Technology Explanation

Research on strength prediction technology for fiber-reinforced plastic injection-molded products

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Abstract

In anticipation of the introduction of global CO_2 emission regulations, there is a growing need to reduce the weight of transportation equipment. Fiber-reinforced plastic (FRP) is attracting attention as a lightweight material. FRP injection-molded products have the potential for both weight reduction and cost reduction. However, it is difficult to predict and control strength because the fiber orientation changes depending on how the products are made, and this has a significant impact on physical properties. Therefore, development has been conducted on a trial-and-error basis, and optimization of part geometry and processing methods has not been studied. In this study, we use simulation to develop a strength prediction technique that considers the anisotropy of physical properties due to fiber orientation. This enables us to realize development without rework and to construct a technology that can optimize the design.

We quantified the fiber orientation in plastic parts, which has been difficult in the past, and improved the prediction accuracy of fiber orientation by resin flow analysis. Based on the predicted fiber orientation information, the physical property anisotropy of fiber-reinforced plastic parts was predicted. A material model for structural analysis was created, and structural analysis considering fiber orientation was performed to improve the accuracy of strength prediction for plastic parts.

It was also found that this technique can be used to predict the fracture behavior of actual plastic part geometry, confirming the importance and effectiveness of studying material strength, including the manufacturing process, when designing fiber-reinforced plastic parts.

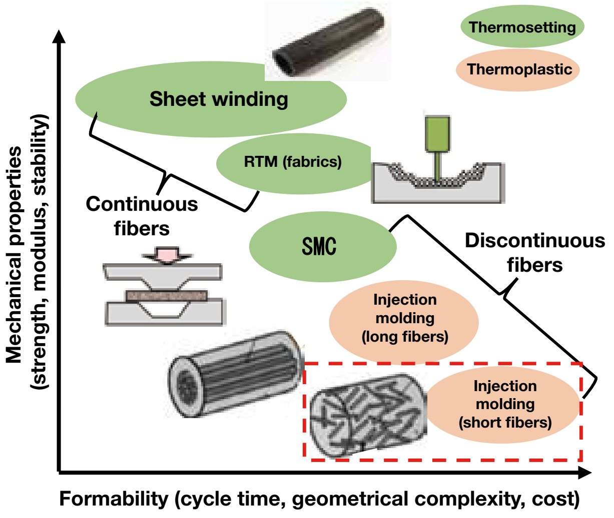
1 Introduction

1.1 Background of the Research

In anticipation of the introduction of global CO_2 emission regulations and market launches of electric vehicles, there is a growing need to reduce the weight of transportation equipment. To respond to the weight reduction need, studies are in progress to replace metallic parts with plastic components that are lighter and easier to process. Since plastic is inferior in mechanical properties to metal, fiber-reinforced plastic (FRP) such as plastic reinforced with glass or carbon fibers is attracting attention as a low-density, high-strength material. FRP is used as structural members in a wide range of fields today.

1.2 FRP Processing methods and its Characteristics

Fig. 1 shows the mechanical properties and productivity characteristics of FRP for various processing methods [1]. FRP varies in mechanical properties and productivity by fiber length. Continuous fibers are superior in mechanical properties but inferior in productivity, so they have limited applications in aircraft, sporting goods, luxury cars, and others. On the other



※RTM:Resin Transfer Molding
SMC:Sheet Molding Compound

Fig. 1: FRP characteristics for various processing methods

hand, discontinuous fibers that can be injection-molded have a good balance between mechanical properties and productivity, thereby having the potential for both weight reduction and cost reduction. This research focuses on FRP injection-molded products.

1.3 Anisotropy of Physical Properties of FRP Injection-Molded Products

FRP injection-molded products have a distribution of fiber orientation and/or fiber length due to the shear stress and elongation flow that occur when resin flows in the mold during injection molding. Because of its higher reinforcement in the direction of fiber orientation, FRP shows anisotropy of modulus, strength, coefficient of linear expansion, and other properties according to the fiber orientation distribution during injection molding. This poses the problem that it is difficult to predict the strength, rigidity, and warpage of molded parts. For example, molded parts may fracture before reaching a required load if their anisotropy of modulus or strength have not been considered. In another case where anisotropy of the coefficient of linear expansion is not considered, molded parts may go out of dimensional tolerance due to warping.

That is why it is difficult to predict the quality characteristics of FRP injection-molded products. Mold changes have been repeated on a trial-and-error basis, resulting in longer development periods and higher development costs. Furthermore, the part geometry has not been optimized since the anisotropy of physical properties due to fiber orientation cannot be exactly predicted. Some parts have been produced using more resin material than necessary in order to ensure quality.

Fig. 2 shows the current and target development flows for FRP parts. The target development flow will allow us to predict the anisotropy of physical properties due to fiber orientation and the mechanical properties of molded parts, thereby enabling the optimization of the part geometry and mold design on the desk. This will contribute to higher development efficiency.

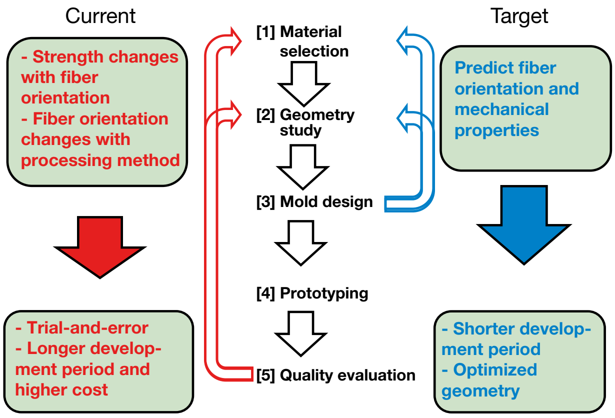


Fig. 2 Current and target development flows

2 Overview of Prediction Technique

In this development study, we predict the anisotropy of physical properties from the fiber orientation generated in the injection molding process and then carry out a structural analysis that considers the anisotropy, improving the accuracy of strength prediction for FRP parts. Fig. 3 illustrates the concept of the prediction technique.

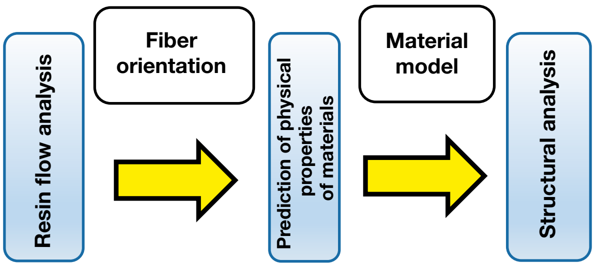


Fig. 3 Concept of strength prediction technique

The first step is to conduct a resin flow analysis and then predict the fiber orientation of injection-molded parts. The next is to create an anisotropic material model based on the predicted fiber orientation. The final step is to carry out a structural analysis using the anisotropic material model, enabling prediction of mechanical properties with the fiber orientation taken into account. Implementation of this technique involves challenges:

[1] Quantitative evaluation of fiber orientation
[2] Improvement of fiber orientation prediction accuracy through flow analysis
[3] Improvement of structural analysis accuracy with fiber orientation taken into account
[4] Improvement of prediction accuracy for strength reduction rate of welds

The following chapter describes what we have addressed to resolve these challenges.

3 Accuracy Testing with Element Specimens

3. 1 Quantitative Evaluation of Fiber Orientation

Photo 1 shows an X-ray CT image of an injection-molded product.

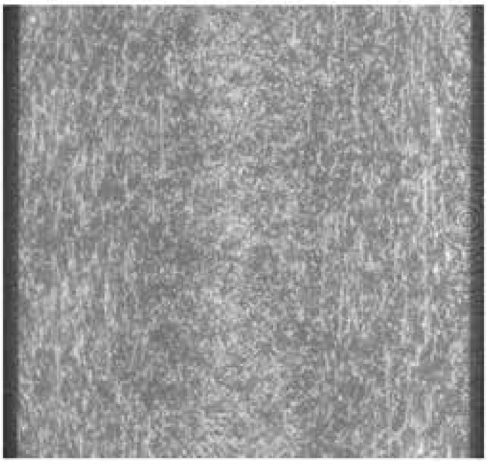
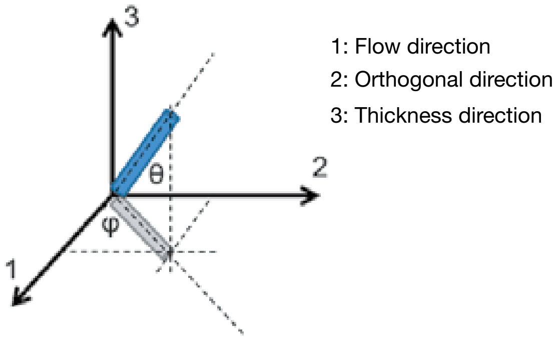


Photo 1 X-ray CT image of FRP

Glass fibers appear in white and plastic in gray. This injection-molded plastic product contains about 30% to 50% fibers of a thickness of about 10μm. Since the fibers are three-dimensionally distributed, it is usually difficult to quantify the fiber orientations. Then, we have conducted joint research with Kanazawa Institute of Technology (KIT) to quantify the fiber orientations from X-ray CT images using the cylinder-model fitting approach [2].

The following describes how to identify glass fibers using the cylinder-model fitting approach. First of all, a cylinder model is placed over each of the fibers obtained in the X-ray CT images. The angle and length of the cylinder models are adjusted so that the models match the actual fibers well, which will determine the parameter values. Calculating the angle of individual cylinder models will quantitatively evaluate the fiber orientation. Next, the part thickness is divided into 21 layers at all observation points and the degree of fiber orientation in each layer is determined. The definition of the degree of fiber orientation is illustrated in Fig. 4. The angle of fibers is indicated by the in-plane orientation angle Φ and the out-of-plane orientation angle θ. The orientation tensor in each direction has been calculated using equations 1) to 3). "N" indicates the number of fibers. The orientation tensor is "a11" in the flow direction (MD), "a22" in the direction orthogonal to the flow direction (TD), and "a33" in the thickness direction (ND) at all observation positions.



Φ: In-plane orientation angle (Flow direction: 90°)
θ: Out-of-plane orientation angle (Thickness direction: 0°)

Fig. 4 Definition of the degree of fiber orientation

$$a11 = \frac{1}{N}\sum_{i=1}^{N}(\sin\theta_i \cos\varphi_i)^2 \qquad (1)$$

$$a22 = \frac{1}{N}\sum_{i=1}^{N}(\sin\theta_i \sin\varphi_i)^2 \qquad (2)$$

$$a33 = \frac{1}{N}\sum_{i=1}^{N}(\cos\theta_i)^2 \qquad (3)$$

It is now possible to three-dimensionally quantify the fiber orientation, which has conventionally been difficult (Fig. 5).

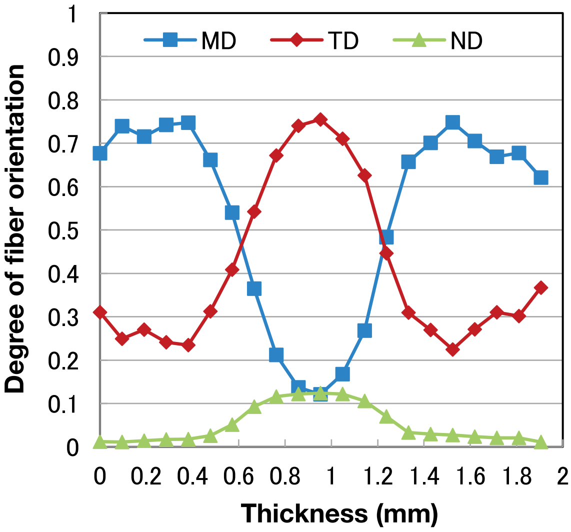


Fig. 5 Quantitative evaluation of fiber orientation

3. 2 Improvement of Fiber Orientation Prediction Accuracy through Flow Analysis

To achieve a structural analysis that considers the anisotropy of physical properties due to fiber orientation, it is necessary to predict the fiber orientation taking place during injection molding. Then, we predict the fiber orientation by analyzing the material flow in injection molding and compare the prediction with the results of the quantification of actual fiber orientation stated above, in order to verify the prediction accuracy.

Fig. 6 shows a flat plate specimen used in testing. The specimen is made of PA66 containing 30 wt% glass fibers.

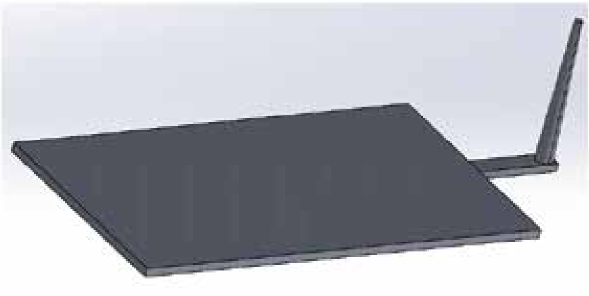


Fig. 6 Overview of specimen geometry

The flow analysis was made with an injection molding software (CoreTech System Moldex3D®). As a prediction model for fiber orientation, the Folger-Tucker model [3], which is a model for predicting orientation behavior of ellipsoids in high-concentration solutions, was used in combination with the iARD (Improved Anisotropic Rotary Diffusion) model[4] to also allow consideration of interference among fibers.

Fig. 7 shows a schematic diagram of the fiber orientation mechanism. In injection molding, the molten material is instantaneously cooled to solidify in the areas where the material has come into contact with the mold. Inside these areas, the molten resin still continues flowing in general cases. There arises a velocity gradient between the solidified layer and the molten layer. It is generally considered that the difference in velocity causes a shear stress to make the fibers position in the direction of the resin flow. In this research, specimens were prepared with two injection speed levels (high and low) since the injection speed greatly affects the thickness of the solidified layer. Then, fiber orientation was compared between the actual test results and the analysis results.

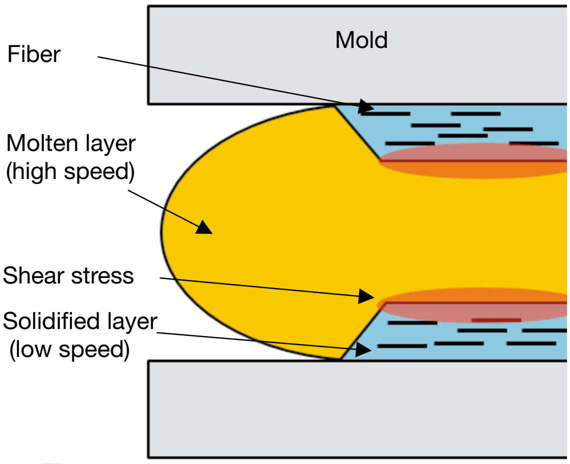


Fig. 7 Schematic of fiber orientation mechanism

Figs. 8 and 9 show the comparison of fiber orientation distribution between the actual test and the analysis. These Figures indicate that the analysis results generally reflect the actual fiber orientation distribution, which has been achieved by adjusting the flow analysis parameters to improve the prediction accuracy for fiber orientation. The Figures also reveal that the trend of fiber orientation distribution varies with injection speed. Specifically, slower injection produces a thicker layer in the direction of the molten resin flow (MD) close to the wall of the mold. This is probably because the solidified layer close to the wall is more likely to grow with slower injection and the shear stress occurring between the solidified and molten layers applies even at its center. Thus, it is possible to reproduce through analysis the fiber orientation distribution for varying injection speeds.

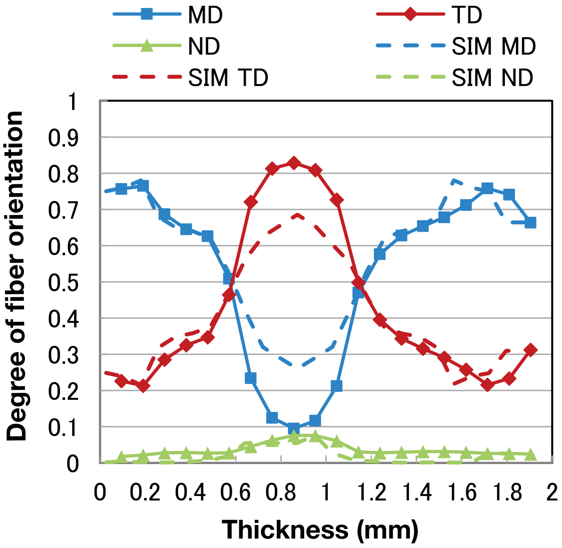


Fig. 8 Comparison of fiber orientation distribution between actual test and analysis (high speed injection)

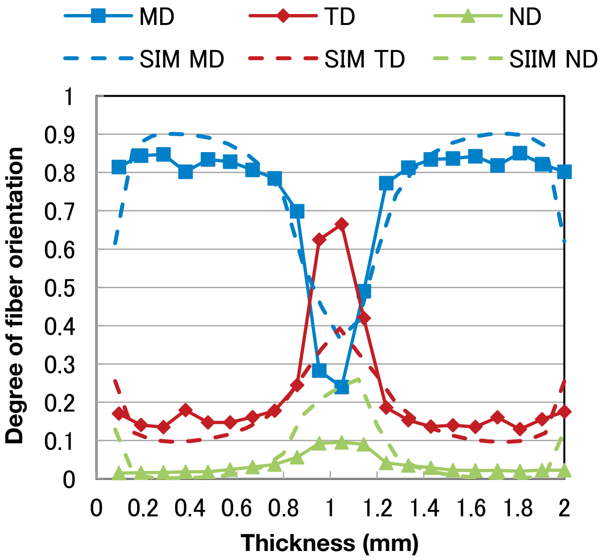


Fig. 9 Comparison of fiber orientation distribution between actual test and analysis (low speed injection)

3.3 Improvement of Structural Analysis Accuracy with Fiber Orientation Taken into Account

This section carries out a structural analysis considering the fiber orientation distribution predicted through flow analysis and verifies the analysis accuracy. A non-linear, multi-scale material modeling software Digimat® (e-Xtreame) was used to predict anisotropic physical properties of the material, and homogenized with the Mori-Tanaka model[5]. Digimat uses the mean field approximation approach. This approach handles the geometry and orientation of glass fibers approximately as ellipses and calculates the strain and stress applied to the resin matrix and glass fibers, determining the total physical properties of the composite containing glass fibers. The mean field approximation approach focuses on the micro stress-strain characteristics of a material to calculate its macro physical properties with its microstructure taken into account. Featuring high-speed calculation, the approach can be combined with the finite-element method to calculate and solve equations.

The structural analysis accuracy has been verified with dumbbell-shaped specimens cut out from the flat plate specimen which was produced in section 3.2, at different angles (0°, 45°, 90°) to the direction of the resin flow (Fig. 10). These specimens were subjected to a tensile test. The resultant stress-strain (S-S) curves were compared with the analysis results. In general, fibers contained in an injection-molded part are likely to be predominantly oriented in the direction of the resin flow. It is therefore considered that the strength of the specimens depends on the anisotropy of their physical properties due to fiber orientation. Specifically, specimens cut out at 0° have a high strength while those cut out at 90° have a low strength. The following verifies that these behaviors can be simulated by analysis.

In section 3.2, we already confirmed that changes in injection speed affect the fiber orientation distribution and that the phenomenon can be reproduced by analysis. To determine the impact of changes in fiber orientation due to variations in injection speed on the physical properties, both a strength evaluation and a comparison with analysis results have been carried out at two injection speed levels: high and low.

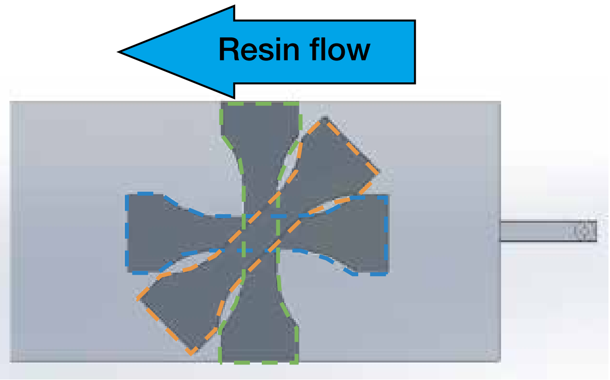


Fig. 10 Locations from which strength test specimens were cut out

Figs. 11 and 12 show the test results. These Figures reveal that the analysis model can reproduce the behavior of the actual specimens. The end point of the S-S curves represents the timing when the specimen fractured. Fracture was determined according to the Tsai-Hill 3D transverse criterion. By considering the breaking strain for each fiber orientation, the analysis model also reproduces fracture timing with good accuracy.

The results also show that the slower the injection speed, the larger the anisotropy with high strength at 0° and low strength at 90°. This is probably attributable to the finding in section 3.2 that a higher degree of fiber orientation is found in the direction of MD for low injection speed. In other words, the injection molding method impacts the fiber orientation, which further affects the physical properties. We have verified that these changes can be reproduced with good accuracy by an analysis model that considers fiber orientation.

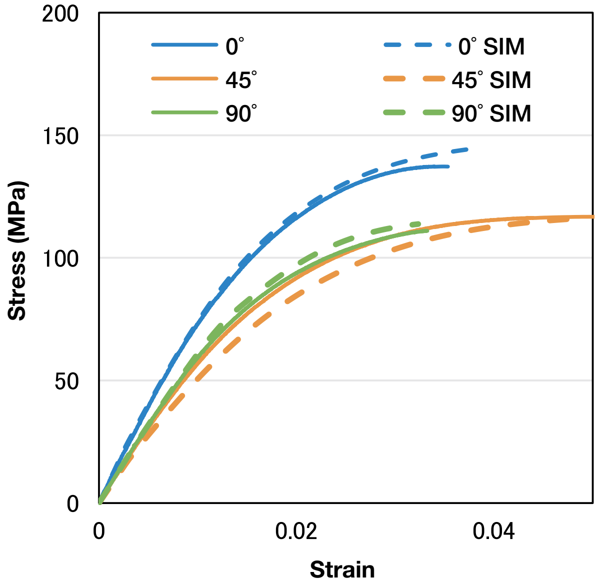


Fig. 11 Structural analysis accuracy for various cut-out angles (high speed injection)

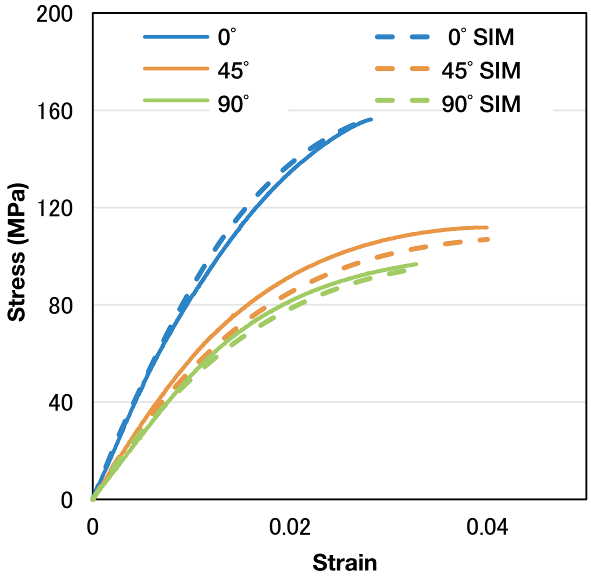


Fig. 12 Structural analysis accuracy for various cut-out angles (low speed injection)

3.4 Improvement of Prediction Accuracy for Strength Reduction Rate of Welds

When a flow of molten resin meets another flow of molten resin during injection molding, a weld line is formed. The weld line substantially degrades the strength of the composite because of the local change in fiber orientation and the existence of a fusion interface (Fig. 13). In fact, it is difficult to completely eliminate the formation of weld lines in injection molding of actual products. Therefore, it is essential to carry out analysis with weld lines taken into account, in order to improve the strength analysis accuracy.

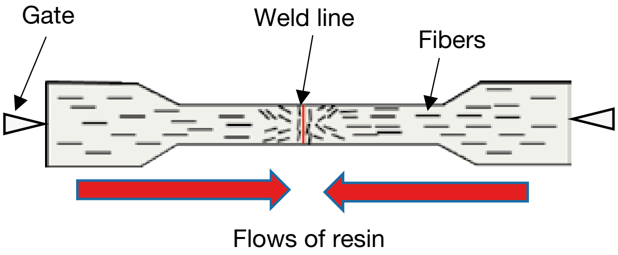


Fig. 13 Schematic of weld line

As stated above, welds may have lower strength due to a local change in fiber orientation and the existence of a fusion interface. Photo 2 shows an X-ray CT image of the fiber orientation distribution of a weld. In the portion where the flows of resin merge, fibers are densely positioned in the direction perpendicular to the direction of the flows of resin. In this way, the weld is the place where there is a local change in fiber orientation and is likely to be a source of fracture partly because of the existence of the fusion interface. By predicting the fiber orientation at the resin merging point by flow analysis and then including the lower strength due to the fusion interface as an analysis variable, we have successfully improved the prediction accuracy for strength of the welds (Fig. 14).

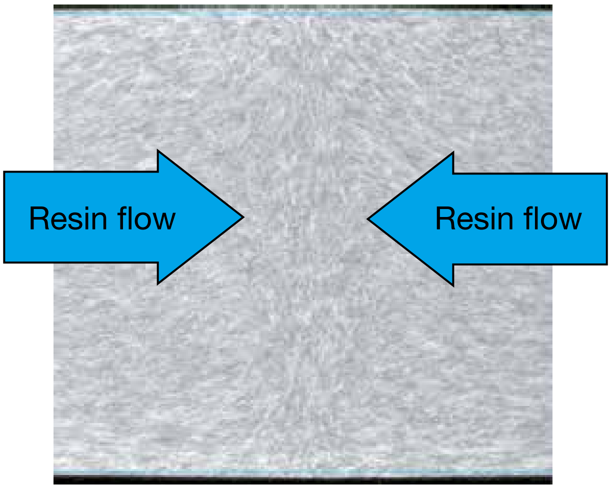


Photo 2 Fiber orientation in the weld

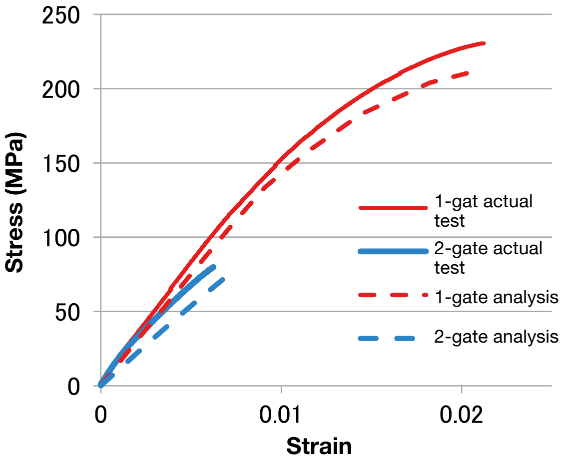


Fig. 14 Prediction accuracy for strength of welds

Through these efforts, we have established an analysis technique with consideration given to the fiber orientation and weld line that substantially affect the physical properties of FRP injection-molded products.

4 Prediction Accuracy Verification with Actual Part Geometry

4. 1 Confirmation of the Effect with Actual Part Geometry

Since it is now possible to carry out the strength analysis considering the fiber orientation and weld line, this chapter verifies the effect of the analysis by using actual parts. An example for plastic bump stoppers for shock absorbers is introduced as follows. The plastic bump stopper is press-fitted into the outer. When the stopper with geometry [1] was press-fitted into the outer, a fracture occurred. Then, the part design was modified on a trial-and-error basis to have another geometry [2], which eventually eliminated the fracture problem (Fig. 15). We then tried to verify that this phenomenon can be reproduced by analysis.

First of all, we examined the flow behavior of resin through resin flow analysis. The examination revealed that the resin flow behavior varies according to the part geometry, resulting in different areas where the weld line is formed. We then conducted a structural analysis that considers the fiber orientation and a lower strength of the weld line. As a result, the analysis successfully reproduced the behavior that the part with geometry [1] fractured while that with geometry [2] did not (Fig. 16). Thus, we confirmed that, when designing FRP parts, it is important and effective to study how to ensure the material strength, including the influence of the manufacturing method.

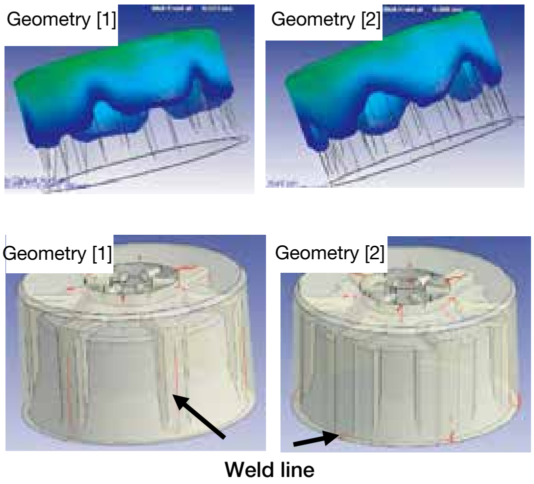


Fig. 15 Weld lines formed in different locations

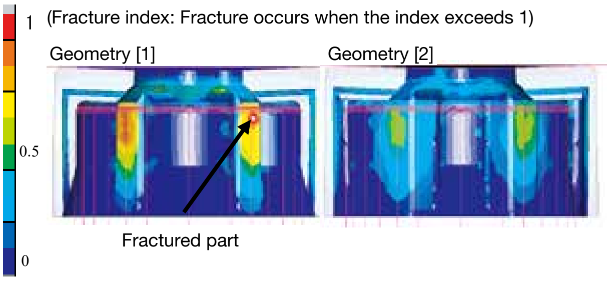


Fig. 16 Analysis of fracture index during press-fitting into the outer

5 Concluding Remarks

FRP injection-molded products have anisotropy or distribution of their mechanical properties due to fiber orientations and/or weld lines generated during the molding process. We have developed a structural analysis technique that considers fiber orientation and welds in the molding process, improving the prediction accuracy for physical properties of plastic parts. It has also been found that the technique can be used to predict the fracture behavior of actual parts of different geometries. We have confirmed that, when designing FRP parts, it is important and effective to study material strength, including the influence of the manufacturing process.

6 Future Prospects

This technique has improved the strength prediction accuracy for plastic parts. We will apply the technique to various actual parts to improve the development efficiency and optimize the part geometry for cost and weight reduction, contributing to higher competitiveness.

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