HIGH SPEED MOULDING OF CARBON FIBER REINFORCED PLASTIC BASED ON NON-WOVEN STITCHED MULTI-AXIAL CLOTH USING INDUCTION HEATING SYSTEM

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SUMMARY

High speed moulding process of Carbon Fibre Reinforced Thermoplastics using induction heating system in combination with non-woven stitched multi-axial cloth (NSMC) was proposed. NSMC is a novel semi-product, in which non-woven fabric plays a supporting material of non-crimp stitched fabric and at the same time will be the matrix of composites.

Keywords: CFRTP, Thermoplastics, Electromagnetic induction, Induction heating, non-woven stitched multi-axial cloth (NSMC), Carbon fibre, Polyamide 6, Compression moulding

INTRODUCTION

CFRP is expanding its demand in the aerospace industry owing to its specific strength and specific stiffness. Within the automotive industry, in order to solve the problems including the draining up of fossil fuels and global warming resulting from CO_2, it is indispensable for mass production vehicle bodies to become more light-weight, and the development of low cost CFRP materials and low cost moulding method are in demand[1,2].

When using CFRP at mass-produced automobiles, in order to make good use of the high strength of carbon fibers sufficiently continuous fibers should be used in the composites. For matrix, the use of thermoplastic that excels in recyclability and productivity is required [3]. For the methods of supplying thermoplastic matrix to continuous fibers, film-stacking method, powder impregnated method [4,5], commingled yarn prepreg method[6,7], cowoven fabric method[8] and other various methods have been used. To overcome the problem of the material handling and manufacturing cost for mass production, however, the suitable thermoplastic semi-product is expected to be developed.

Furthermore as for the moulding method of the continuous fiber reinforced thermoplastics, method such as the hot press compression has been considered. In mass production situations, however, due to the extended time needed for pre-heating and cooling of the moulds and materials, the pre-heating equipment and multiple tooling moulds are necessary. Therefore the development of an applicable moulding method for mass production is expected to be developed. For the high-speed temperature raising process, there is the electromagnetic induction heating method that is being applied in heat treatment of metal materials. This high-speed processing using electromagnetic induction is a technology that is using the high-frequency alternating current to create a skin effect onto the inductor's surface; and the surface is heated by the eddy current that is concentrating in the surface. In processing of composite material, using such high heating responsiveness, the heating of the nozzle part and nesting in injection process [9,10], the welding of the thermoplastic composite [11], the heating devices for compression moulding [12], etc are being applied.

In this study, firstly thermoplastic semi-product using continuous carbon fibers, the non-woven stitched multi-axial cloth (NSMC), is developed. By using this semi-product and induction heating compression system (IH system), high speed compression moulding process of carbon fiber reinforced thermoplastic (CFRTP) is proposed. From the evaluation of the mechanical properties of such processed specimen, the advantageous of the CFRTP manufactured by the NSMC and the IH system is discussed.

DEVELOPMENT OF NON-WOVEN STITCHED MULTI-AXIAL CLOTH

The non-crimp stitched fabric (NCF, multi-axial multi-ply fabric: MMF) has been developed for the purpose of being used in the aerospace industry [13]. The composite products using NCF for its reinforced fiber has been reported to have better mechanical properties than the fundamental textile materials [14-16].

For the methods of supplying thermoplastic matrix to continuous fibers, film stacking method and other various methods have been used. To overcome the problem of the material handling and manufacturing cost for mass production, however, the suitable thermoplastic semi-products is expected to be developed. In previous research of Jute fiber reinforced PLA thermoplastic composite, the authors proposed the manufacturing process using non-woven fabric as the matrix for composites instead of films [17]. The non-woven fabric has a superior advantage for matrix in drapability, non-dusted materials and easy handling, and allows easy controlling of resin amount. However, we still have the same complexity problem in material handling as the film stacking method when manually layering the reinforced fiber with the matrix in shape of non-woven fabric together.

In order to eliminate the manual layering procedure, thermoplastic semi-product: the non-woven stitched multi-axial cloth (NSMC, Benny-Toyama Co. Ltd., Japan), which is using the non-woven fabric for matrix shown in Fig. 1 is developed [18]. NCF and non-woven fabric are stitched together at the same time in the manufacturing process of NCF and they are supplied in one single sheet. NSMC has not only a advantages of NCF, such as fewer directional disorder of fibers and so on, but also the advantages of non-woven fabric in terms of cheaper manufacturing cost, easy handling and drapability. Furthermore, NSMC has the advantage of supporting the NCF not to disorder during the handling of semi-product. Thus NSMC is said to be an semi-product of lower manufacturing cost for CFRTP.

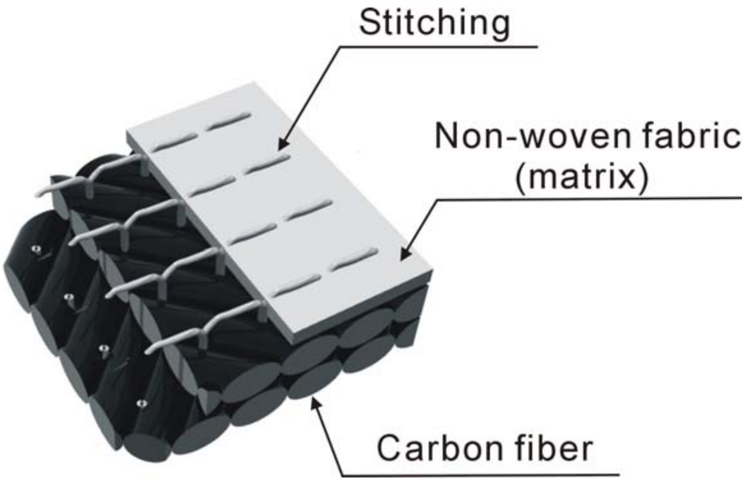

Figure 1 Non-woven Stitched Multi-axial Cloth (NSMC).

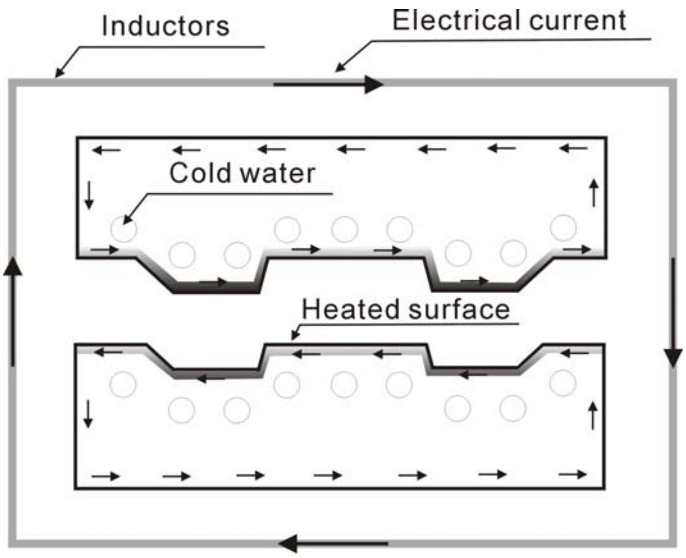

Figure 2 Schematic drawing of induction heating system.

HIGH SPEED MOULDING USING INDUCTION HEATING SYSTEM

Compression Moulding using Induction Heating System

For moulding process, high-speed processing using electromagnetic induction (IH system) developed by Roctool Co. (Cage System®) was used. Fig.2 shows the current flow of Cage System. When an electrical current runs through an inductor, a magnetic field will be generated. The magnetic field penetrates the mould placed inside the inductor, and creates induced currents on the mould surface. Since the current concentrates within the mould surface, the mould surface generates heat by the Joule effect. This high-speed processing allows heating of only the mould surface by the skin effect, instantaneously. Furthermore, it is possible to cool the moulding down by flowing through cooling water to a cooling pipe within the mould.

Moulding Conditions

For the processing of CFRTP, the mechanical characteristics of both moulding products by the IH system (shown in Fig. 2) and by the traditional hot press system equipped with vacuum functions are being compared. The moulding conditions are shown in Table 1, the moulding pressure was set at 2 MPa or 4MPa and the moulding temperature was set at 250 °C. As for the semi-product, NSMC shown in Fig.1 was used and two types of multi-stacking sequences $[+45°/-45°]_{3S}$ and $[0°/+45°/90°/-45°]_{2S}$ had been processed. The composition of the NSMC used in this research as shown in Table 2, for the non-woven fabric for matrix, the non-woven fabric that has been produced by the melt blown method with Polyamide 6 is adopted. The non-woven fabric and NSMC are stacked to become a fiber volume fraction of 50% and a moulded thickness of 2 mm.

When applying the IH system, the material is placed on the mould and the mould is closed. After applying the pressure, the temperature of the mould is raised up to 250 °C; with the hold time being kept constant, it cools down to 50°C. When applying to the hot press system, the temperature of the mould is preheated and remains constant at 250 °C; after the material is put in place and being pressed. After the hold time at maximum temperature, the products are then taken out from the mould and are cooled down naturally.

Table 1 Moulding conditions of the specimens.

<table>
<tr><th>Specimen</th><th>Hold time (s)</th><th>Forming method</th><th>Stacking sequence</th><th>Pressure (MPa)</th><th>Temperature (°C)</th></tr>
<tr><td>A-1</td><td>0</td><td rowspan="8">IH system</td><td rowspan="5">$[+45°/-45°]_{3S}$</td><td rowspan="12">2</td><td rowspan="13">250</td></tr>
<tr><td>A-2</td><td>10</td></tr>
<tr><td>A-3</td><td>20</td></tr>
<tr><td>A-4</td><td>30</td></tr>
<tr><td>A-5</td><td>60</td></tr>
<tr><td>B-1</td><td>0</td><td rowspan="3">$[0°/+45°/90°/-45°]_{2S}$</td></tr>
<tr><td>B-2</td><td>30</td></tr>
<tr><td>B-3</td><td>60</td></tr>
<tr><td>C-1</td><td>120</td><td rowspan="5">Hot press</td><td rowspan="2">$[+45°/-45°]_{3S}$</td></tr>
<tr><td>C-2</td><td>300</td></tr>
<tr><td>D-1</td><td>120</td><td rowspan="3">$[0°/+45°/90°/-45°]_{2S}$</td></tr>
<tr><td>D-2</td><td>300</td></tr>
<tr><td>E-1</td><td>300</td><td>4</td></tr>
</table>

Table 2 Composition of NSMC.

	±45°	0°/+45°/90°/-45°
Carbon fiber (g/m^2)	330	500
Nylon 6 (g/m^2)	200	150

Temperature History of Moulds

In order to compare the temperature of the mould surface within the IH system and the hot press system, the temperature of the mould surface at the time of processing was measured. The temperature history of mould surface is shown in Figs. 3 and 4. During the temperature raising process, for the hot press system to get its mould temperature raised up to 250 °C from 50 °C approximately 50 minutes is needed; while the IH system only needed approximately 70 seconds to reach 250 °C. Furthermore, the cooling of IH system only took approximately 150 seconds. It is considered that in order to heat up the hot press mould completely the heat capacity is huge and as a result the heating needs enormous energy and time. On the other hand, the heat capacity of the IH system for heating up the mould surface is small and it is capable of reheating and cooling at short time frame. As per abovementioned, when applying the IH system, it is not necessary to preheat the material, and it is capable of speedily heating up and cooling down with the material being kept within the mould; so it is said to be a suitable processing method for mass production of the thermoplastic composite.

Heating Feature of Carbon Fiber by Induction Heating System

Since IH system uses the electromagnetic induction for heating up the mould, electrically conductive carbon fiber itself may be heated by electromagnetic induction effect. The typical non-conductive materials of glass fiber, aramid fiber and jute fiber and electrically conductive carbon fiber are placed in a Teflon box and it is placed on the mould of IH system and hot press system. The temperature of these fibers is measured using a thermocouple under the same processing condition of processing of composites.

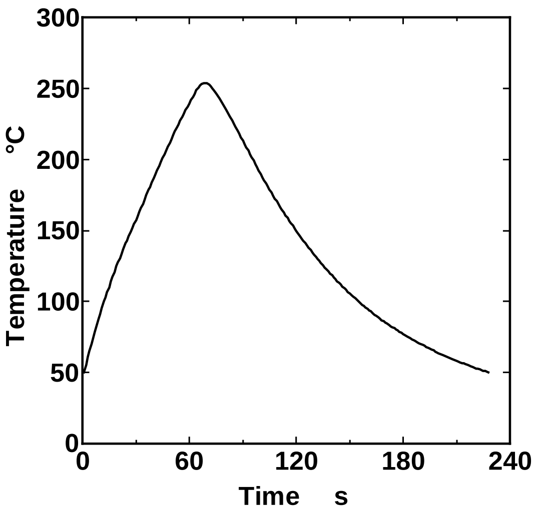

Figure 3 Temperature history of mold surface (IH system).

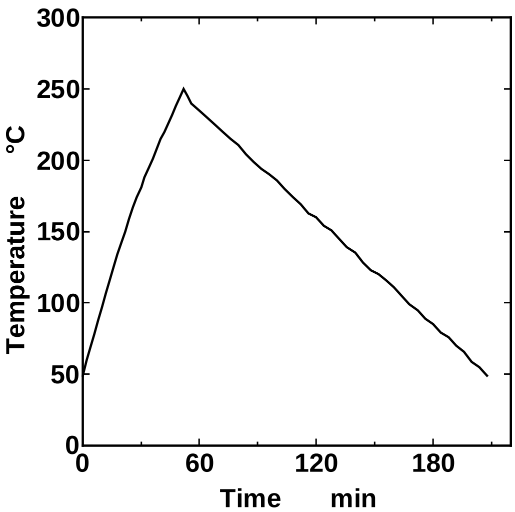

Figure 4 Temperature history of mold surface (Hot press).

The temperature testing result of the carbon fiber and the inner surface of the Teflon box within the mould for IH system and hot press system is shown in Fig. 5. The temperature of carbon fiber within the IH system is higher than the temperature of the inner surface of the Teflon box, whereas for the hot press system the temperature of the carbon fiber is lower than the inner surface of the Teflon box. For the hot press system, the Teflon box was heated by the mould surface and heat transferred to the carbon fiber in the box. As for the IH system, however, in addition to the heat transfer from the mould the carbon fiber is self-heated by the electromagnetic induction effects. Therefore, the temperature of carbon fiber is higher that of the temperature of Teflon box.

Fig. 6 shows the result of the temperature history to each fiber within the IH system mould. For carbon fiber that is electrically conductive, the temperature is higher than the inner surface of the Teflon box; and for non-conductive glass fiber, aramid fiber and jute fiber, the temperature is lower than the inner surface of the Teflon box. Based on this result, it is clear that carbon fiber that is electrically conductive generates heats by electromagnetic induction effects.

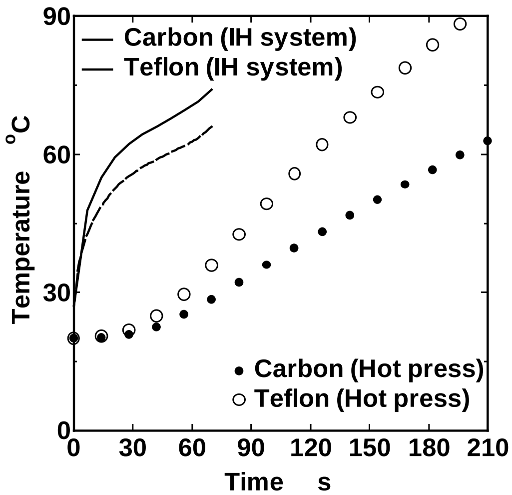

Figure 5 Temperature history of carbon fiber and Teflon box.

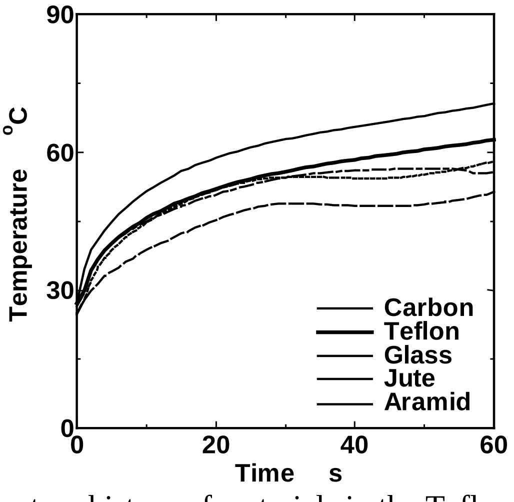

Figure 6 Temperature history of materials in the Teflon box (IH system).

MECHANICAL PROPERTIES BY BENDING TESTS

Specimens and Experimental Procedure

According to the previously mentioned methods the moulded compositess are cut by the water jet in size of 60 mm × 15 mm for $[+45°/-45°]_{3S}$ and in size of 80 mm × 15 mm for $[0°/+45°/90°/-45°]_{2S}$ as bending test specimens. Three point bending test is conducted following the test procedure described in JIS-K7017 by using the Instron testing machine (Instron 5566). The displacement rate is at 1.6×10^{-2}mm/s (1mm/min) and the tests are carried out in the air at the laboratory's room temperature. The specimen thickness is at 2mm.

The void contents X_v is calculated by substituting the moulded material's theoretical density and the actual tested density into the following formula.

$$X_v = \frac{\rho_{th} - \rho_{meas}}{\rho_{th}} = 1 - \frac{\rho_{meas}}{\rho_{th}}$$

Here ρ_{th} represents the theoretical density and ρ_{meas} represents the actual tested density.

Experimental Result and Discussions

Figs.7 and 8 shows the results of bending tests. Regardless of the layered composition, for the specimen manufactured by IH system 30 seconds of the temperature holding time is the enough time for resin to impregnate in carbon fabrics and over 30 seconds the bending strength is almost constant. On the contrary, the specimen moulded by the hot press system with the moulding pressure at 2 MPa and regardless of the hold time, only low bending strength is recognized. As shown in the specimen E-1, if the moulding pressure is at 4 MPa and the hold time is at 300 seconds, it is capable of achieving the same level of bending strength as specimen B-2 and B-3 that used the IH system.

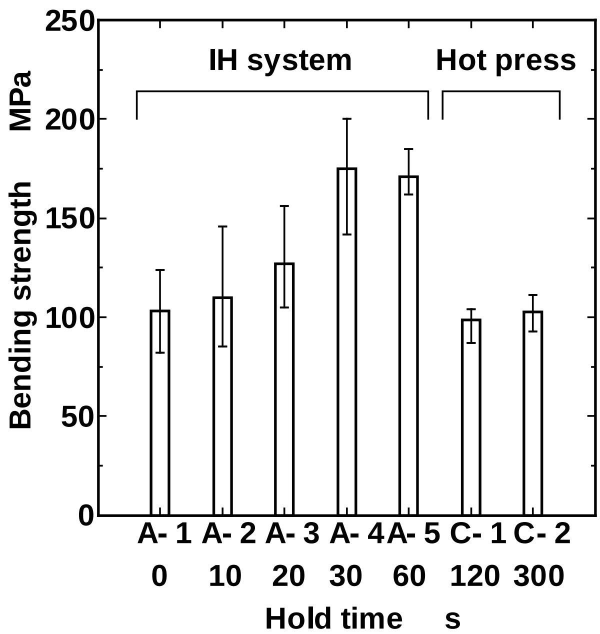

Figure 7 Bending strength of CFRTP ($[+45°/-45°]_{3S}$, Specimen A and C).

Fig. 9 shows the relationship between the void content of the specimen to the bending strength. Whichever the layered composition is, it is clear that when the void content drops the bending strength raises. The specimens in $[0°/+45°/90°/-45°]_{2S}$ moulded by IH system has 550 MPa of bending strength and the void contents was lower than 5%.

From the above result, when using the IH system due to the heated carbon fiber by electromagnetic induction good resin impregnation can be achieved in lower processing pressure and shorter period of time than the traditional hot press system. Therefore IH system is said to be a suitable processing method for CFRTP.

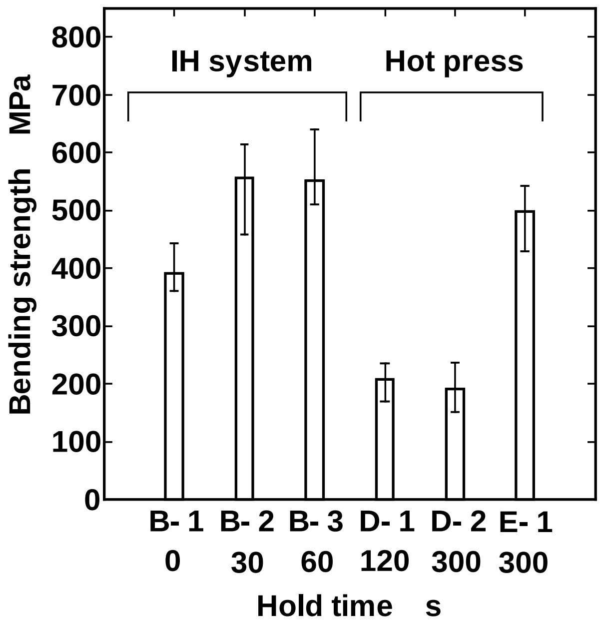

Figure 8 Bending strength of CFRTP ($[0°/+45°/90°/-45°]_{2S}$, Specimen B, D and E).

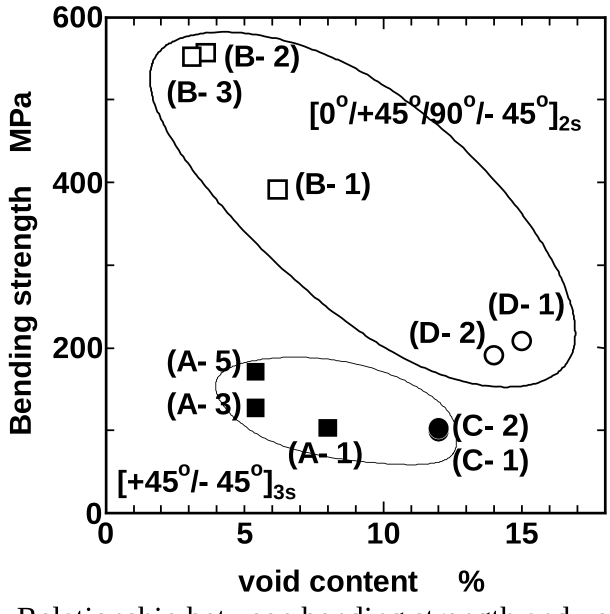

Figure 9 Relationship between bending strength and void contents.

CONCLUSION

As an semi-product of Carbon Fibre Reinforced Thermoplastics (CFRTP), Non-woven Stitched Multi-axial Cloth (NSMC) that uses continuous carbon fiber is developed. High speed moulding process of CFRTP based on NSMC using induction heating system was proposed. From the evaluation of the mechanical properties of the processed composites, the superiority of the processed CFRTP by using the NSMC together with IH system is examined. The investigation yielded the following conclusions:

1) NSMC is the semi-product for CFRTP, having the good mechanical properties of NCF and advantage of non-woven fabric as matrix in material handling, manufacturing cost and drapability.

2) IH system requires little thermal capacity when heating the surface of the mould and it can shorten the moulding cycle drastically in comparison to the hot press method.

3) According to the electromagnetic induction effects, not only the mould but also the carbon fiber itself was heated by induced current; making it possible to generate heating from within materials.

4) When using the IH system due to the heated carbon fiber by electromagnetic induction good resin impregnation can be achieved in lower processing pressure and shorter period of time than the traditional hot press system. IH system is said to be a suitable processing method for CFRTP.

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