



Influence of one-dimensional material flow on mechanical properties and fiber orientation distribution of thin-ply carbon fiber reinforced thermoplastics sheet molding compounds

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ABSTRACT

The molding flow of carbon fiber reinforced thermoplastic sheet molding compounds (CFRTP-SMC) is complex and requires a comprehensive understanding of underlying processes. This study investigates the material behavior during compression molding processes, focusing on the influence of the ratio of initial material charge area over mold area (charge ratio) on mechanical properties. The results highlight the CFRTP-SMC material's excellent flowability and moldability and confirm that the mechanical properties and internal morphology change with charge ratios. In addition, a correlation between mechanical properties and internal morphology is established through quantitative analysis of fiber orientation distributions using X-ray computed tomography. This comprehensive investigation not only sheds light on the molding behavior of CFRTP-SMCs, but also underscores the importance of material charge ratios in influencing the mechanical properties. This study also provides a case study for validating numerical process models.

1. Introduction

To reduce fuel consumption and CO₂ emissions, weight saving of transport systems is the key. Several types of carbon fiber reinforced thermoplastics (CFRTP) have been developed for application in lightweight structures in mass-production automobiles to improve the recyclability of composite materials and the sustainability in transport [1]. However, in the process of forming components with complex structures, long-fiber systems are difficult to control due to the lack of flexibility of fiber orientations during forming. Traditionally, injection molding has been applied. However, it only provides relatively low-performance components owing to discontinuous fibers, relatively lower fiber volume fraction and flow-induced orientation variation. The length of fiber greatly impacts composite materials' mechanical properties and formability. Fiber reinforcements are categorized into short fibers (SF), sheet molding compounds (SMC), long discontinuous fibers (LDF), and continuous fibers. Continuous fiber composites excel in mechanical properties but are limited in forming complex shapes, while SF composites can form intricate parts but lack strength. LDF composites offer a balance, and SMC composites provide unique characteristics

[2–4]. And SMC material, which utilized chopped fibers in a polymer resin (normally thermosetting), can be molded into complex structures with a relatively high fiber volume fraction of approximately 50–60 % [5,6]. The difference between long fiber thermoplastics (LFTS) and CFRTP-SMC exist on the morphology of fiber. In CFRTP-SMC, fibers are gathered into tows, and the tows are randomly distributed, resulting a higher fiber volume fraction. To verify the application of SMCs, the analysis of forming processes is unavoidable, which was considered to influence the material performance significantly [7].

For traditional thermosetting SMCs, various works on the compression molding process have been conducted. Hohberg et al. [8] explored the way to get viscosity of SMCs and delves into rheological characterization of different SMC types, enhancing understanding of viscosity and friction parameters [9]. They also compared the flow behavior of glass fiber reinforced SMC and carbon fiber reinforced SMC, discovered the difference in material flow [10]. Dumont et al. [11] focused on the viscous behavior of SMC, relationships between stress and strain rates, and between stress and fiber content, proposed a nonlinear viscous and transversely isotropic model. The compression molding parameters' influence on mechanical properties of molded SMC was investigated by

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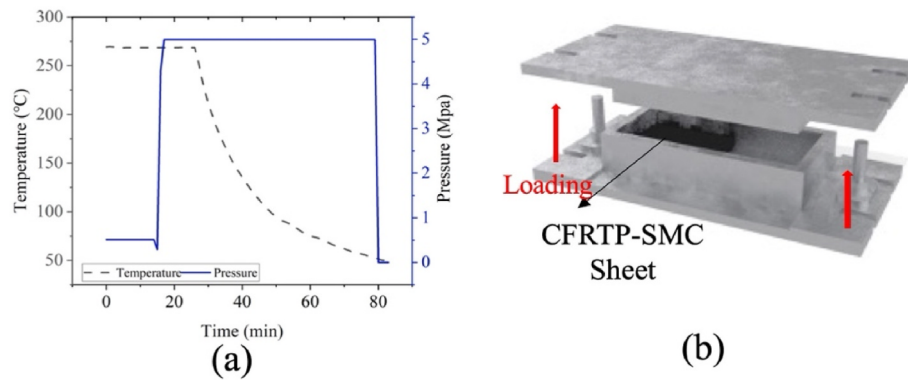


Fig. 1. Compression molding (a) conditions and (b) raw material in the mold.

Trauth et al. [12] on different charge percentage and by Kim et al. [13] on the mold geometry and mold temperatures and mold closing speeds [14]. Also, various simulation methods have been proposed and verified on different scales, mold geometries and mold flow directions [15–19]. At the same time, it was pointed out by Schladitz et al. [20], Tang et al. [21] and Bauer et al. [22] that fiber orientations have a strong connection with the failure behavior, fatigue performance and homogenized stiffnesses, respectively. Little research about SMCs shows the direct effects of material flow on the mechanical properties and internal morphology. Singh and Shrivastava [23] investigated the fiber orientation effect on woven fabric and Lu et al. [24] build a model to capture the mechanical behavior of unidirectional fiber reinforced polymers (UD-FRPs) considering fiber orientation. But how flow affects them and the interaction between them have not been explicitly stated of CFRTP-SMC. And few of these studies have investigated fiber orientation distribution (FOD) changes quantitatively using X-ray computed tomography (CT scanning) or analyzed FOD variations during compression forming based on the statistical distribution of fiber orientations.

A high-performance thermoplastic SMC material developed by the Takahashi laboratory was called chopped carbon fiber tape reinforced thermoplastics (CTT). It is made of chopped ultra-thin prepreg tapes and has a similar morphology as the traditional SMCs, so it is also called carbon fiber reinforced thermoplastics sheet molding compounds (CFRTP-SMC) in this work. It is a new SMC system, considering its thermoplastic and thin-ply characteristics. It has also been studied in various ways, including but not limited to the molding process [25], the mechanical properties [26,27], the internal geometry [28], manufacturing process [7] and numerical analysis [29]. Previous studies have indicated that CFRTP-SMC has a high fiber volume fraction, with excellent formability, which is determined by the material's ability to be molded into complex shapes and strong mechanical properties [30–32]. In related research, fiber orientation was obtained by CT scanning method [28,33–35], and the accuracy of this method has been investigated by Cai et al. [36]. Previous studies have demonstrated that the mechanical properties and internal morphology of CFRTP-SMC are of great interest during compression molding.

Although numerous studies have investigated the flow of SMC materials, there is limited research on the flow characteristics of CFRTP-SMC made of prepreps with a thickness of less than 100 μm . CFRTP-SMC exhibits superior mechanical properties compared to traditional SMCs, but it remains unclear whether its flow characteristics are similar to those of other SMCs. Furthermore, while some studies have indicated that flow can alter the anisotropic behavior of SMC materials using anisotropic parameters [37–40], there is a lack of research on how the initial filling rate of the flow affects these parameters and the distribution of these effects on the molded flat plate.

In this study, fiber movements caused by one-directional material flow were quantified in FOD analyses via CT scanning. This study for the first time builds the connection between the internal morphology and

Table 1

Size of the raw CFRTP-SMC sheet with different charge ratios before molding.

Raw sheet size (mm)	Charge Ratio	Weight (g)
125 × 250	1	92
125 × 167	1.5	92
125 × 125	2	92
125 × 100	2.5	92

the mechanical properties of CFRTP-SMC during a one-dimensional flow process. This research also establishes the change of internal morphology during compression molding through a combination of FOD analysis and flexural tests of plates with different charge ratios.

2. Experimental study

2.1. Material and compression molding process

The CFRTP-SMC material used in this research consists of randomly oriented ultra-thin (50 μm) unidirectional semi-prepreg strands manufactured from carbon fiber tow (TR 50S, Mitsubishi Rayon Co., Ltd.) and Polyamid-6 film (PA6, DIAMIRONTM C, Mitsubishi Plastics, Inc.). The fiber volume fraction is approximately 50 % and a strand size is 19 mm × 5 mm. These characteristics result in excellent mechanical properties and good flowability during the compression molding.

During the manufacturing process, a 30-ton hydraulic press (Pinette Emidecau Industries, France) was used for the forming process. To ensure that the material can fully flow in the mold and be formed into a stable molded plate, the temperature is set at 270 °C, 50 °C higher than the melting temperature of PA6 220 °C. In the automatic molding cycle in Fig. 1(a), the temperature was firstly increased to 270 °C with a gradient of 20 °C per minute. The pressure was increased to 2 MPa and held for 5 s for preliminary contact, and then released for a short period of time (set to 3 s) to remove any voids between the intermediate material layers. The pressure was calculated from the loading force (156 kN) and the molded plate area, which is 125 mm × 250 mm in all cases. The pressure was then increased to 5 MPa and held for 10 min to begin forming. Finally, the pressure was released, and the temperature was gradually reduced to the room temperature at a rate of 20 °C/min to complete the entire molding process, as shown in Fig. 1(a). Under normal molding conditions, a small number of CFRTP-SMC tapes were extruded from the mold and burrs were formed along the periphery of the mold. The weight loss from the intermediate material to CFRTP-SMC plate is about 3 %–5 %.

To study the changes in material flow during the molding process, Charge Ratio (CR) is defined as a measure of the degree of flow. This is defined as the ratio of the material area after molding to the material area before molding. The raw material was initially placed to the left end of the mold e.g. with a size of 250 mm × 100 mm for CR of 2.5, as shown

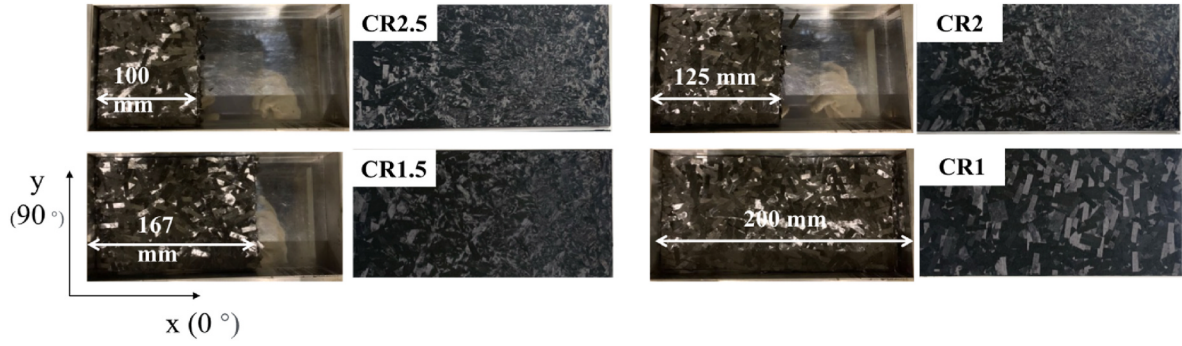


Fig. 2. CFRTP-SMC in the mold before and after molding with different charge ratios.

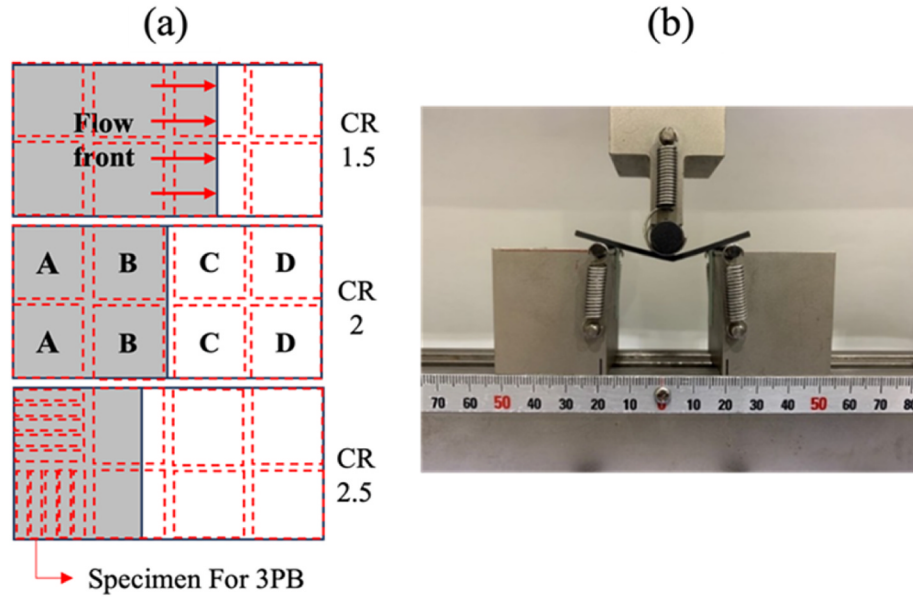


Fig. 3. Sampling method (a) for each plate with different CRs and (b) three-point bending tests to measure mechanical properties.

in Fig. 1(b). The CR was varied from 1 to 2.5 depending on the initial area of the raw material, with an increment of 0.5, as shown in Table 1. Under the same molding condition, the weight of the raw material for each CR was kept the same, and the raw material fully filled the mold. As a result, the molded plate had a constant density, and the final molded plates had the same thickness (125 mm × 250 mm × 2 mm) by controlling weight. Fig. 2 shows the CFRTP-SMC sheet before molding with four CRs. As the CR increased, the material flowed further to the right during molding.

2.2. Test set-up

Each molded plate in Fig. 2 was divided into eight regions to evaluate its mechanical properties along 0° (one-dimensional flow direction) and at 90° (perpendicular to the one-dimensional flow direction). The cutting method is shown in Fig. 3(a). The CFRTP-SMC raw materials were in gray color. The schematic of different charge ratios shows the flow circumstance, with four regions (A, B, C and D) in one plate and bending specimens cut from each region along two directions. The one-dimensional flow direction was from A to D.

Three-point bending tests were performed with a span of 40 mm and a loading speed of 1 mm/min using a screw-driven universal testing machine with a 5 kN load cell (AUTOGRAPH AGX plus, Shimadzu Co.) according to JIS K 7017 standard, as showed in Fig. 3(b). The thickness and width of every specimen were measured and averaged at three

random points. With all the data obtained, the maximum stress in the outer surface of the test specimen occurs at the midpoint and can be calculated as follows.

$$\sigma_f = \frac{3PL}{2bd^2} \quad (1)$$

where σ_f is the stress in the outer fibers at midpoint, of which the maximum is flexural strength. P is the load at certain point on the load-deflection curve, L refers to the support span, and b and d stand for the width and thickness of the specimen, respectively.

The flexural strain for any deflection can be calculated with the equation below.

$$\varepsilon_f = \frac{6Dd}{L^2} \quad (2)$$

where D is the maximum deflection on the center of the beam.

The flexural modulus was calculated from two discrete points on the load deflection curve. The selected points were chosen at two pre-defined strain points in the linear region. Here, 0.05 % and 0.25 % strains were selected.

$$E_f = \frac{\sigma_{f2} - \sigma_{f1}}{\varepsilon_{f2} - \varepsilon_{f1}} \quad (3)$$

The experiment setting of reference plate without one-dimensional flow (CR = 1) was identical to other specimens (CR = 1.5, 2, and 2.5).

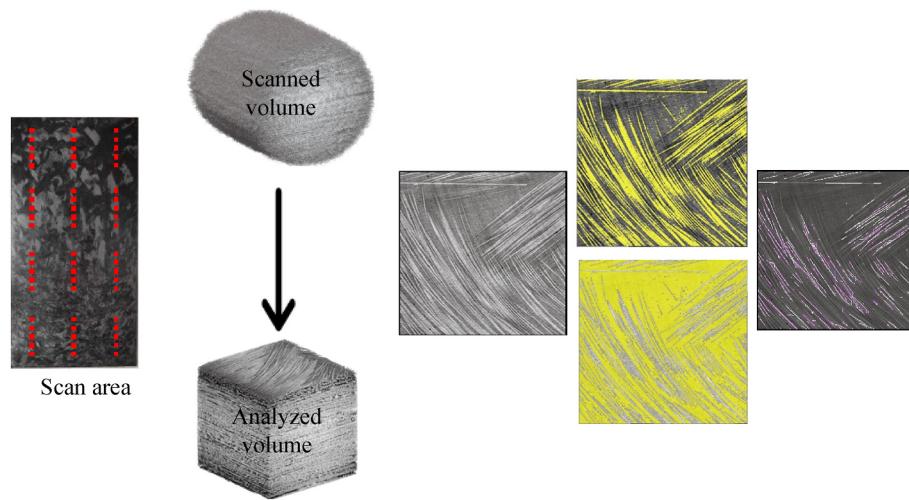


Fig. 4. Schematic of the sampling, scanning and analysis process for CFRTP-SMC.

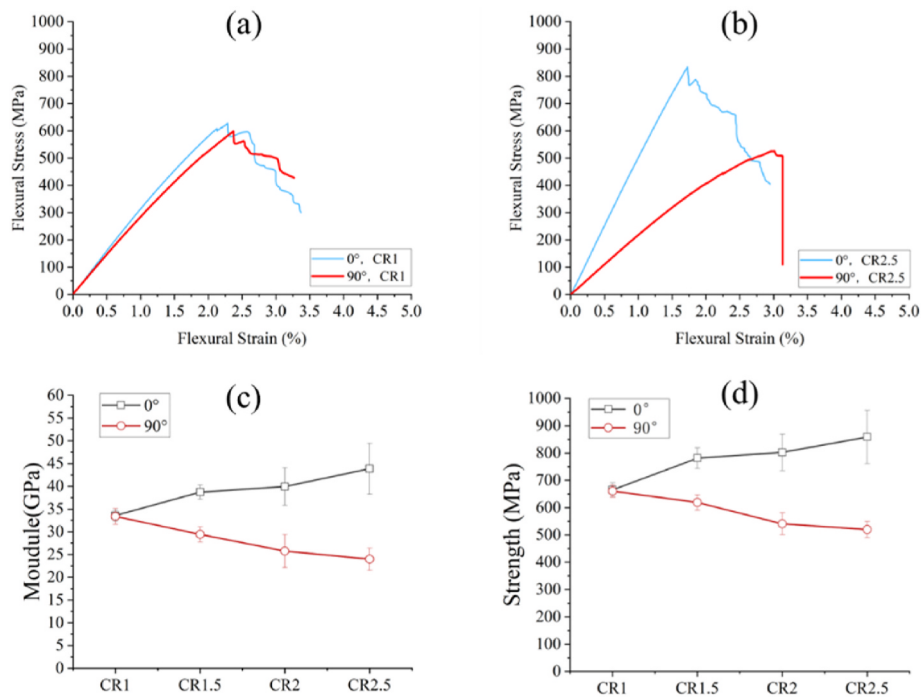


Fig. 5. Typical strain-stress curves from three point-bending tests of different charge ratios of (a) CR = 1, (b) CR = 2.5, and in different directions charge ratios bring changes in (c) modulus, (d) strength.

The nominal thickness of all plates was 2 mm. The span of the three-point bending specimens was 40 mm, and the total length was 60 mm.

2.3. Fiber orientation distribution (FOD) analysis

A SHIMADZU inspeXio SMX-100CT X-ray CT scanner was used to determine the FOD. Given the scan area limitation of the scanner, and the strand size is 19 mm × 2 mm, a group of 15 specimens with a scan size 2 mm × 2 mm × 2 mm each, was collected for each region to increase the amount of data available. As previous research showed, a specimen number of higher than 15 is enough for this material to get a convergent FOD value [36]. The following settings were employed for CT analysis: voltage of 55 kV, current of 65 μA, 1440 times of view, 16 average settings, a slice thickness of 12 μm, and a field of view of 1 mm × 1 mm × 1 mm. As a result, the scan time for a single specimen was 28 minutes, and the voxel size of the resulting volumetric image was 1.9

μm.

The raw images obtained from the CT scanner were cylindrical, which were constructed into a cubic volume for more accurate subsequent volumetric image processing and analysis. The three-dimensional structure of the image was reconstructed through CT imaging using an image processing software (TRI/3D-BON, RATOC System Engineering Co., Ltd.). The three-dimensional model can be sectioned into multiple layers along different directions. The fiber orientation was then analyzed layer-by-layer. The size for each model is around 700 μm × 700 μm × 700 μm taken at the mid-plane of the molded plates, as shown in Fig. 4.

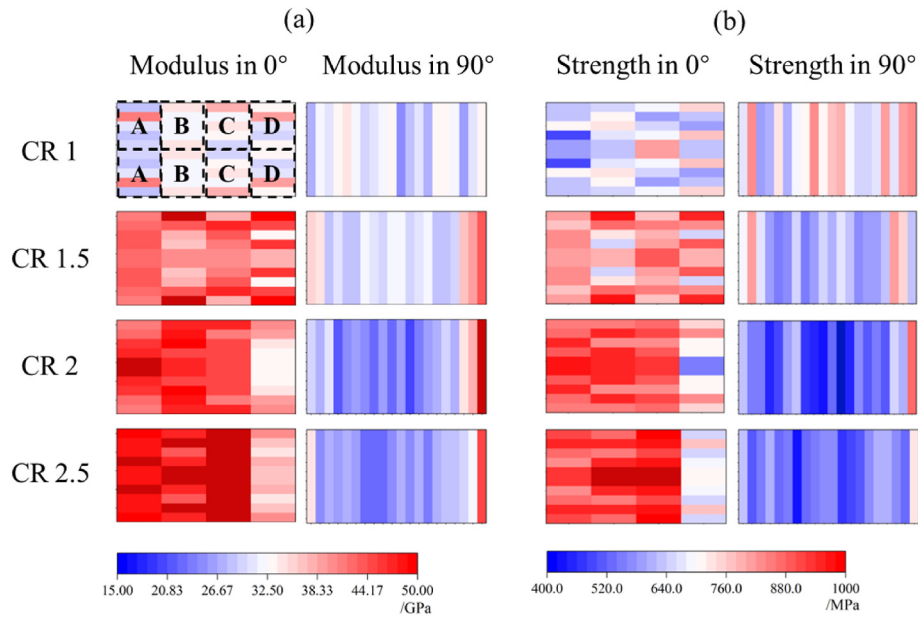


Fig. 6. Schematic of (a) modulus and (b) strength distribution based on three-point bending tests.

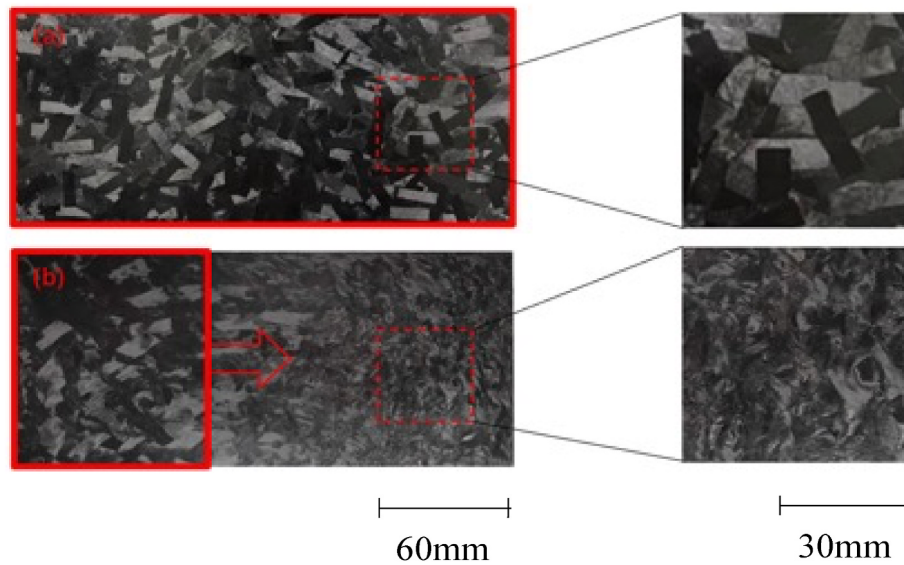


Fig. 7. Difference in tape morphology on surface for (a) CR1, (b) CR2.5.

3. Experimental results

3.1. Mechanical properties

Three-point bending tests were conducted of each specimen as shown in Fig. 3(b). For each region (A, B, C and D), five specimens were used to test the mechanical properties along 0° , other five specimens were used to represent the mechanical properties along 90° . When analyzing the results of the three-point bending experiments, the changes in flexural modulus and strength were focused on. The modulus of each specimen was calculated according to Equation (3). The original in-plane isotropy of raw CFRTP-SMC sheet changes with the flow during compression molding, as the comparison of modulus and strength at 0° and 90° is shown in Fig. 5(c) and (d). The plate shows different mechanical properties along two directions at different CRs. The regional difference is also obvious. The detailed comparison and distribution based on the result of three-point bending tests is shown in Fig. 6. The

figure is a schematic contour map of the distribution of modulus and strength based on the test results of five specimens for each region, and the data between the test data was linked using a straight line. From Fig. 6, a variation of the modulus and strength can be observed. This comparison generally highlights that while the modulus and strength in the 0° direction are enhanced with an increase in CR, they decrease in the 90° direction.

However, as demonstrated in Fig. 6, this phenomenon also indicates an uneven distribution of mechanical properties and regional variation. This is due to the variation in mechanical properties due to flow, as well as the discrete nature of the test results using three-point bending specimens of a finite size of 60 mm x 10 mm. The region difference mainly exists between the end of flow (D) and the other regions (A, B, C). At the end of flow, the one-directional enhancement phenomenon weakens. Region D shows a more uniform distribution, which is close to the mechanical properties of formed CFRTP-SMC plate without on-dimensional flow (CR = 1). The reason for this will be shown in next

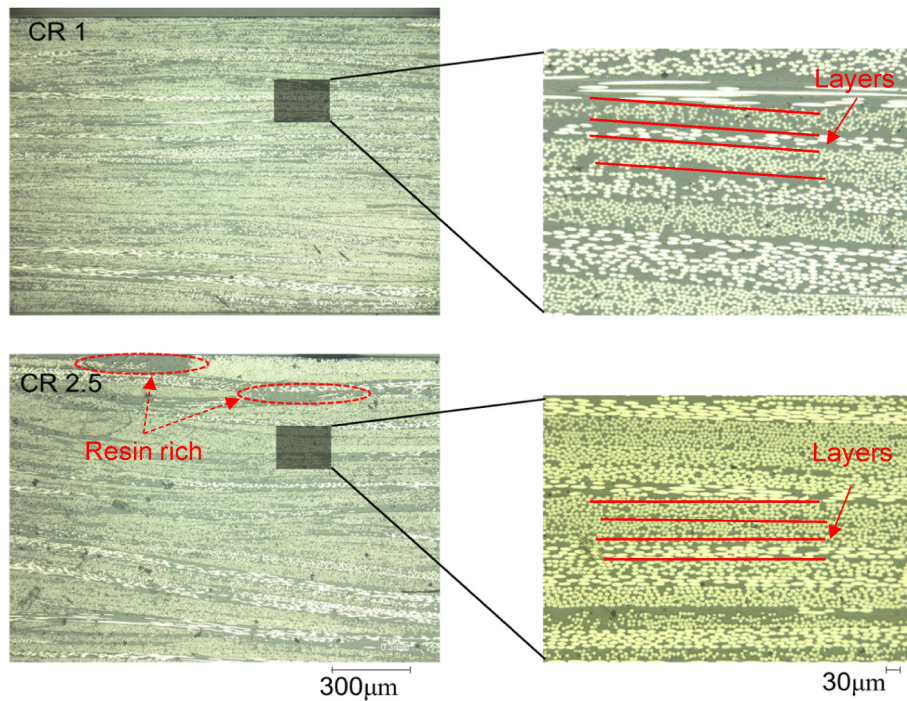


Fig. 8. Cross-section of the molded plate through optical microscopy.

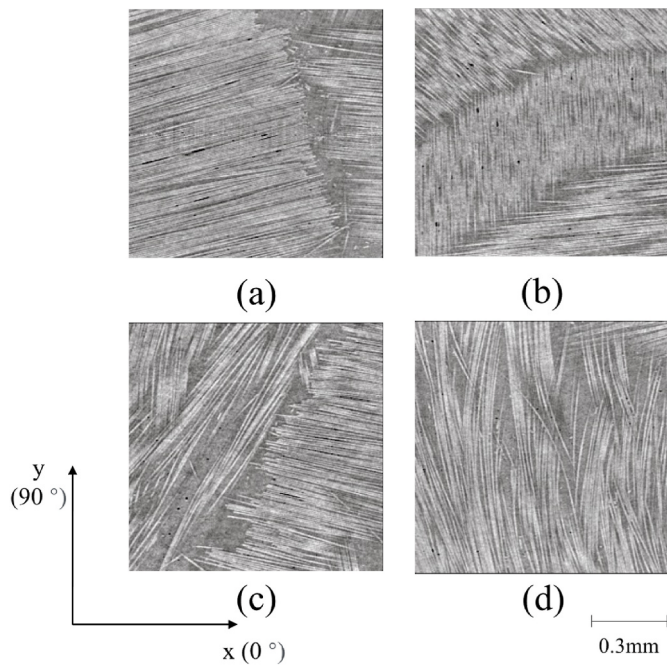


Fig. 9. CT images of two typical situations: (a) CR1, fibers along 0° , (b) CR1, fibers along 90° , (c) CR2.5, fibers along 0° , (d) CR2.5, fibers along 90° .

section.

3.2. Comparison of morphology and FOD

As shown in Fig. 7, the surface morphology of the molded plates varied with different CRs. Some twisting and distortion of the fiber tape can be observed from the surface. This variation indicates possible changes in the internal morphology. The measured modules showed the largest change between CR2.5 and CR1 at the same location.

Detailed observations using an optical microscope reveal that at lower magnifications, CR2.5 exhibits a more irregular internal morphology with significant interlayer variations and more resin-rich regions compared to CR1. However, at higher magnifications, local areas of CR2.5 still display a layered structure, as illustrated in Fig. 8.

CT images of the two specimens are therefore shown in Fig. 9 to further illustrate the internal morphology changes related to these two CRs at the same location and thickness. The top two images in Fig. 9(a) and (b) are specimens from CR1 Region B, and the bottom two images in Fig. 9(c) and (d) are specimens from CR2.5 Region B. Two typical images, each showing the fiber oriented in two perpendicular directions, are shown to illustrate the change. Fibers oriented along the X-axis (Fig. 9(a) and (c)) and Y-axis (Fig. 9(b) and (d)) show completely different orientations. Since the X-axis is the one-dimensional flow direction, the fibers parallel to the flow direction mainly show the movement of tapes in the flow direction, which means the tape shape will no longer hold the same as the original. The fibers perpendicular to the one-dimensional flow direction mainly exhibited bending and separation changes.

For $CR = 1$, the carbon fiber tape was randomly distributed on the PA6 film during the fabrication of the CFRTSP-SMC preforms. In addition, the size of the image volume used for analysis was limited to ensure high resolution for computed tomography observations. As a result, it is difficult to identify overlapping regions or specific trends in the in-plane FOD histogram. However, at $CR = 2.5$, although randomness is still evident, a clear trend emerges as shown in the figure. More fibers are oriented toward the two ends of the histograms, which correspond to the flow direction of the one-dimensional flow. In contrast, the out-of-plane FOD histogram shows that most fibers are parallel with the in-plane direction, regardless of the change in charge ratios.

Quantitative assessment of fiber orientation frequencies within the in-plane angle ϕ ranging from 0° to 180° elucidates the FOD across various regions labeled A, B, C, and D.

To analyze the deviation in fiber orientation frequency from the baseline distribution, it is assumed that the non-flow CR1 material exhibits a uniform fiber orientation distribution. This baseline is used as a reference to compute deviations in the fiber orientation frequency for materials with different CR values. The methodology involves the

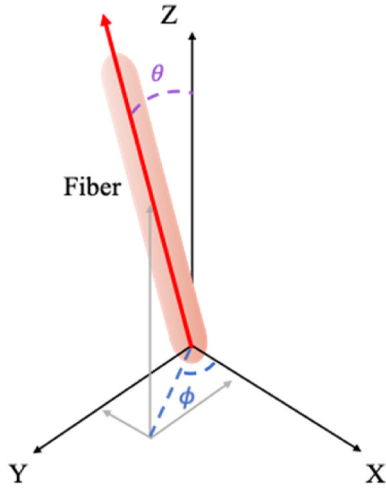


Fig. 10. Schematic of fiber orientation.

following steps:

Assuming a uniform distribution, the baseline number of fibers in each angular range θ_i for CR = 1 is given by:

$$N_{\text{baseline}}(\theta_i) = \frac{N_{\text{total, baseline}}}{n} \quad (4)$$

where $N_{\text{baseline}}(\theta_i)$ represents the total number of fibers for CR = 1, and n denotes the number of angular ranges (i.e., the number of segments the entire orientation range is divided into).

For a given material with a different CR value (CR = 1.5, 2, 2.5), the actual number of fibers within each angular range θ_i is determined and denoted as $N_{\text{CR}}(\theta_i)$. The total number of fibers for this material is $N_{\text{total, CR}}$.

To quantify the deviation, we first calculate the fiber orientation frequency in each angular range for both the baseline and the material with a different CR value. The frequency for the baseline is:

$$f_{\text{baseline}}(\theta_i) = \frac{N_{\text{baseline}}(\theta_i)}{N_{\text{total, baseline}}} \quad (5)$$

And the frequency for the material with a different CR value is:

$$f_{\text{CR}}(\theta_i) = \frac{N_{\text{CR}}(\theta_i)}{N_{\text{total, CR}}} \quad (6)$$

The deviation $\Delta f(\theta_i)$ in each angular range is then computed as:

$$\Delta f(\theta_i) = f_{\text{CR}}(\theta_i) - f_{\text{baseline}}(\theta_i) \quad (7)$$

Given that the baseline frequency is uniformly distributed, it simplifies to:

$$f_{\text{baseline}}(\theta_i) = \frac{N_{\text{baseline}}(\theta_i)}{N_{\text{total, baseline}}} = \frac{1}{n} \quad (8)$$

Thus, the deviation can be expressed as:

$$\Delta P(\theta_i) = \left(\frac{N_{\text{CR}}(\theta_i)}{N_{\text{total, CR}}} - \frac{1}{n} \right) \times 100\% \quad (9)$$

To visualize the frequency changes, the data is fitted using the poly4 function in Origin software (OriginLab Corporation). The poly4 function fits the data points to a fourth-degree polynomial, allowing for a continuous curve representation of the frequency deviations. The fitting function is given by:

$$y = a + bx + cx^2 + dx^3 + ex^4 \quad (10)$$

where a, b, c, d , and e are fitting parameters, and x represents the angular range.

The in-plane angle ϕ and out-of-plane angle θ in Fig. 10 are analyzed as shown in Fig. 11. A color bar is used to illustrate the differences in ϕ and θ . The out-of-plane angle θ centered on 90° with all CRs, which means few fibers stay on the layer of each. Since the internal geometry showed in Fig. 11 still have a clearly hierarchical structure, the material can be considered as a two-dimensional random material. These out-of-plane angle results show that most of the orientation of the fibers are at 90° or in-plane so the following analysis will mainly focus on in-plane ϕ distribution.

The quantitative fiber orientation frequency can be analyzed from the in-plane angle ϕ , ranging from 0° to 180° , as shown in Fig. 12. The figure here shows the change of FOD in A, B, C and D regions. The horizontal axis represents the range of in-plane angle, and vertical axis is the frequency change. The frequency change of fiber in-plane angle ϕ was calculated by subtracting the frequency of fibers measured in that range for CR1 (same as the uniform distribution of raw material without one-dimensional flowing). The FODs obtained at the four regions can be related to the test results. The result comparison clearly shows the change caused by the flow. Contrary to the uniform distribution of raw CFRTS-SMC sheet [26,27], the fiber frequency shows an increase around 0° and 180° , which means that more fibers are re-oriented towards the

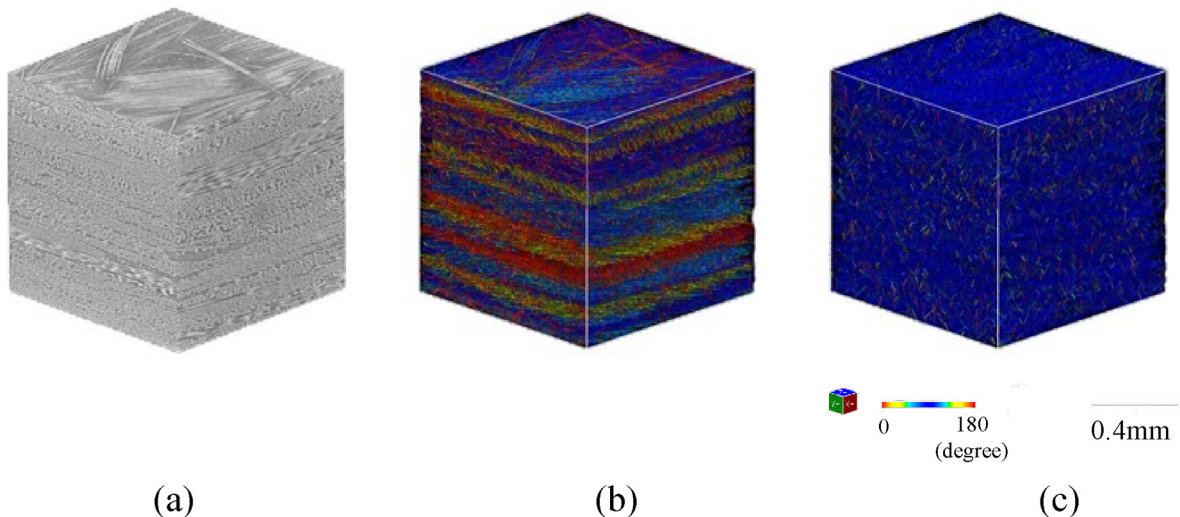


Fig. 11. Models of CR2.5 generated from TRI/3D-BON showing (a) microstructure, (b) in-plane fiber orientation, (c) out-of-plane fiber orientation.

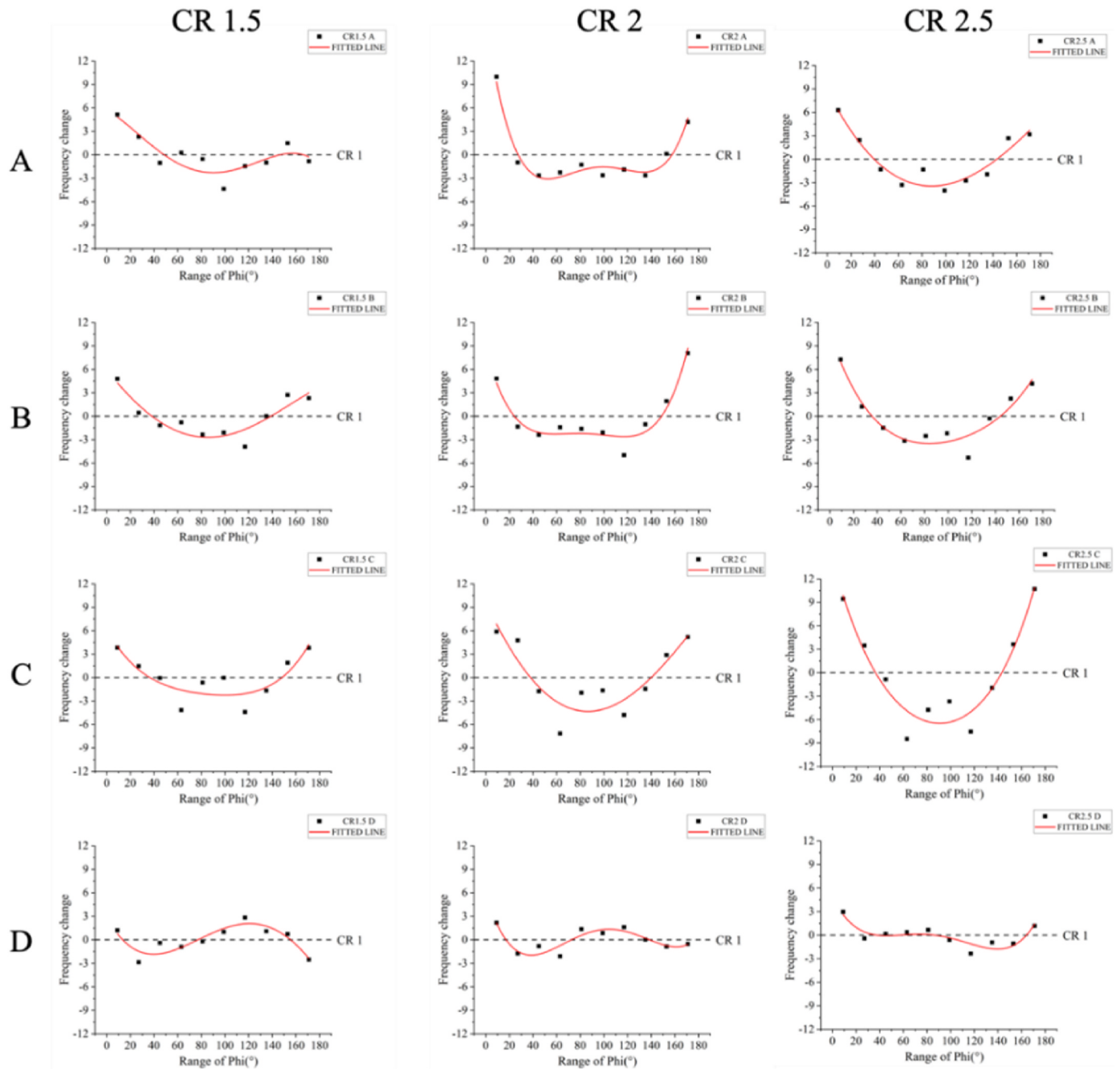


Fig. 12. Fiber orientation distribution (FOD) results of the in-plane angle ϕ with different charge ratios and in different regions.

flow direction in the A, B, and C regions. In contrast, in the flow end region D opposite to the flow front region A, the FOD here tends to have a closer distribution to the flow-free state (CR1). All the distribution results are consistent with the three-point bending test results.

4. Discussion

This study focuses on the statistical variation of FOD in one-dimensional flow during compression molding of CFRTP-SMC. The selected region for the analysis of fiber orientation distribution (FOD) using CT scanning was the middle portion of the 2 mm - thick molded sheet, which is 1 mm thick. In the experimental results it was demonstrated that for CFRTP-SMC material, the flow has a significant effect on its FOD at the mid-plane through thickness. However, the statistical variation of FOD in the thickness direction was not studied directly due

to the limited CT data.

The potential change of FOD in the upper and lower half of the specimen can be indirectly demonstrated through three-point bending tests. Because a three-point bending test subjects the material to both tensile and compressive stresses, this results in a flexural modulus that is often lower than Young's modulus obtained from tensile tests. Nonetheless, related studies have shown that the tensile and flexural moduli of thin-ply CFRTP-SMC are similar [41,42]. Furthermore, after conducting extra reversed bending tests of the previous specimens with a charge ratio of 2.5, it was found that the specimens in different regions exhibited nearly identical flexural moduli, as shown in Fig. 13. Additionally, a comparison of the stress-strain curves of the four selected specimens revealed no significant change of elastic response, as shown in Fig. 14. Therefore, it can be postulated that the FODs in the upper and lower halves through thickness are statistically indifferent for

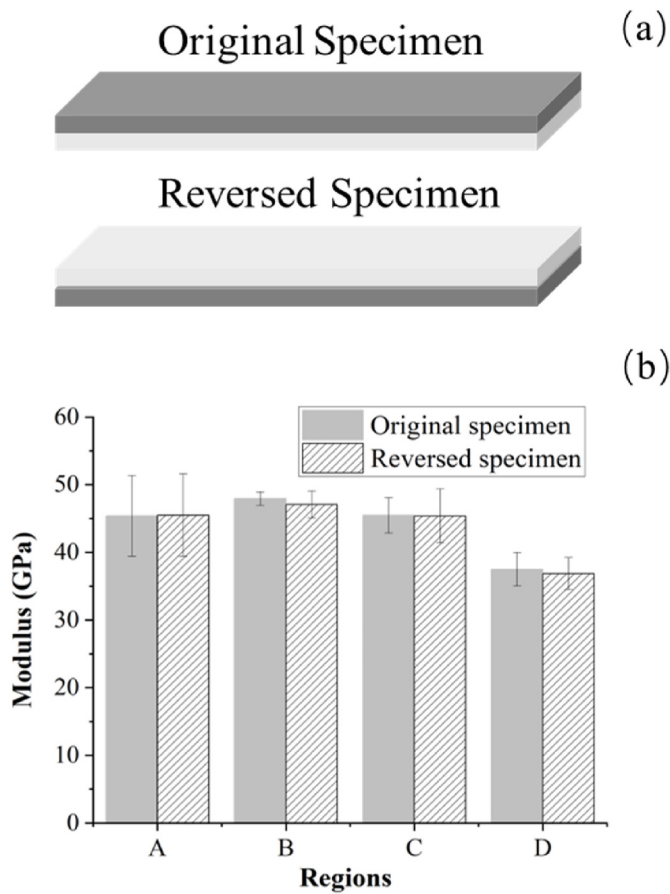


Fig. 13. (a) Schematics of the original and reversed three-point bending specimens, (b) modulus comparison of the flipped specimens with CR2.5 in different regions.

CFRTP-SMC materials. However, this serves as an indirect validation of FOD through the comparison of flexural modulus which represents the average value through the thickness. Optical microscopy of the cross-sections also revealed no significant differences in morphology between the upper half and lower half.

The experiment in this study demonstrates a strong correlation between fiber orientation and mechanical properties. When there is an increase in modulus and strength, the FOD in the corresponding region correlates to a concentration towards certain angles, i.e. more aligned against the testing direction. Understanding this relationship is important for industrial applications, such as selecting appropriate charge areas and optimizing reinforcement regions to achieve stronger mechanical properties through a controlled fiber flow. This study is particularly novel concerning thin-ply and thermoplastic SMC systems such as the current CFRTP-SMC material, whereas other research focused more on thermosetting SMC systems with typical tape thicknesses [8,10,12–15,39,40].

5. Conclusions

In this study, one-dimensional flow during compression molding of thin-ply carbon fiber reinforced thermoplastic sheet molding compounds (CFRTP-SMC) was systematically investigated, revealing the remarkable flowability and moldability of the material under specified molding temperature and pressure. The mechanical properties and internal morphology of one-dimensional flow-molded CFRTP-SMC were investigated, with a special attention paid to the effect of charge ratios. Three-point bending tests and internal morphology characterization were performed, which elucidated the occurrence of a flow-direction strengthening phenomenon with a simultaneous weakening phenomenon in the perpendicular direction. Furthermore, this directional strengthening effect was found to be positively influenced by increasing the charge ratio. X-ray CT scanning and analysis were used to quantitatively analyze the fiber orientation distribution (FOD). Substantial variation in fiber orientation was observed over different charge ratios and regions, showing clear distinctions in between different regions and charge ratios. This study elucidates the influence of flow on the

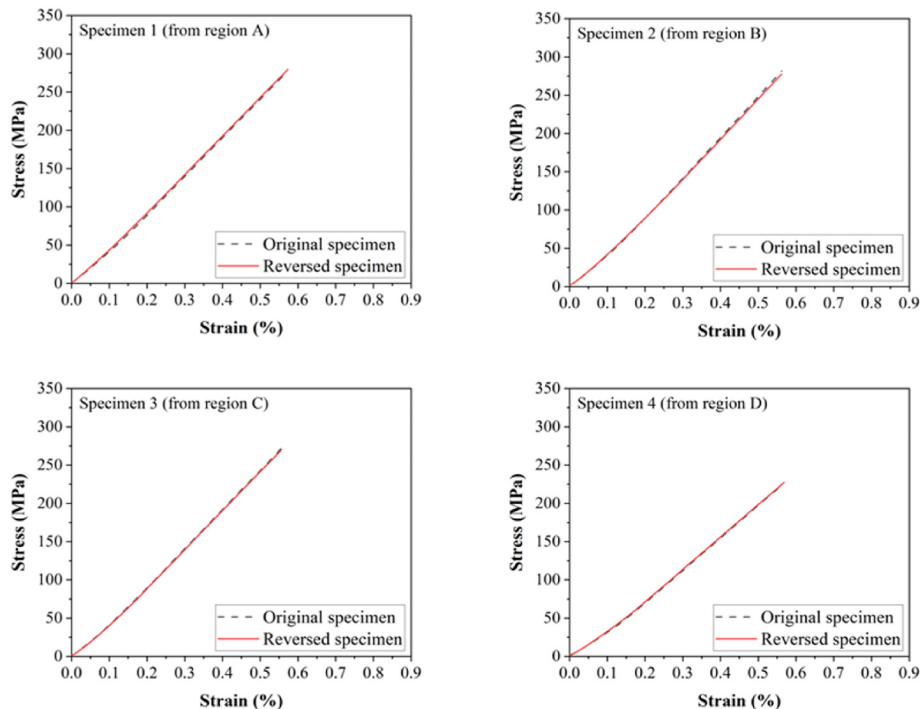


Fig. 14. Strain and stress curves of four flipped specimens in four different regions.

mechanical properties and internal morphology and confirms the relationship between the material charge state and mechanical properties by fiber orientation as molded. The charge ratio affects the uniformity of the cured material, with CR1 showing the best uniformity and the closest to in-plane isotropy. Material flow causes in-plane anisotropy, and using CR1 could aid in accurate predictions and designs. A charge ratio of around 1.5 is acceptable but the observed flow effects were greater in even higher charge ratios. These findings are specific to the materials used in this study, and optimal charge ratios may vary in the industry. Consequently, this study represents a notable advance in the understanding of the internal structure and fiber orientations of CFRTP-SMC during compression molding, with the potential to improve the design and manufacturing processes of these materials and to validate process simulation models.

CRedit authorship contribution statement

Zihao Zhao: Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Yi Wan:** Writing – review & editing, Supervision, Resources, Project administration, Methodology, Investigation, Conceptualization. **Xiaodong Xu:** Writing – review & editing, Funding acquisition. **Jun Takahashi:** Writing – review & editing, Supervision, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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