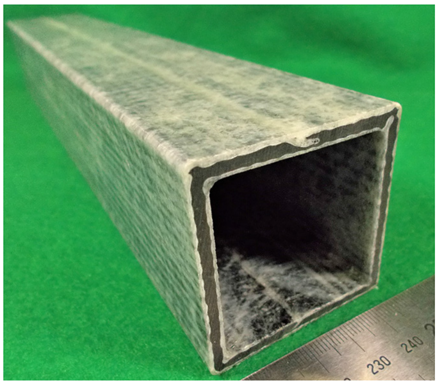
Derivation of Low-cost and High-speed Forming of Carbon Fiber Reinforced Plastic



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Carbon Fiber Reinforced Plastic (CFRP) is used for purposes which require high specific intensity, but the materials and molding for CFRP are relatively expensive in general and molding takes a long time. This research applies the pultrusion method utilized in Glass Fiber Reinforced Plastic (GFRP) to CFRP, aiming to achieve low-cost and high-speed molding. In addition, we conducted a simulation of the viscosity distribution of resin inside the mold in order to extract the optimum molding conditions with the minimum number of prototypes. As a result, we successfully molded a satisfactory CFRP prismatic pipe after only 2 prototypes.

1. Introduction

In recent years, CFRP has been widely applied to products such as aircraft and automobiles. Due to the increased volume of use, the price has decreased, but the range of application is still limited. On the other hand, although the pultrusion of GFRP is limited to uniform section shapes, it is one of the least expensive molding methods for composite materials, and is currently used mainly for molding corrugated panels. The application of this method to the molding of CFRP beam materials would enable dramatically low-cost molding compared with the conventional method, which would further lead to a wider range of application.

Generally speaking, however, Carbon Fiber (CF) is 5μm to 7μm in diameter, whereas Glass Fiber (GF) is 10μm to 24μm in diameter. Therefore, CF is thinner and requires some fire retardant to be added to the thermosetting resin to make it flame resistant, as a result, the resin viscosity increases, it is generally difficult to fully impregnate the resin with CF. To impregnate and achieve defect-free molding without pores, etc., the viscosity characteristics of the resin inside the mold need to be properly controlled. In terms of GFRP, there have been numerous trial-and-error molding tests with various different conditions conducted repeatedly to see what went right and what went wrong, during the process of which the conditions have been optimized. This paper introduces a process where the optimum conditions for CFRP pultrusion are extracted by conducting a simulation of resin viscosity distribution, which has never been done before.

2. Viscosity distribution simulation

2.1 Pultrusion utilizing thermosetting resin

Pultrusion is a method of continuously molding uniform sectional beam-shaped materials in a longitudinal direction by inserting fibers impregnated with resin in heated molds. This simulation selected thermosetting resin, which is relatively cheap, from among the various types of resin. The viscosity of thermosetting resin decreases before hardening when heated. Subsequently, a phenomenon called gelation occurs as the hardening progresses, where complex viscosity behaviors such as an acute increase in viscosity are observed. **Figure 1** illustrates in a schematic diagram the hardening behaviors occurring inside a mold.

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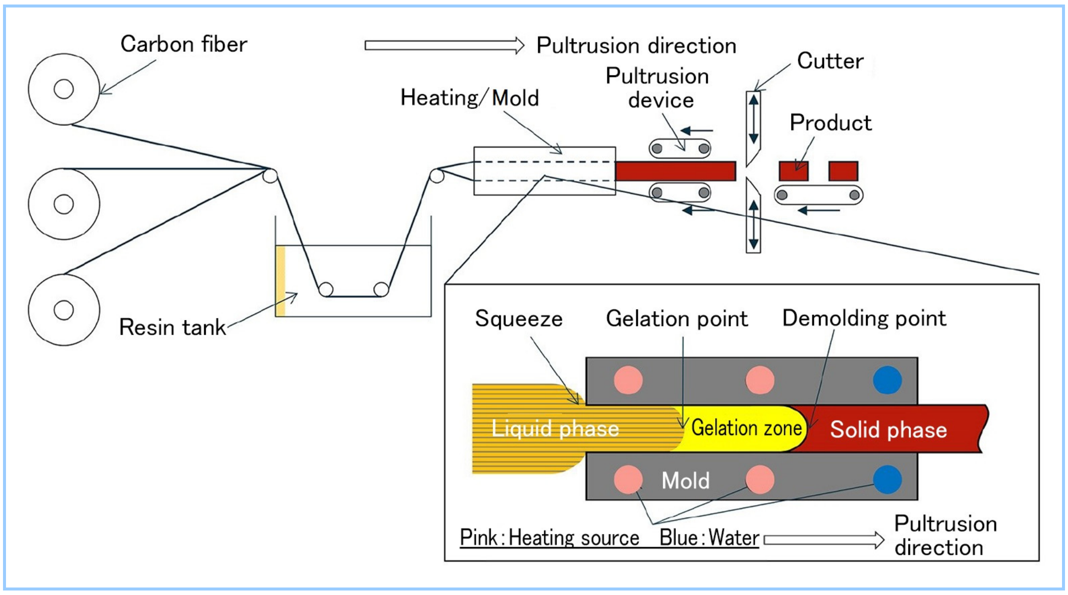

Figure 1 Hardening behaviors occurring inside a mold

2.2 Calculation process

Figure 2 is the calculation flowchart adopted in this research. Heating unset thermosetting resin at a certain temperature changes the resin viscosity while inducing an exothermic phenomenon due to chemical reactions. Since these reactions occur in succession, a simple analytical approach was applied to the series of temperature changes accompanied by the exothermic phenomenon and the corresponding viscosity changes.

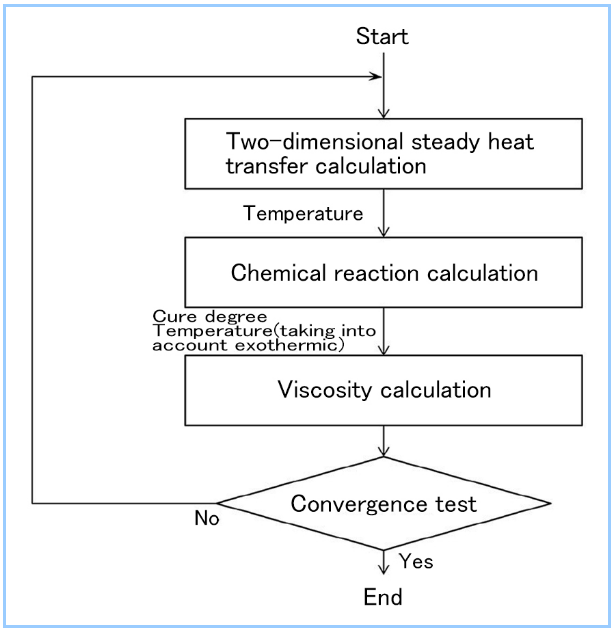

Figure 2 Calculation flowchart

Firstly, two-dimensional steady heat transfer calculations were carried out taking into account the mixture of resin and fibers inside the mold, the mold itself and the ambient air.

Chemical reaction calculations were then conducted based on the results of the first set of calculations. Upon carrying out the chemical reaction calculation, the cure extent of the resin was estimated based on the curing heat value where the general Kamal Formula was utilized as a reaction formula[1]. The curing heat value was measured with the Differential Scanning Calorimetry (DSC). **Figure 3** presents a comparison between the calculation and experiment results in terms of the relationship between the temperature of the resin used and its cure extent.

Secondly, the shear rate of the resin and the temperature dependence of viscosity were measured by the Dynamic Mechanical Analysis (DMA) where the Castro-Macosko Formula[2] was utilized as a viscosity prediction formula combined with a curing reaction formula. **Figure 4** shows a comparison between the calculation and experiment in terms of the relationship between the temperature of the resin used and its viscosity.

A simulation of viscosity distribution was conducted utilizing these formulas.

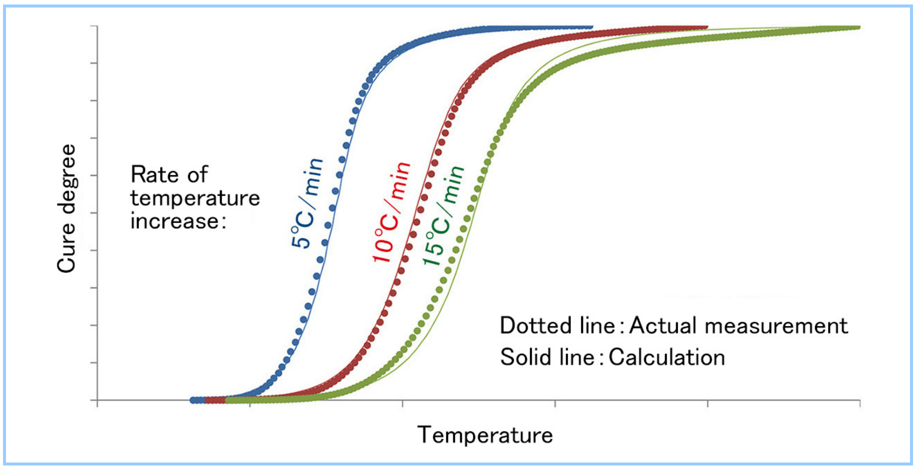

Figure 3 Relationship between temperature of resin used and its cure degree

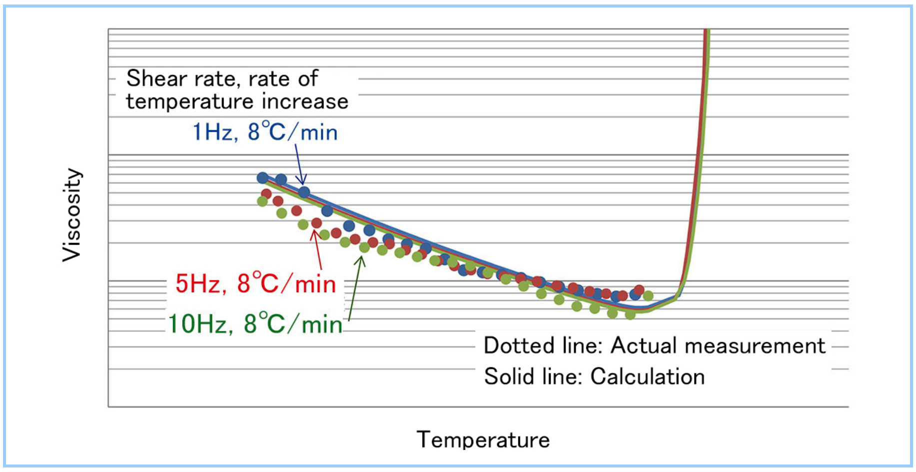

Figure 4 Relationship between temperature of resin used and its viscosity

3. Verification test

A molding test was conducted for verification purposes, using a mold capable of the pultrusion of a 50mm-square and 4mm-thick hollow rectangular cylinder. In the pultrusion, the temperature of the mold is controlled by applying heat with a heater to harden the resin, but there is no heater in the core. Therefore, the challenge is to determine the conditions to maintain the temperature of the mold even in the through-thickness direction. **Figure 5** depicts the relationship between different portions of the mold and temperature, cure extent and viscosity, respectively, as well as a comparison between the actual measurements and calculated values. In this figure, based on the relationship between different portions of the mold and the corresponding temperature values provided in the top chart, the cure extent and viscosity calculated according to the temperature are shown in the middle and bottom charts,. From the figure, we can see that the actual measurements and the calculated values are highly consistent with high accuracy. **Figure 6** is a contour figure showing the optimum conditions based on the results in Figure 5. Figure 6(a) and 6(b) show temperature distribution and cure extent distribution respectively. As can be seen from Figure 6(a), the boundary between purple and blue is slanted at the entrance portion of the mold and the temperature distribution in the thorough-thickness direction is uneven, but at the exit portion which has a significant impact on the cure extent, the boundary between red and orange becomes more vertical and temperature distribution in the thickness direction, it becomes even . Accordingly as the boundary of colors becomes almost vertical as shown in Figure 6(b), we can confirm that the calculation successfully obtained desirable conditions where hardly any uneven distribution of the cure extent was found in the through-thickness direction.

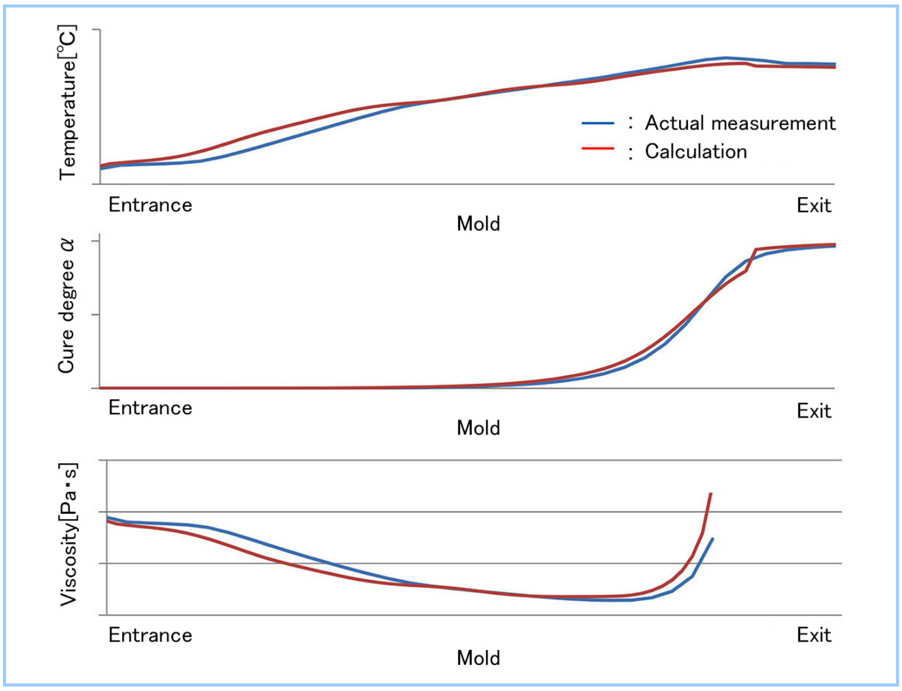

Figure 5 Relationship between different portions of mold and temperature, cure degree and viscosity

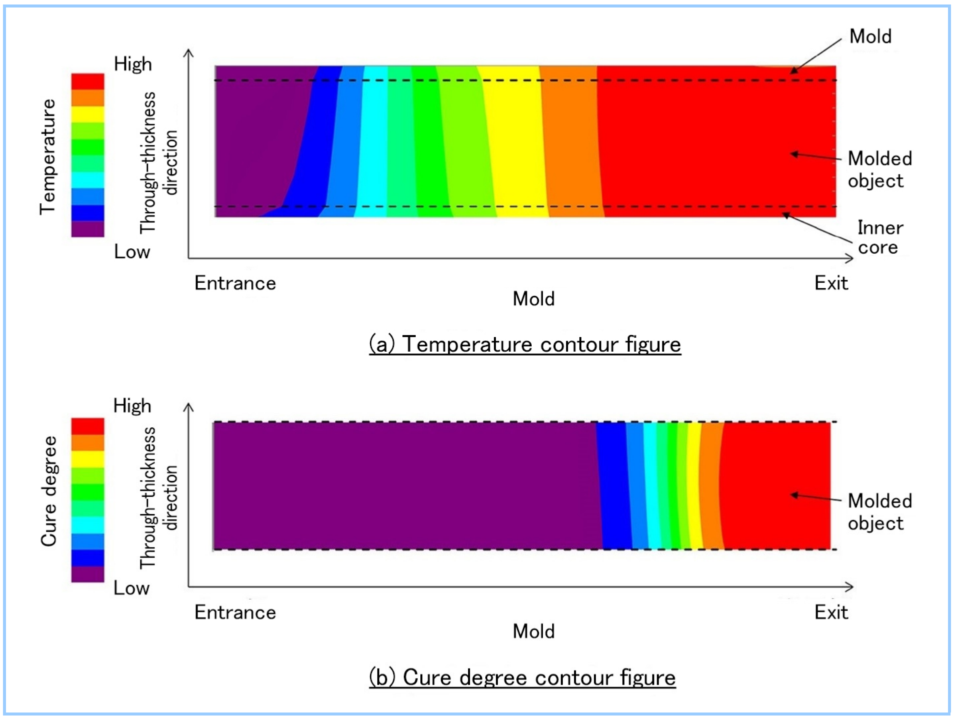

Figure 6 Contour figure showing results of optimum conditions

Next, we examined the inside of a prototype hollow rectangular cylinder molded under the optimum conditions by cutting it at an arbitrary position and polishing the cross-section as shown in **Figure 7**. The image in the center is the whole cross-section and enlarged views of individual portions are placed around it. The dark area in the center image is embedded resin for polishing and the light-colored portion surrounding it is the molded object. On the right-hand side of this figure, two representative values of the Volume of fiber (Vf) are indicated, including where the average Vf of all the portions measured was 61.0%. Furthermore, the quality was confirmed to be excellent with no major internal defects such as cracks or pores.

Finally, we cut out flat bar test pieces from the prototype and conducted a tensile test on it to examine the strength. **Figure 8** is a load-strain diagram of a representative test piece, which confirms that it has a strength level equivalent to rolled steel for general structure (SS400). Furthermore, there is high linearity in the load and strain, whereas no evidence of rupture in the resin was observed.

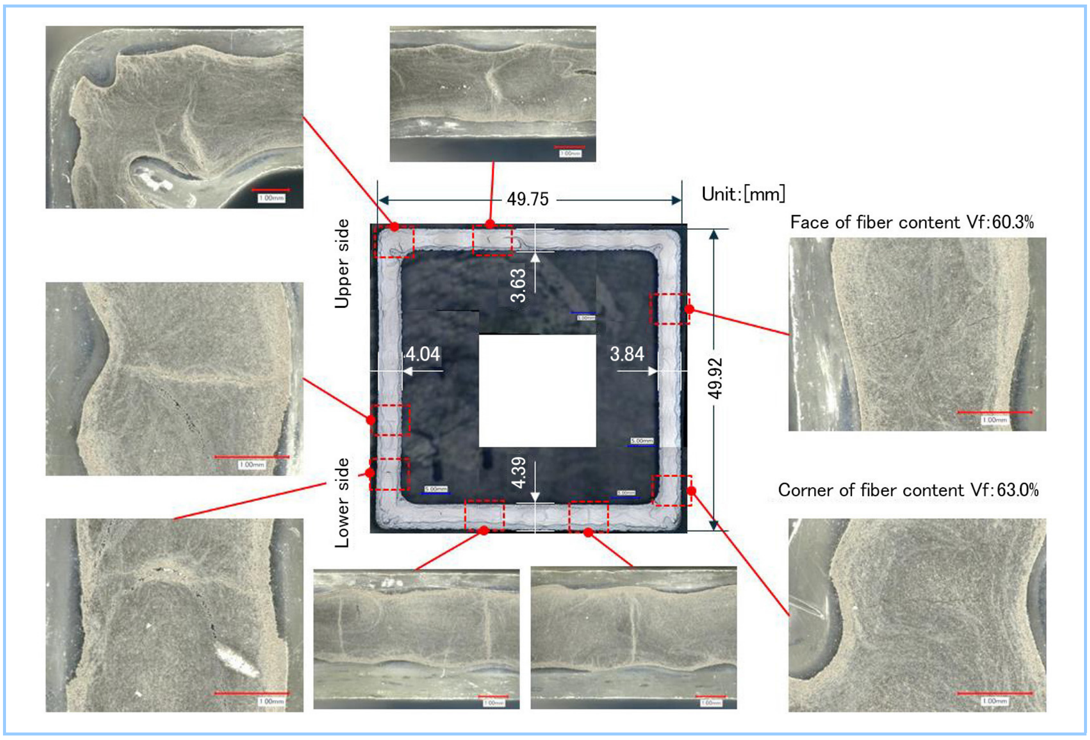

Figure 7　Cross-section of prototype hollow rectangular cylinder

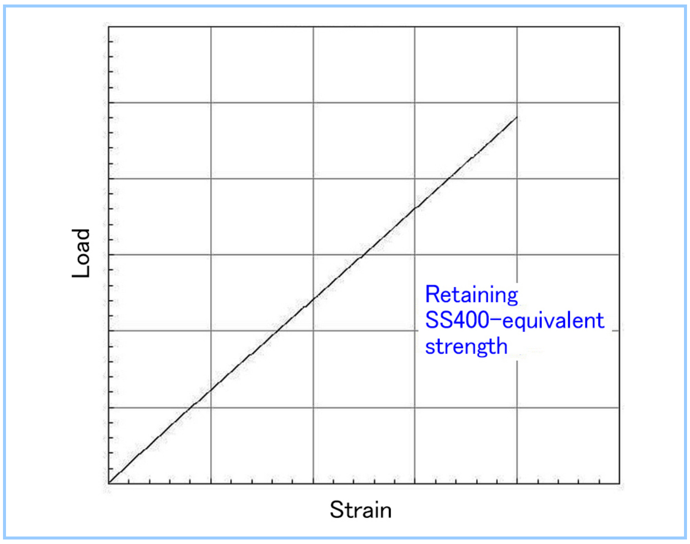

Figure 8　Load-strain diagram of cut-out flat bar test piece

4. Conclusion

This paper explained that our new viscosity distribution simulation can be used for actual pultrusion, which resulted in successful molding of a satisfactory prototype. Viscosity distribution simulation and pultrusion technologies are essential techniques for the manufacture of parts made of composite materials. Since there is high demand for light-weight structural members, we will endeavor to widen the application of these techniques to various products, while continuing to work on further sophistication so that we can contribute even more to the low-cost and high-speed production of composite materials.

References

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(2) Castro J. M. et al., SPE Tech. Papers, 26 (1980), p.434