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Technical Paper:

Development of Warm-Press-Forming Method of CFRTP Motor Vehicle Floors with Complicated Shapes

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In this paper, some large automotive parts with complex shapes are produced to report the results of our efforts to develop press molding technologies for thermoplastic carbon fiber-reinforced plastic (CFRTP). Members of industry, academia, and the government collaborated to realize this project. The project includes a molding experiment, CAE analysis, and material strength measurements. In the material test, a tensile test, bending test, heat distortion test, and torsion test are carried out to produce several stress-strain curves. Applying the new analytical model in the simulation shows that accuracy is improved. As a result, by measuring the temperature change during the forming of complex shapes, a large automotive part with a complex shape was successfully molded in a short time. Other productivity improvements are also reported on.

Keywords: CFRTP, die and mold, warm-press-forming, forming simulation

1. Introduction

The precision with which automobile bodies can be formed has advanced in recent years owing to the large number of experiments and analyses that have been done. Simulation technology has also advanced dramatically [1, 2]. The accuracy of simulations of not only press forming [3] but also injection molding [4] and casting [5] has improved, and the causal relationships involved in the formation of defects is becoming clear [6]. This has been aided by advances in measurement technology, which have made it possible to carry out quantitative measurements in a short time [7].

Furthermore, environmental considerations have led to a growing demand for the production of lightweight and high-strength automobiles, and this demand has resulted in the use of materials with high specific strengths [8, 9]. Although composite materials are now used for such high-specific-strength materials, carbon fiber reinforced plastics (CFRP) are costly as well as difficult and time-consuming to form. As a result, their use in mass production has been sluggish. Moreover, CFRP is an anisotropic material [10] which requires complex analyses, such as multi-scale analyses [12] based on modeling the material parameters at a microscopic level [11]. Various analytical models have been proposed [13], including one with anisotropic material parameters proposed by the authors [14, 15]. For simple models, the Ruess theory has been applied to carry out forming simulation [16, 17], while warm-press-forming simulation [18] has been used in recent years to demonstrate the effects of shear deformations [19] and shear locking [20] on the forming process [21].

In this study, we employ forming-simulation technology to develop a press-forming technology to produce large, complex-shaped automobile products from carbon fiber-reinforced thermoplastic resin (CFRTP) for mass-production purposes. While CFRTP is suitable for mass production since the final product shape is achieved by cooling, the introduction of new equipment would increase manufacturing costs. Considerable cost cutting can thus be expected if CFRTP forming can be applied to the metal-press production process. The authors thus aimed to establish a technology to manufacture large, complex-shaped, car parts using existing metal mechanical presses.

Although many experiments [24, 25] have been conducted in the past to warm-form CFRTP to produce simple [22] or hemispherical [23] shapes, there have been very few attempts to produce shapes with protrusions and indentations of various sizes and shapes in which fiber deflection is constrained [26].

This research and development project is a joint industry-academia-government undertaking, in which the parties involved are respectively charged with material testing, CAE analysis, and warm forming, in an effort to resolve issues in each field. As a result of this undertaking, it has become possible to form a large car-floor part with indentations and protrusions within one minute. We also report on the prototypes that were produced using this technology.

2. Material Testing

2.1. Testing Method

Since the material characteristics of CFRTP are affected by the forming conditions, the characteristics were determined by tensile, flexure, torsion, and thermal strain tests. The CFRTP used in the tests was a stampable sheet consisting of four laminations of 0/90-degree oriented orthogonal plain-weave prepreg (3K) with an acrylic-resin base. The test specimen had the dimensions 25 × 250× 1 mm, and the span distances were set with each test according to JIS (Japanese Industrial Standards).

To examine the effects of quasi-isotropy, the tensile test was conducted to determine material constants for various combinations of the fiber directions in the laminations at the specified temperatures (25–200°C) in a constant-temperature oven. The stress-strain diagram was obtained using Autograph AGIS-500kN (Shimadzu Corp.) as the testing machine. The test conditions were determined based on JIS-K7165, and the test speed was set at 2 mm/min. Strain measurement was carried out with a strain gauge and by using the image correlation method.

The flexure test was carried out using the same temperature conditions with an Instron 5582 (Instron), an electromechanical universal testing machine. The flexure test was also conducted using an HD-PC-3 heat distortion tester (Yasuda Seiki Seisakusho, Ltd.), and the thermal strain test was carried out using the flatwise method (K7191-2; 2007 (ISO-75-2; 2004)).

The torsion test was done with a TO-1020 torsion testing machine (Maekawa Testing Machine Mfg. Co., Ltd.) only at room temperature (20°C) within the range ±10°. A span distance of 120 mm was used.

2.2. Test Results

The stress-strain diagram for various lamination patterns for the tensile test at an environmental temperature of 20°C is shown in **Fig. 1**, where the notation [0]4 indicates a stampable sheet consisting of four laminations of 0/90-degree-oriented material.

The 0/90-degree-oriented material exhibits the highest modulus of longitudinal elasticity; the 45-degree-oriented material exhibits the lowest. It can be seen that the 45-degree-oriented material exhibits considerable nonlinearity. The stresses and strains of the remaining lamination patterns lie in between these two materials.

In the flexure test, shown in **Fig. 2**, the flexural strength was found to increase as the forming temperature of the stampable sheet increased. The forming temperature used to form the stampable sheet test specimen from prepreg was the heating temperature of a small hot-pressing machine (MP-WCL with water cooling board, Toyo Seiki Seisaku-sho, Ltd.). The test specimens were formed under the following conditions. Four layers of degreased prepregs were placed on top of each other in the test-specimen mold, and they were pressed at 5 MPa when the hot-pressing machine reached the required temperature. They were held in that state for 30 seconds, and then they were cooled while the pressure was still applied by passing a chiller through the pressing plate. When the temperature was reduced to 40°C, the pressure was removed, and the specimen was removed from the mold.

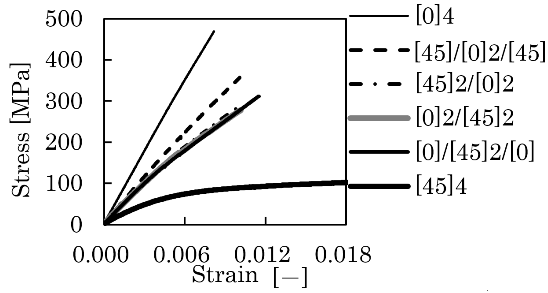


Fig. 1. Stress-strain diagram for different lamination patterns.

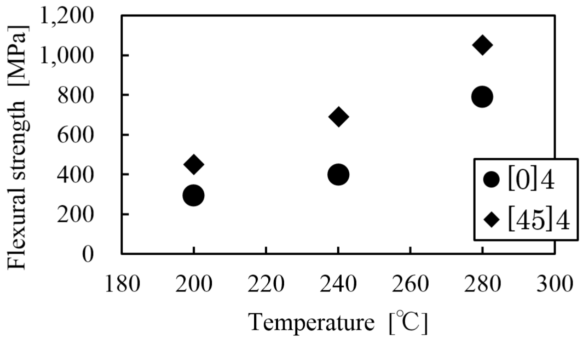


Fig. 2. Relation of flexural strength and stampable sheet forming temperature.

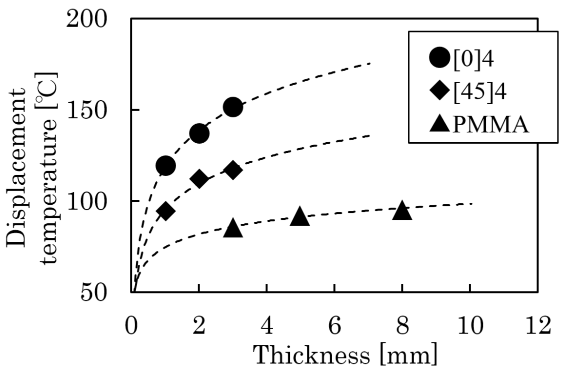


Fig. 3. Results of thermal strain test of base material (PMMA) and stampable sheet.

Figure 3 shows the results, i.e., the softening point temperature, of the thermal strain test using stampable sheets formed at 200°C. The base material, PMMA, softens at around 100°C, and a CFRTP sheet with a thickness of 3 mm softens at around 150°C. Therefore, it is not necessary to raise the temperature to above 200°C even if the thickness is increased, and it is possible to form at a temperature of about 150°C for the purpose of

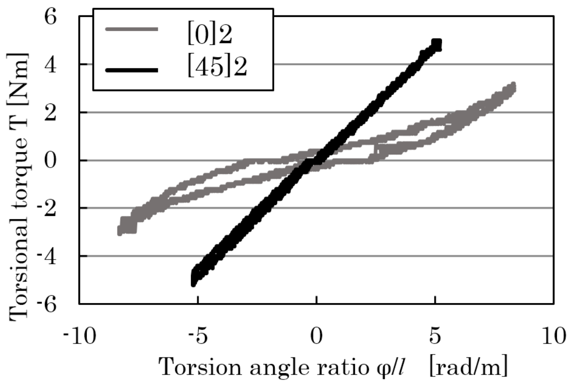


Fig. 4. Hysteresis loop observed in torsion test.

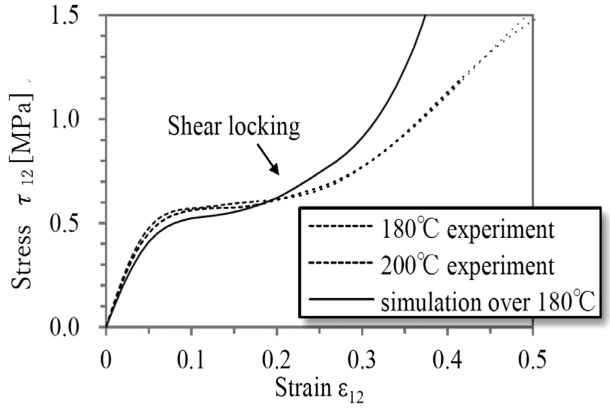


Fig. 5. Results of high-temperature tensile tests for stampable sheet and simulation results.

mass production. In this case, the 45-degree material deforms at a lower temperature, but, as **Fig. 2** shows, higher strength is achieved by orienting the laminations at 45° at 200–240°C. Therefore, the required strength must also be taken into consideration when the forming temperature is selected.

In other words, although it is not necessary to use temperatures above 200°C for the purpose of mass production, we can expect to produce a higher grade of product by orienting the material at 45° at 200–240°C for assembly points that require high strength. The reason for this is that, since the strain is governed by the shear angle in continuous fibers oriented at 45°, the strain increases in the stress-strain diagram at low loads, but the normal stress increases after shear locking has occurred, as shown by Nishi et al. [27]. The stress due to shear locking results in increased strength even when the modulus of elasticity is low. This is because the three-dimensional weave of two crossing fibers limits the shear angle and because the two fibers bear the normal load. As a result, the strain is higher than in the 0-degree material.

In the torsion test, shown in **Fig. 4**, a hysteresis loop is evident. In other words, since the 0/90° oriented material displays non-linearity while the ±45° oriented material displays linearity, the different fiber orientations produce different loading histories under transverse shear deformation.

3. Forming Simulation

3.1. Material Testing Parameters

As an example of the tensile test at high temperature, **Fig. 5** shows the results of the ±45° oriented four-ply material at 180°C and 200°C. The broken curve and the solid curve represent the experimental and simulation results, respectively. The graphs display a non-linear tendency since the temperature is above the glass-transition temperature, and the stress increases drastically above a certain strain.

Conventional textile fiber models have a complex 3D structure and are unsuited to determining the out-of-plane flexure characteristics observed in press forming from the in-plane tensile and compressive characteristics. Thus, Nishi et al. [15, 27] proposed a model which takes nonlinear stiffness into account, where the membrane and shell elements are combined in order to consider the out-of-plane stiffness of the fiber matrix. This has made it possible to obtain the stress-strain diagram in the region exceeding the shear locking angle shown in **Fig. 5**.

3.2. Press Forming Simulation

By incorporating these parameters obtained from material tests at various temperatures, it has become possible to analyze the warm-press forming process of the S-type rail shown in **Fig. 6** [27]. The relation between the temperature and time, however, must be determined by experiment. The results show that the temperature is low at sections that come into contact with the metal die, which is expected to increase the stiffness and degrade the formability. Moreover, the occurrence of wrinkles at the flat section caused by shear deformation is also observable.

Figure 7 shows the result, based on the above method, of warm-press forming simulation of a car floor part that has indentations and protrusions of various sizes. It shows the strains in the fiber bundle direction of the [0]4-degree oriented material, where those sections displaying large strains have a high probability of cracking. Based on the material test results in **Fig. 1**, this cracking was considerably reduced when the lamination direction was changed by using the [45] 4-degree oriented material. This change of direction resulted in the forming of a floor part free of cracks, as described later.

While this made it possible to prevent cracks due to tensile forces, we now discuss the effect of compressive forces. **Fig. 8** shows the curvature distribution of the sheet using a symmetrical boundary model. It shows that the curvature is within ±0.03 at all positions, demonstrating that there is no possibility of wrinkle formation on the flat section.

4. Warm-Press Forming Experiment

In the past, thermal setting resin was mainly used in CFRP, and this made CFRP unsuitable for mass produc-

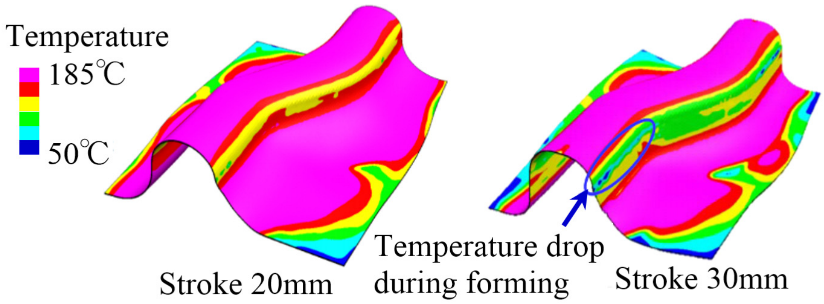


Fig. 6. Results of warm-press simulation of S-type rail made from [0]4 stampable sheet.

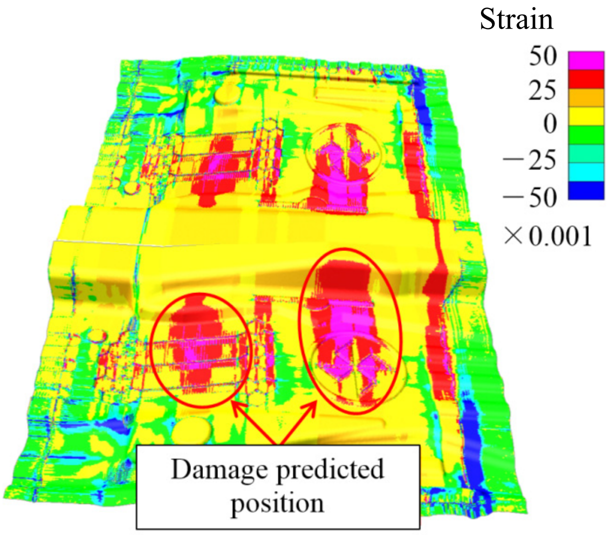


Fig. 7. Simulation result of strains in the fiber-bundle direction of a car floor part made from [0]4 material.

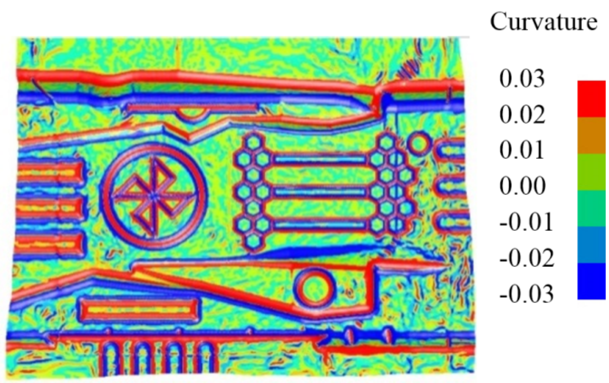
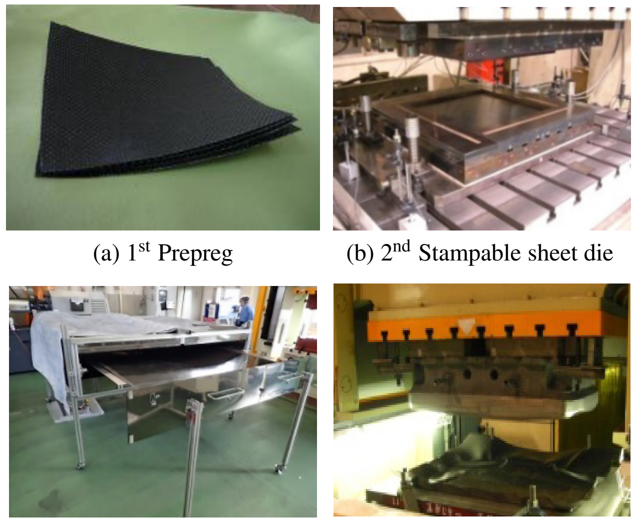


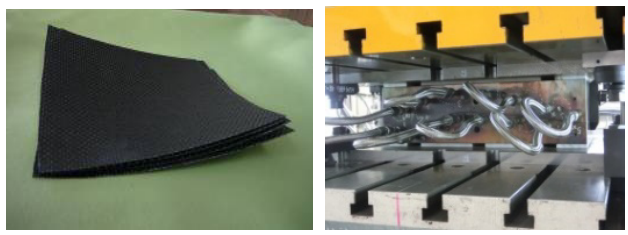
Fig. 8. Curvature distribution in symmetrical boundary model.



(a) 1st Prepreg (b) 2nd Stampable sheet die

(c) 3rd Reheat (d) 4th Warm press forming

Fig. 9. Method in which warm-press forming is carried out after reheating.



(a)1st Prepreg (b) 2nd Mold with temperature control

Fig. 10. Temperature-controlled forming.

tion. It was therefore our goal to make it possible to form parts in a short time by using CFRTP, which obtains its final formed shape by cooling. Since heating of the entire mold would require increasing the cost of the metal die, we considered two types of forming: cold forming, in which only the stampable sheet is heated and the metal die is used for cooling, and adjustable-temperature forming, in which the temperature of the metal die is adjusted.

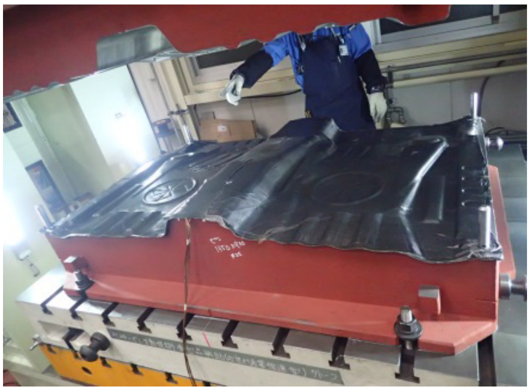
In **Fig. 9**, (a) shows four sheets of prepreg, which are made into a stampable sheet with the die in (b), and the prepreg stampable sheet is reheated by the device in (c) and cold-formed with the die in (d). This method requires a metal die to produce the stampable sheet and a device for reheating.

Figure 10 shows a method in which the prepreg is directly set in the die shown in (b) to produce the final shape.

Based on the simulation results, adjustments were incorporated in the metal die for the car floor, and the conditions required for forming were determined.

The procedure illustrated in **Fig. 9** is as follows. Four sheets of prepreg were laid on top of each other at 45° angles, heated to about 200°C, and pressed at 5MPa (the

(a) Stampable sheet before forming



(b) Immediately after forming

(c) Floor part (the diagonal cross is a mark showing bonding between SSs)

Fig. 11. Warm-press process for forming car floor part.

(a) Before bonding and forming

(b) After bonding and forming

Fig. 12. "B-pillar" part for automobile body produced by bonding aluminum alloy and CFRTP.

Fig. 13. Formula racing car prototyped from CFRTP.

same pressure used for the test specimens) with a 300 t pneumatic press (Sanki Seiko Co., Ltd.). After being subjected to pressure for 30 seconds, the sheets were cooled to produce a single, 1000 × 1500 mm stampable sheet.

This stampable sheet was heated to 200°C with a separate pre-heater, transported to the metal die, shown in **Fig. 11(a)**, and then immediately pressed, as shown in **Fig. 11(b)**, to obtain the shape shown in **Fig. 11(c)**. Using a 2000 mm/min forming stroke, the forming time, including the cooling and holding time, was 40 seconds. The fiber direction in **Fig. 11(c)** is 45° against the sides of the floor part.

This technology was later successfully used to give a designed form to a part in which an aluminum alloy part was bonded to CFRTP, as shown in **Fig. 12**. Improving the bonding strength is the next issue, but it is becoming possible to obtain high bonding strength by imparting certain features to the material surface.

Furthermore, a "formula racing" (open-wheel) car was produced with CFRTP, as shown in **Fig. 13**. Its characteristic shape demonstrates that deepdrawing is possible. As this technology has improved for incorporation into the assembly process, various developments have taken place since this report was originally written [28].

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