Heating properties of carbon fibers subjected to direct resistance heating

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Abstract

To mold carbon fiber reinforced thermoplastics (CFRTP), it is necessary to impregnate carbon fiber with thermoplastic resin by heating the materials. Electromagnetic induction heating and direct resistance heating are available heating methods. The electromagnetic induction heating has a high production cost because of the complex equipment used. In contrast, the direct resistance heating is performed with a simple piece of equipment and low power consumption. It is thus better to use direct resistance heating for low-cost CFRTP molding. A process of CFRTP molding is here proposed using direct resistance heating of carbon fibers in non-crimp fabric (NCF). The resistance heating characteristics of NCF and the influence of resistance heating upon mechanical properties of carbon fibers are discussed. The temperature distribution in 0° and 90° layers were found sufficient and it took 70 s to reach 250°C in the temperature history when heat is applied to the NCF [0°/90°] using direct resistance heating. From the results of tensile tests of a single carbon fiber, the tensile strength did not decrease by resistance heating at 300°C for 300 s.
Keywords: carbon fiber, non-crimp fabric, direct resistance heating.

1 Introduction

In the automobile industry, it is necessary to reduce the weight of cars for better fuel consumption economy. In recent years, carbon fiber reinforced plastics (CFRP) are expected to be used for lightweight component parts [1]. The application of CFRP will make it possible to reduce car weight, because CFRP has a higher specific strength and specific rigidity than conventional lightweight materials such as high strength steel and aluminum alloys [2]. However, with

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CFRP, the issues of high cost and low recycling of thermosetting resins arise; therefore CFRP is used only in non-mass-produced cars.

The use of thermoplastic resin as matrix in carbon fiber reinforced thermoplastics (CFRTP) is expected. This is due to CFRTP being better with regard to recyclability and productivity than CFRP. Therefore CFRTP is suitable for mass-produced car parts [3]. In order to make effective use of mechanical properties of carbon fibers, it is necessary to use continuous fibers as the reinforcing material. Semi products with continuous fibers are the non-crimp fabric (NCF) and the fabric as continuous fibers, however NCF is superior to latter in strength. NCF with non-woven cloth was developed as semi product for CFRTP, because it is superior in terms of production cost and handling of materials.

In the molding of CFRTP with the semi product which consists of carbon fiber NCF and non-woven cloth, it is necessary to impregnate carbon fiber NCF with thermoplastic resin by heating the semi product. Electromagnetic induction heating and direct resistance heating are available heating methods. When an electrical current runs through a coil around a mold, a magnetic field will be generated. The magnetic field penetrates the mold placed inside the coil and creates induced currents on the mold surface. Since the current concentrates within the mold surface, the mold surface generates heat according to the joule heating [4]. However, the facilities for efficiently inducing current become complicated and the equipment cost is high. Direct resistance heating is a heating method that may resolve these issues. When an electrical current runs through the materials, it will be heated by joule heat. Therefore this method can run with simple equipment and low power consumption. This heating method already has been applied for metal heating and CFRTP welding [5–7]. By using direct resistance electrical heating through the materials, an efficient molding process of CFRTP can be achieved.

In this study, the heating properties of carbon fiber NCF were evaluated for the development of a CFRTP molding technique using direct resistance heating. To clarify the heating properties of carbon fibers by direct resistance heating, temperature uniformity and history was evaluated. Single carbon fibers were obtained from NCF heated by direct resistance heating. The mechanical characteristics of single carbon fibers were assessed by tensile testing.

2 Direct resistance heating characteristics of carbon fibers

2.1 Materials and experimental methods

The non-crimp stitched carbon fabric of [0°/90°] with a weight per unit area of 300 g/m^2, made of PAN-based carbon fibers, was used. Specimens with dimensions of 100 mm in length and 25 mm in width were cut from this carbon fiber NCF.

In order to compare the temperature distributions and histories of both sides of the NCF with 0° and 90° orientation during direct resistance heating of the NCF, temperature distributions and histories of each surface were observed.

Fig. 1 shows a schematic drawing of the temperature distribution measurement. Both 10 mm ends of the carbon fiber NCF were fixed with clips and connected to the high-frequency power supply (T162-6014AAH, THAMWAY, JAPAN) using cables. The power was supplied to the carbon fiber NCF through an impedance converter (T010-6012A, THAMWAY, JAPAN). With regard to the conditions, the frequency was 20 kHz and the impedance ratio was power:load = 9:1. When the temperature distribution of the layer at 0° orientation had reached 250°C, the temperature distribution of both layers was observed using infrared thermography (TVS-500, NEC Avio, JAPAN). When the specimens were cut from carbon fiber NCF, fibers with both end parts against fibers of 0° orientation might be cut. In order to investigate the effect of fracture of fibers at 0° orientation on the temperature distribution, the temperature distribution of a specimen with 5 mm width with fibers at 0° orientation in the central area being cut out was measured (as shown fig. 2).

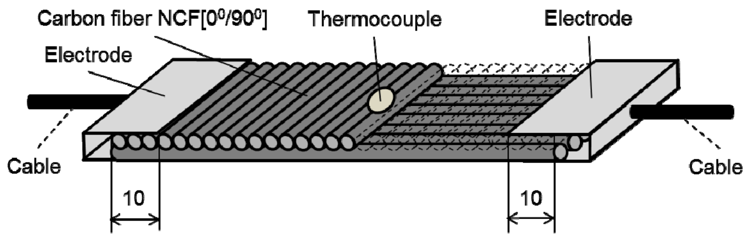


Figure 1: Schematic drawing of temperature distribution measurement.

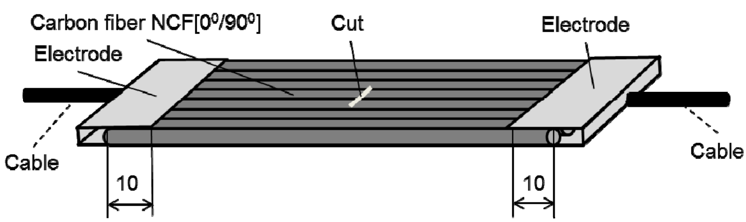


Figure 2: Schematic drawing of temperature distribution measurement with central area cut.

The current might not flow to 90° layer in comparison to 0° layer. In order to investigate the effect of 90° orientation with respect to the electrodes on the temperature distribution, the temperature distribution with the fibers of 90° orientation not connected to the electrodes was measured (as shown fig. 3).

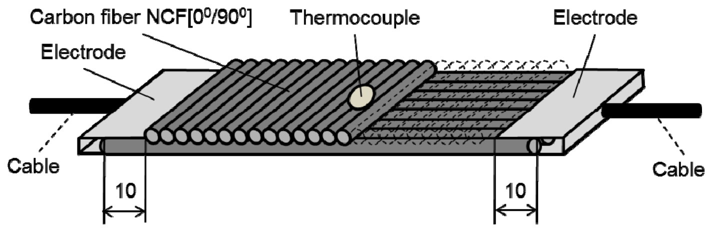


Figure 3: Schematic drawing of temperature distribution measurement without connecting 90° fibers to the electrodes.

Heating rates were measured between each of the NCF heated by direct resistance heating. Fig. 4 shows schematically the method and the thermometric points (1–3) in the NCF heating experiment. NCF laminated to $[0°/90°]_{2S}$ was used. Direct resistance heating was applied in the same way as in the temperature distribution measurements. K-type thermocouples were fitted in between the laminated NCF. The heating rates were measured with thermocouples and recorded per second with graphic recorder (OMRON Co. Ltd., Japan). The direct resistance heating was stopped, after the temperature of the carbon fiber NCF had reached 250°C. In addition, the NCF was naturally cooled to room temperature. When CFRTP is molded, non-woven fabrics that are insulated are sandwiched in between the NCF. In order to simulate CFRTP molding, Teflon sheets that have heat resistance and insulation properties were sandwiched between the NCF in this experiment. From the results including the heating rates of each layer, the adaptation of CFRTP molding using direct electrical resistance heating was considered.

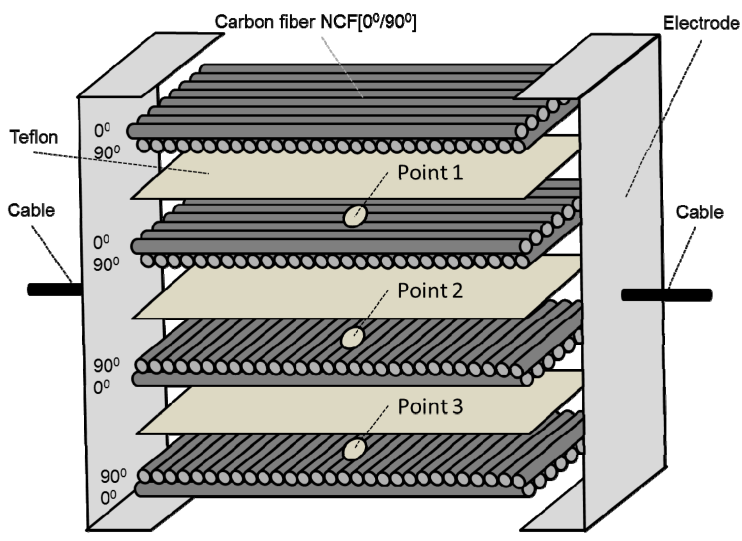
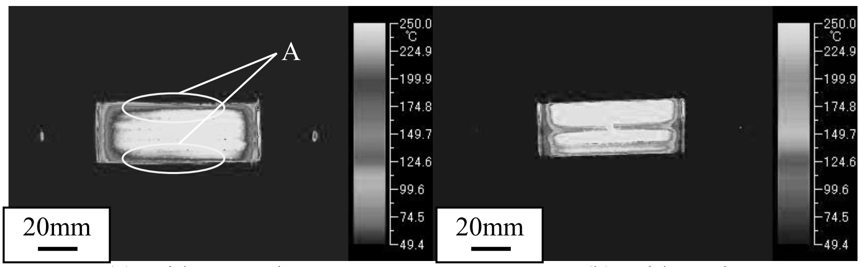


Figure 4: Schematic method and thermometric points (1–3) in the experiment of NCF heating.

2.2 Results and discussion

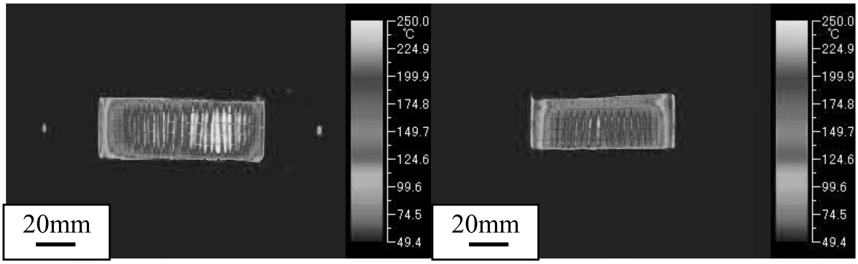
Fig. 5 shows the temperature distribution in the 0° layer, when the central area of that layer reached 250°C. From fig. 5(a), it is evident that the central area of the 0° layer was uniformly heated to 250°C. It was confirmed that direct resistance heating could heat carbon fibers NCF. However, fig. 5(a) shows that the temperature of both end areas against fibers of 0° orientation, designated A areas in fig. 5(a), was lower than in the central area, because there were areas of fibers of 0° orientation being cut when the carbon fiber NCF was cut to the dimension of the specimen. This was caused by the current not flowing in the A areas of 0° layer, therefore the temperature of end areas of 0° layer could not reach 250°C. This is confirmed by fig. 5(b) showing that the temperature distribution of 0° layer with 5 mm width of fibers at 0° orientation in the central area being cut out was similar to that of fig. 5(a).



(a) Without cutting. (b) With cutting.

Figure 5: Temperature distribution in 0°orientation layer.

Fig. 6 shows the temperature distribution of 0° layer when the central area of the 0° layer reached 250°C. The temperature of the 90° layer was lower than that of 0° layer as shown in fig. 6(a). The current flowed to the fibers of 0° orientation between the electrodes and the temperature rose due to heat generated by joule heating of carbon fibers. The current could not flow to the fibers of 90° orientation between the electrodes, therefore the temperature of 90° layer was lower than that of 0° layer. However the temperature of 90° layer reached 250°C. It was reported that the electric conductivities of the 0° and 90° layer are $5.50\times10^3\ \Omega^{-1}m^{-1}$ and $2.04\times10^2\ \Omega^{-1}m^{-1}$, respectively, in CFRP that its content rate is 0.621 [8]. Therefore, the current flow in 90° layer is less than that of the 0° layer. In addition, the temperature distribution of the 90° layer where fibers of 90° orientation were not connected to the electrodes, shown fig. 6(b), was similar to that of fig. 6(a). Fig. 7 shows the temperature histories of both layers of NCF [0°/90°] when the fibers of 90° orientation were connected to the electrodes and those with fibers not connected to the electrodes. The 90° layer was heated at lower temperature than the temperature of the 0° layer. The temperature of the 90° layer was increased gradually, with the temperature of the 0° layer held at 250°C. Therefore, the 90° layer was heated by heat transfer from the 0° layer and its temperature does not reach the temperature of 0° layer.



(a) 90° fibers connected to the electrodes. (b) 90° fibers not connected to the electrodes.

Figure 6: Temperature distribution in 90° orientation layer.

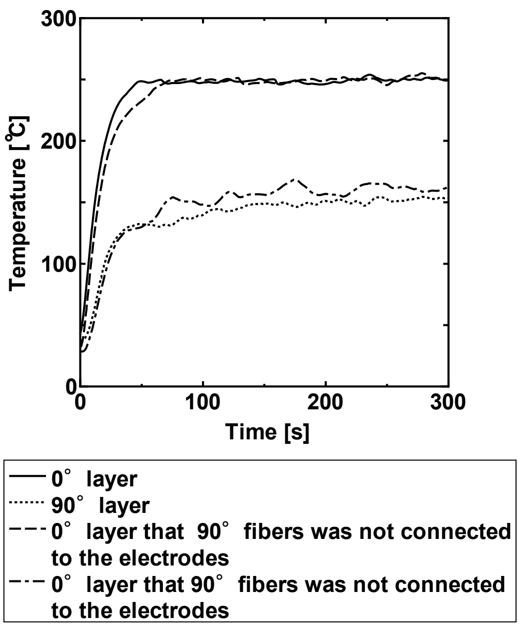


Figure 7: Temperature history of NCF [0°/90°].

Fig. 8 shows the temperature history of NCF $[0°/90°]_{2S}$ heated using direct resistance heating. From fig. 8, it is evident that there was no difference in the heating rates of each layer. In addition, it took 70 s to reach 250°C as the temperature of each layer rises. From the results, it is evident that the heating rate from the direct resistance heating is equivalent to that of the electromagnetic induction heating system [4]. In addition, there were no differences between temperature histories of each layer due to fiber orientation as shown in fig. 8. Therefore, each layer can be heated to the same temperature and at the same heating rate due to 90° layer being sandwiched between 0° layers in CFRTP molding applying direct resistance heating to carbon fiber NCF. In addition, it is possible to prevent lack of impregnation of the matrix due to difference in fiber orientation.

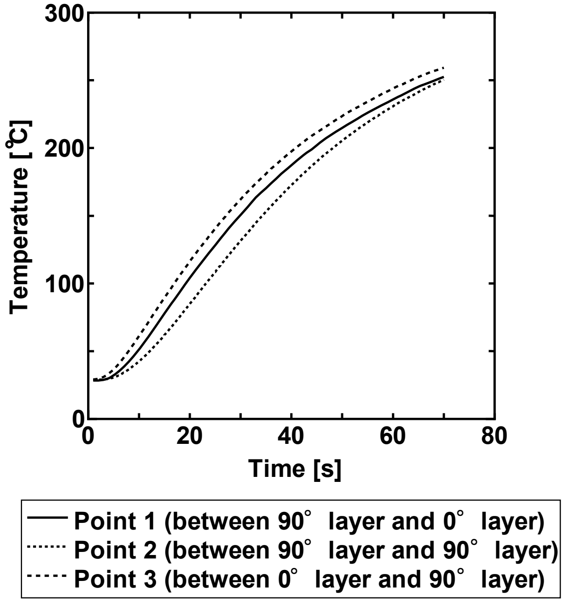


Figure 8: Temperature history of NCF $[0°/90°]_{2S}$.

3 Mechanical characteristics of carbon fibers heated by direct resistance heating

3.1 Materials and experimental method

In order to clarify the influence of direct resistance heating on the mechanical properties of carbon fibers, the mechanical characteristic of carbon fibers heated using direct resistance heating and those unheated were evaluated.

NCF heated to 300°C for 300 s using direct resistance heating and NCF not heated were used. The direct resistance heating was performed in the way described in section 2.1. Single carbon fibers were obtained from the central area of the 0° layer of each carbon fiber NCF for tensile testing and measurement of the diameter of single carbon fiber. The fiber length for the tensile test and the measured fiber diameter were 60 mm and 10 mm, respectively. The fibers were fixed with cyanoacrylate adhesive in a tab for the tensile test specimen and with carbon tape to a tab and coated with platinum for specimen diameter measurement. Figs 9 and 10 show schematically the specimens for tensile test and diameter measurement, respectively.

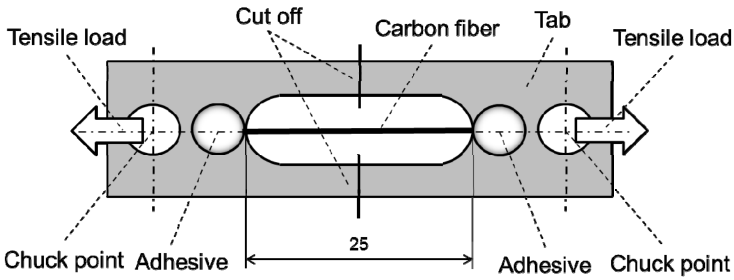


Figure 9: Single carbon fiber specimen for tensile test.

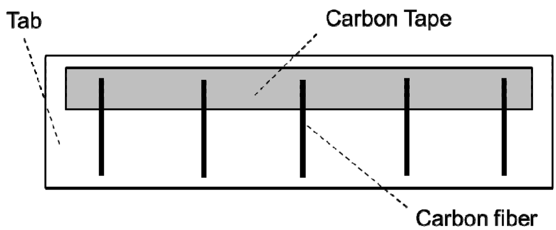


Figure 10: Single carbon fiber specimen for diameter measurement.

Tensile tests were performed using an electro hydraulic servo controlled testing machine for micro materials (MMT-11NV-2, Shimadzu Co., JAPAN), following the recommended testing procedures as described in JIS-R-7606. The load was applied to the specimens at a displacement rate of 1.67×10^{-5} m/s. After both ends of the tab were pinned to chuck points of the testing machine, the middle of tab shown in fig. 9 was cut to load the fiber. The tensile tests were thus performed by loading only the fiber. The single carbon fibers were observed by SEM (JSM-6390LT, JEOL Ltd., JAPAN) to measure their diameter.

3.2 Results and discussion

The tensile strength of single carbon fibers was plotted onto Weibull probability paper as shown in fig. 11. In addition, table 1 shows the Weibull parameters obtained from fig. 11. The shape parameters (m) of carbon fibers heated and unheated were 7.54 and 7.19 respectively; there were no difference in the dispersion of each data. In addition, the scale parameter (σ_0) of carbon fiber heated and unheated were 3.49 GPa and 3.36 GPa, respectively; there was no difference in scale parameter in the presence and absence of direct resistance heating. From these results, it is clear that the strength of carbon fibers was not reduced by direct resistance heating at 300°C for 300 s.

Table 1: Weibull parameters of CF-1 (room temperature) and CF-2 (temperature: 300°C, holding time: 300 s).

Specimen	Shape parameter (m)	Scale parameter (σ_0) [GPa]	Average strength [GPa]
CF-1 Room temperature	7.19	3.36	3.18
CF-2 Temperature:300°C Holding time:300s	7.54	3.49	3.30

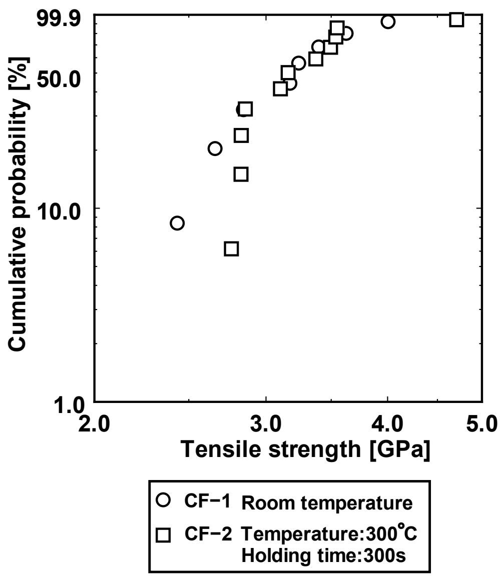


Figure 11: Cumulative probability of carbon fiber strength.

4 Conclusions

The heating properties of carbon fiber NCF were evaluated for the development of a CFRTP molding technique using direct resistance heating. To clarify the effect of direct resistance heating on the heating properties of carbon fibers, the temperature history was recorded and its uniformity assessed. The mechanical characteristics of single carbon fibers obtained from NCF heated by direct resistance heating were assessed through tensile tests. The investigation yielded the following conclusions:

1. It took 70 s for the temperature to reach 250°C when carbon fiber NCF $[0°/90°]_{2S}$ was heated using direct resistance heating.
2. From the results of tensile tests on a single carbon fiber extracted from the carbon fiber NCF heated to 300°C for 300 s using direct resistance heating, it was evident that the tensile strength was not reduced.

The direct electrical resistance heating can thus be safely applied to CFRTP molding.

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