reinforcement with jute fibre appears to increase the impact resistance. Moreover, the impact resistance of jute/C-PLA composite increased drastically when it is subjected to 120 s of annealing time. Therefore, it is evident that the annealing time had influenced the impact resistance of the jute/C-PLA composite.

Fig. 6 shows the relationship between the annealing time and crystallinity degree of C-PLA. Fig. 7 shows the relationship between the crystallinity degree of C-PLA and the impact resistance of jute/C-PLA composites. As the annealing time becomes longer, the impact resistance and the crystallinity degree of C-PLA become higher. The fractured surface of the J/C0 specimen observed by SEM is shown in fig. 8. Pull-out of the fibre bundle was observed and pulled out fibre bundles were observed for all other specimens moulded under different conditions. Cross sections of the specimens observed by SEM are shown in fig. 9. A lot of voids were observed in specimens J/C0 and J/C60. However, voids were hardly observed in J/C120 and J/C600. It is considered that voids are caused in the cooling stage, due to the contraction percentage of jute fibre and PLA being different. Fig. 10 shows the results of the void fraction for jute/C-PLA composites. The void contents of J/C60 and J/C0 are 6.3% and 6.4%,

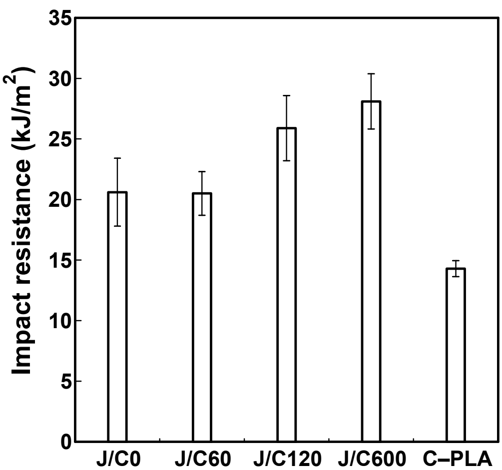

Figure 5: Impact resistance of JFRTP and C-PLA.

those of J/C120 and J/C600 are relatively small, showing values from 2 to 4%. When the annealing time becomes longer, void content decreases as the pressure is applied during the cooling and the annealing time. The contact area of the fibre bundle and the resin increases when the void rate becomes small. Since the frictional drag increases when the fibre bundle is pulled out, it is considered that the absorption energy increases for specimens with longer annealing time.

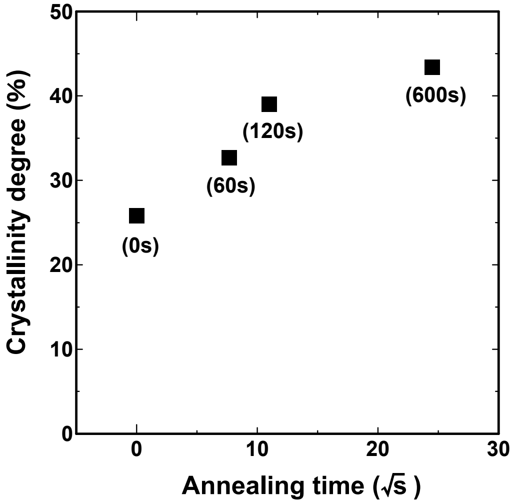

Figure 6: Relationship between annealing time and crystallinity degree.

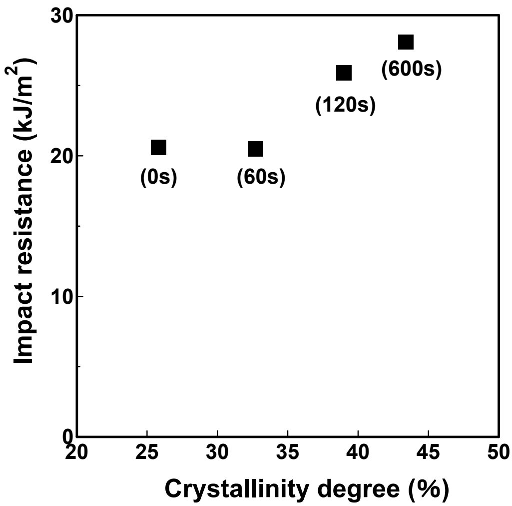

Figure 7: Relationship between crystallinity degree and impact resistance.

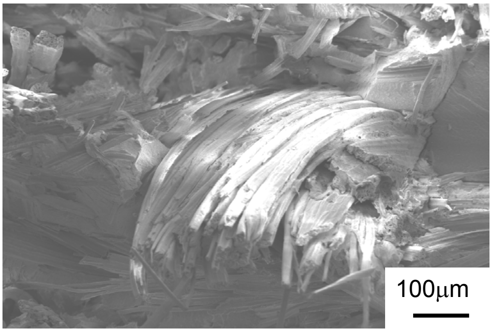

Figure 8: SEM observation of the fractured surface.

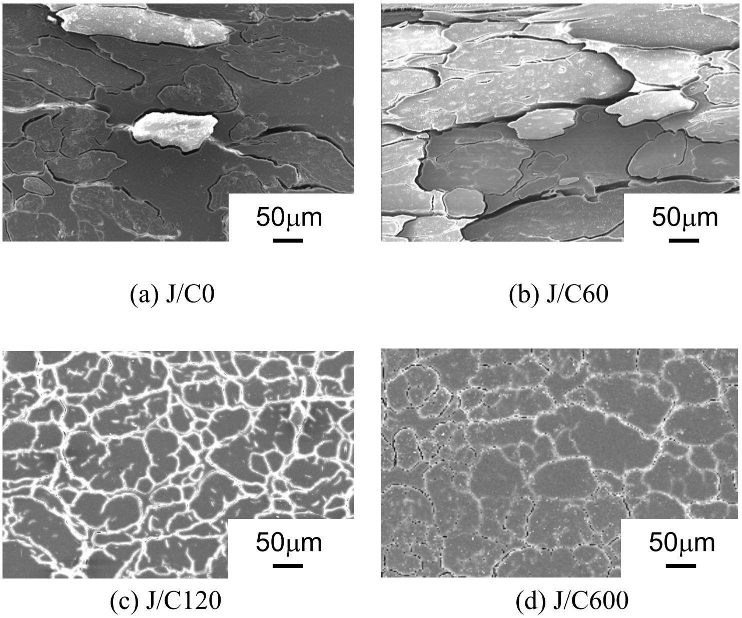

Figure 9: SEM observation of the cross section.

4.2 Bending properties

Fig. 11 shows the bending strength for the jute/C-PLA composite obtained by a three-point bending test. The bending strength of the jute/C-PLA composite is higher than the bending strength of C-PLA due to its reinforcement with jute fibres. Fig. 12 shows the load-displacement curves of jute/C-PLA and C-PLA. The bending moduli of J/C0 and C-PLA are 5.5 GPa and 2.9 GPa, respectively. The bending modulus of jute/C-PLA was enhanced by fibre reinforcement.

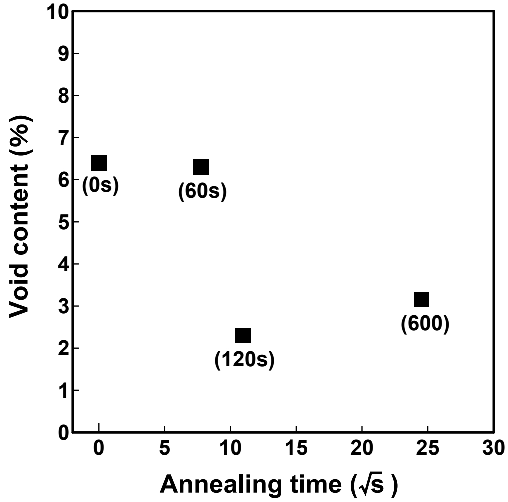

Figure 10: Relationship between annealing time and void content.

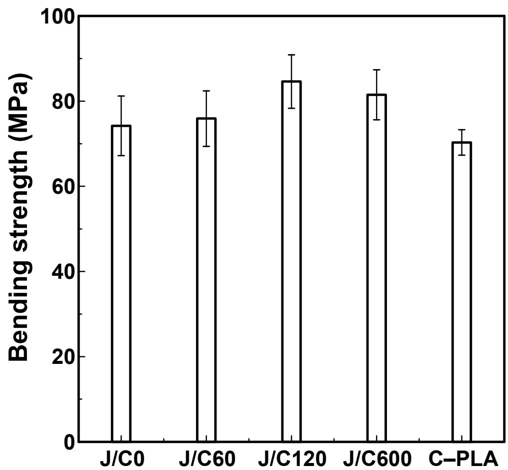

Figure 11: Bending strength of JFRTP and C-PLA.

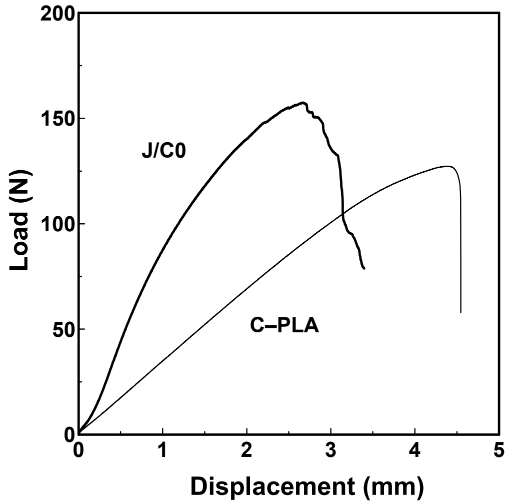

Figure 12: Load-displacement curves of JFRTP and C-PLA.

5 Conclusions

In this study, jute continuous fibre and PLA with a nucleating agent were used to develop high impact resistance JFRTP. The impact performance and bending properties of JFRTP were discussed. The investigation leads to the following conclusions:

1. As the annealing time becomes longer, the crystallinity degree of C-PLA is improving.
2. As the annealing time becomes longer, the impact resistance of JFRTP is improving, due to the smaller void content.
3. The impact resistance and bending modulus of C-PLA improve by the reinforcement with jute continuous fibres.

Acknowledgements

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