Article

Effects of Heating and Cooling of Injection Mold Cavity Surface and Melt Flow Control on Properties of Carbon Fiber Reinforced Semi-Aromatic Polyamide Molded Products

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Abstract: Fiber reinforced thermoplastics (FRTP), which is reinforced with glass or carbon fibers, are used to improve the mechanical strength of injection-molded products. However, FRTP has problems such as the formation of weld lines, the deterioration of the appearance due to the exposure of fibers on the molded product surface, and the deterioration of the strength of molded products due to the fiber orientation in the molded products. We have designed and fabricated an injection mold capable of melt flow control and induction heating and cooling that has the functions of both heating and cooling the injection mold as well as the function of controlling the melt flow direction using a movable core pin. In this study, the above-mentioned mold was used for the molding of carbon fiber reinforced semi-aromatic polyamide. As a result, we found that increasing the heating temperature of the mold and increasing melt flow control volume contribute to the prevention of the generation of a weld line and the exposure of fibers on the molded product surface, as well as to the formation of a flat surface and increased bending strength. The relationships of these results with the carbon fiber orientation in the molded products and the crystallization of semi-aromatic polyamide were also examined in this study.

Keywords: heating and cooling of injection mold; melt flow control; carbon fiber reinforced semi-aromatic polyamide; fiber orientation; bending strength; weld line; crystallization

1. Introduction

Polymers are light with excellent shapability. However, they have lower mechanical strength than metals. To address this problem, fiber reinforced plastics (FRP), which is reinforced with glass or carbon fibers, has been put to practical use and applied to structural members where high mechanical strength is required. Recently, the injection molding of fiber reinforced thermoplastics (FRTP) containing short fibers has been widely carried out to mass-produce molded products with complex shapes. In injection molding, a V-notch-shaped weld line [1] is generated in the melt front meeting area. This is where melt fronts divided by an insert, such as a pin or a block, in a mold cavity rejoin each other downstream of the insert. The weld line degrades the appearance of molded products. Also, as shown in Figure 1 (1), fibers in an FRTP are locally oriented parallel to the melt front meeting area, i.e., along the thickness direction of molded products, leading to the occurrence of anisotropy. The local deterioration of strength in the melt front meeting face results in the reduced strength of molded products [2,3]. In addition to the weld line, the exposure of fibers on the molded product surface results in a rough surface, which degrades the appearance of the product. Various measures are taken at production sites to address these problems. Rapid heat and cool injection molding is an example of a measure to prevent the generation of weld lines. With this method, the melt is injected into the mold while heating the mold cavity surface to a temperature close to, equal to, or higher than the melting point, Tm, or the glass transition point, Tg, of the polymer to slow the solidification of the melt and prevent the formation of a V-notch. The transferability of the cavity surface to the molded product surface is also improved. Variations of this method include rapid heating cycle molding (RHCM) [4], which circulates hot water or water vapor within the mold; the electric heater method, which heats the mold using a cartridge, sheath, or ceramic heater embedded in the mold [5,6]; and the induction heating method, which uses electromagnetic induction [7,8,9]. On the other hand, the local deterioration of strength in the melt front meeting area is prevented by the method shown in Figure 1 (2). With this method, one of the two flows is blocked immediately after the two melt fronts meet and the melt is allowed to flow only from the other direction. This induces an internal melt flow that goes through the meeting face, causing the fibers near the meeting face to orient parallel to the melt flow direction. As a result, the deterioration of strength is reduced because the fibers increase resilience against tensile and bending forces. The suggested methods to induce such an internal melt flow are as follows: (1) the push–pull method [10], with which the melt is injected alternately from two injection cylinders, (2) shear-controlled orientation in injection molding (SCOLIM) [11], which uses a passage-switching device placed between the injection cylinder and the mold, (3) the press α method [12], which drives a core block or a core pin in the mold, (4) the rotary core method [13], (5) the in-mold core pin driving method [14], and (6) the rotary runner exchanger method [15].

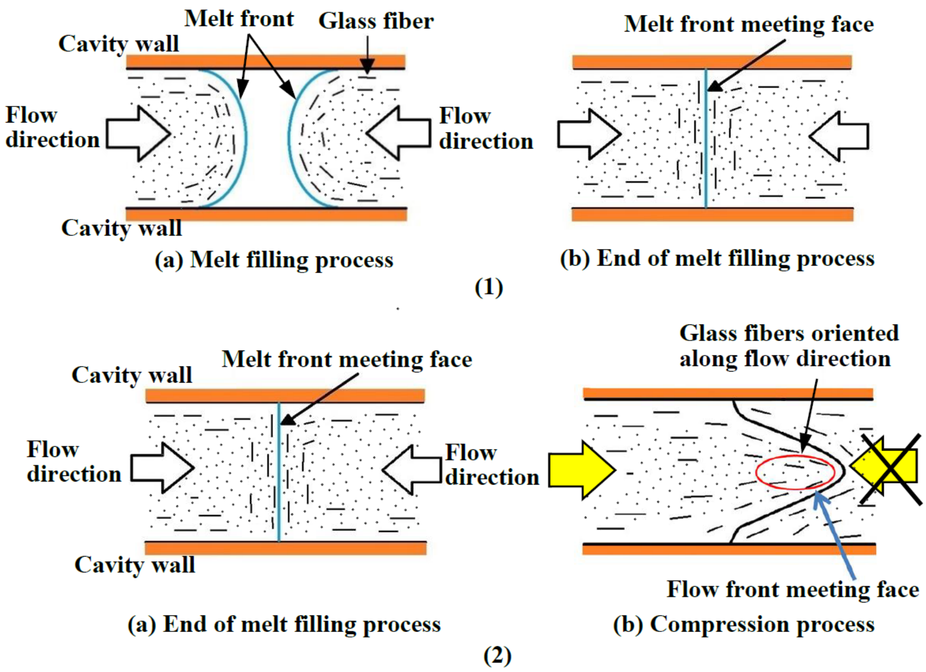

Figure 1. Fiber orientation around melt front meeting area: (**1-a**) and (**1-b**) Schematic diagram of the melt front meeting area; (**2-a**) and (**2-b**) Method of improving strength in the melt front meeting area.

However, there have been few detailed reports on how to achieve all the above purposes simultaneously, namely, the prevention of the generation of a weld line in the melt front meeting area and the exposure of glass fibers on the molded product surface as well as the prevention of the deterioration of strength due to the local orientation of fibers, although an attempt has been made to improve both the appearance and strength of molded products by combining the heating of the mold by RHCM with core driving [16]. The effects of the heating conditions of the mold and the conditions of core driving on the strength and appearance of molded products and the orientation of glass fibers have not been systematically evaluated.

We newly designed and fabricated an injection mold capable of both melt flow control using a movable core pin and induction heating and cooling at the same time. Using

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this mold, we evaluated the effects of differences in the heating conditions of the mold and the conditions of melt flow control on the appearance, fiber orientation, and mechanical strength of molded products made of polypropylene reinforced with short or long glass fibers [17].

In this study, the above-mentioned mold was applied to the molding of short carbon fiber reinforced semi-aromatic polyamide, which has already been widely used for automotive components because of its excellent mechanical strength, heat resistance, and dimensional stability. Then, the effects of the heating and cooling conditions of the mold and the conditions of melt flow control on the appearance and mechanical strength of molded products were evaluated.

2. Molding process and mold structure

Figure 2 shows the method of controlling the melt flow in the melt front meeting area (hereinafter referred to as "melt flow control"). The rotary runner exchanger method [15] is adopted in this mold. The long rectangular cavity used in this study has dimensions of 99 (L) × 23 (W) × 2 (T) mm and two-point gates facing each other. A movable core pin, which is rotationally driven, is placed in the middle of a runner to switch the direction of the flow channel from the cavity to the well cavity. First, the cavity surface is induction-heated to a certain temperature and then the melt is injected into the cavity. Measures are taken to prevent the generation of a weld line in the melt front meeting area and to improve the surface property of molded products in the melt filling process shown in Figure 2 (1). After the melt fronts meet, the induction heating is stopped and cooling water at a certain temperature is introduced into the mold in the holding pressure process shown in Figure 2 (2). Then, the melt flow from Gate A is blocked and the flow channel is directed to the well cavity by rotating the movable core pin by 90°. The melt flow is further directed to the well cavity by the compensation flow from Gate B, which is generated by the holding pressure. As a result, an internal melt flow occurs in the melt front meeting area. The aim of inducing such an internal melt flow is to improve the appearance and strength of molded products through the control of the fiber orientation in the products. As a reference for the comparison of strength, molded products obtained by one-point gate molding are fabricated by fixing the movable core pin in the position shown in Figure 2 (2) throughout the injection molding process.

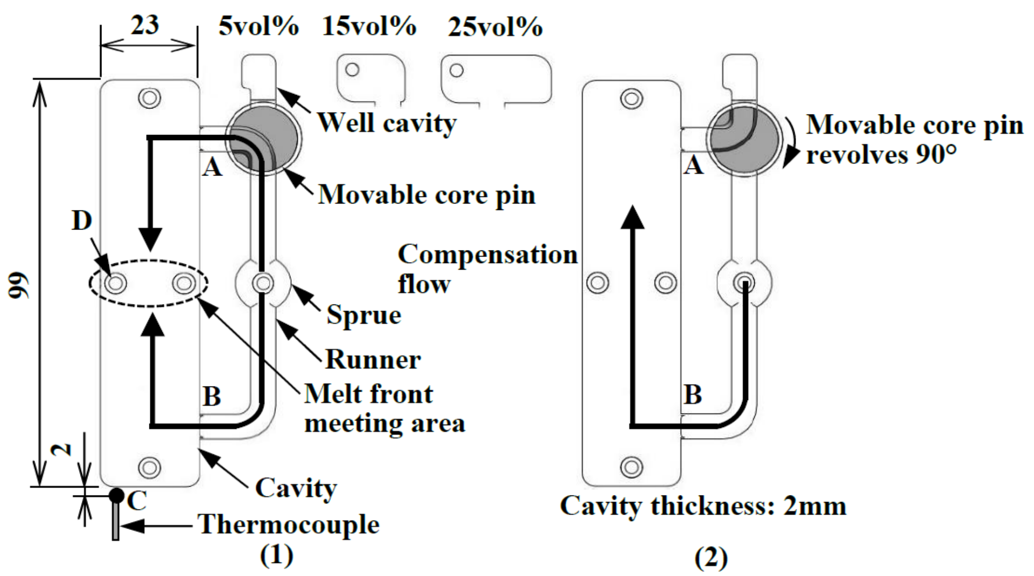

Figure 2. Method of melt flow control [unit: mm]: (**1**) Melt filling process; (**2**) Holding pressure process.

Figure 3 shows the appearance of the injection mold capable of melt flow control and induction heating and cooling. An electromagnetic induction coil is embedded in each of the insert blocks placed on the stationary and movable mold sides. A cavity insert

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equipped with the movable core pin and an oil hydraulic cylinder are installed on the movable mold side. The movable core pin is rotated using this oil hydraulic cylinder to switch the direction of the flow channel. Figure 4 shows the appearance of the cavity insert and movable core pin. The movable pin is inserted in the hole located midway along the runner. The induction coils are installed in the rectangular grooves at the back of the insert.

The temperature of the cavity insert is controlled on the basis of the temperature measured using an alumel–chromel sheath thermocouple (⌀ 1.6 mm), which is inserted at point C in Figure 2. The volume of the well cavity used in this study is 5, 15, or 25 vol% of the volume of the mold cavity as shown in Figure 2. The effects of these three melt flow control volumes on the appearance, fiber orientation, and strength of molded products are examined while changing the well cavity.

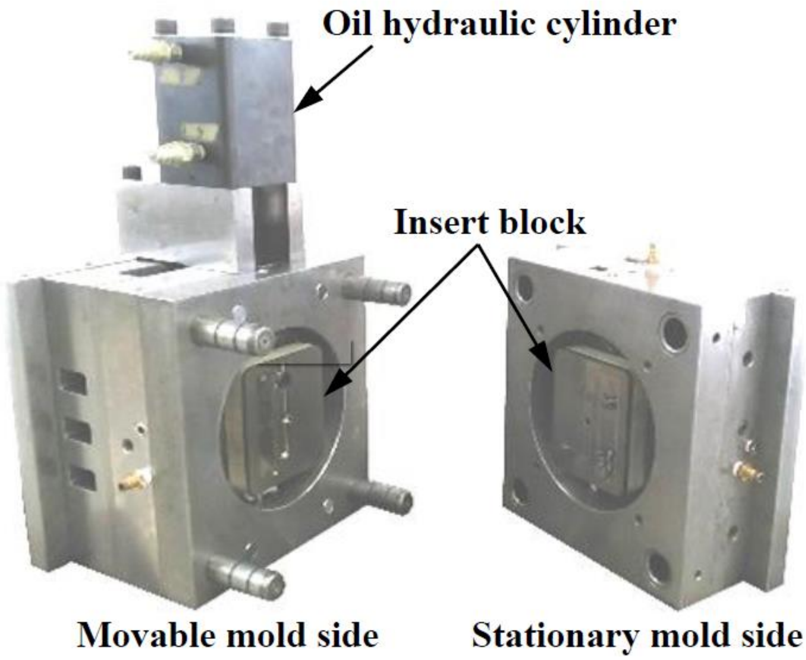

Figure 3. Appearance of the injection mold capable of melt flow control and induction heating and cooling.

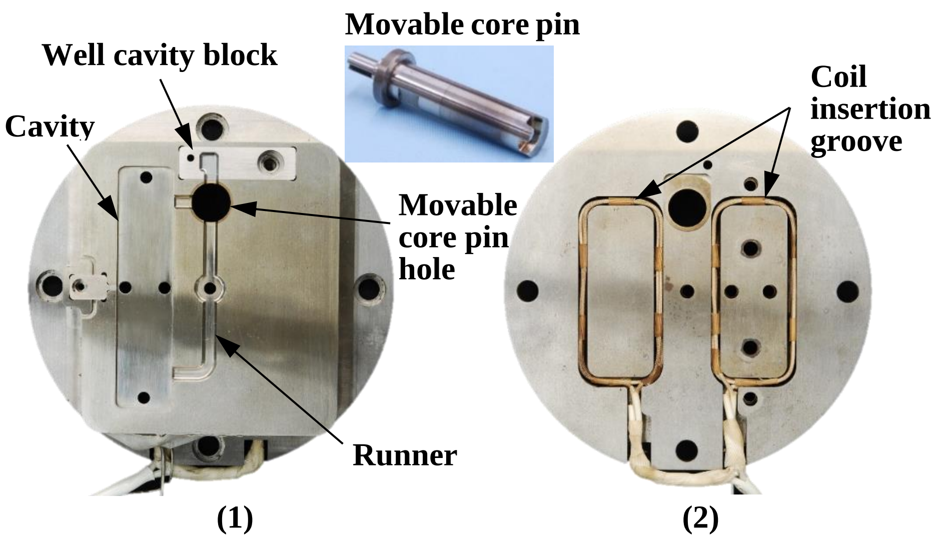

Figure 4. Appearance of the cavity insert and movable core pin: (1) Front view; (2) Back view.

3. Experimental method

A stationary induction heater (SK-NF002SA; Ju-OH Inc.) is used for the induction heating of the mold. A mold temperature controller (TYPE TA-32; Stolz Co., Ltd.) is used for cooling the mold. An injection molding machine (ROBOSHOT S-2000 i50A; Fanuc Ltd.) with a maximum clamping force of 500 kN is used in the experiments. The polymer used in the experiments is short carbon fiber reinforced semi-aromatic polyamide MXD6 (Reny C36-B43; carbon fiber content, 30 wt%; Mitsubishi Engineering-Plastics Corporation).

Table 1 shows the molding conditions. Normal molding is carried out by maintaining the insert temperature at 95 °C. Heat and cool molding is carried out by injecting the melt into the cavity after increasing the insert temperature from 95 to 140, 160, and 180 °C, stopping the heating after the injection, and decreasing the insert temperature to 95 °C. Because the T*m* of the semi-aromatic polyamide used in this study is 243 °C, the solidification of melt in the cavity is not completely inhibited under the above heating conditions during the molding process. The rotation of the movable core pin is started at the start of the holding pressure process. The start time of melt flow control is set as the start time of the rotation of the movable core pin. Melt flow control is started manually by an operator who is checking the waveform of melt pressure obtained using an indirect quartz pressure transducer (Type 9221; Kistler Japan Co., Ltd.) inserted immediately below ejector pin D in Figure 2. The start time of melt flow control varies by ±0.1 s because the melt flow control is started manually.

The effect of the difference in melt flow control volume on the strength of molded products is examined using three well cavities of different volumes as described above. To examine the effects of differences in the cooling conditions of the mold on the strength of molded products, the cooling water temperature circulated within the mold is changed to 20, 50, and 80 °C. The cooling of the mold is started at the start of the holding pressure process.

Table 1. Molding conditions.

Cylinder temperature	(°C)	280-280-275-270-80*)
Mold temperature	(°C)	(1)95 (2)95→140/160/180→95
Injection rate	(cm^3/s)	23.9
Holding pressure	(MPa)	80
Holding pressure period	(s)	15
Melt flow control volume	(vol%)	5/15/25

*) Nozzle-Metering-Compression-Feed zone-Under hopper

The appearance and cross sections of the molded products are observed and the surface shape is measured using a shape analysis laser microscope (VK-9700; Keyence Corporation). The fiber orientation is observed on cross section E along the thickness direction of the molded products as shown in Figure 5 (1). The distribution of the fiber orientation in the molded products at arbitrary positions is quantitatively determined using a fiber orientation identification and evaluation system (Bethel Co., Ltd.), which is based on the periodic heating and infrared radiation thermometer method [18]. With this method, the distribution of the fiber orientation is determined on the basis of the diffusion of heat applied periodically to a molded product. To exclude the effect of the fiber orientation in the skin layer formed near the molded product surface, the distribution of the fiber orientation is determined in samples of 1 mm thickness obtained by polishing and removing the top and bottom layers, each of 0.5 mm thickness, from the molded products as shown in Figure 5 (2). The distribution of the fiber orientation is observed at the points of intersection of lines ①–⑤ and lines a–c. The obtained results show the average distribution of the fiber orientation along the thickness direction observed at the above points of intersection of the 1-mm-thick samples.

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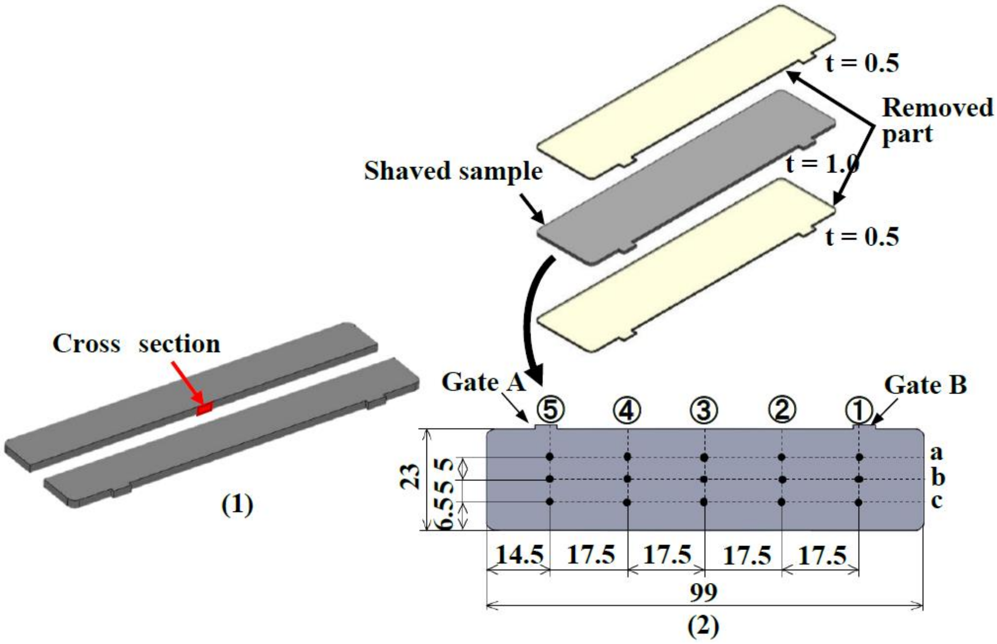

Figure 5. Observation positions of fiber orientation: (**1**) Observation area along the thickness direction; (**2**) Observation position on the shaved sample [unit: mm].

A universal tester (Tensilon RTC-1225A; Orientec Co., Ltd.; maximum load cell force, 2.5 kN) is used to measure the bending strength of the molded products. A three-point bending test is performed by applying load through indenters pressed onto line ③ in the melt front meeting area as well as lines ② and ④ in Figure 5 (2) to determine the bending strength at each point. The distance between the supporting points is 32 mm and the bending speed is 2 mm/min.

4. Results

4.1. Results of observing molded product surface

Figure 6 shows the results of observing the surface in and around the melt front meeting area of the molded products. Figures 6 (1) and (2) show the surfaces of the molded products obtained by normal molding at a constant temperature of 95 °C. Fibers are exposed and a weld line is generated on both surfaces of the molded products obtained by two-point gate molding without [Figure 6 (1)] and with [Figure 6 (2)] melt flow control. A V-notch is not formed in these molded products, but the meeting face in the melt front meeting area where the fiber orientation changes appears as a weld line. These results indicate that melt flow control does not affect the molded product surface when the mold is not heated. Figures 6 (3) and (4) show the surfaces of the molded products obtained by heat and cool molding (95 °C→180 °C→95 °C). The weld line disappears and the exposure of fibers is reduced. The molded product surface is smooth regardless of whether or not melt flow control is performed. The surface of the molded product obtained with melt flow control [Figure 6 (4)] is slightly smoother than that without melt flow control [Figure 6 (3)]. The surface shape in the melt front meeting area of the molded products obtained by heat and cool molding (95 °C→180 °C→95 °C) is observed using a shape analysis laser microscope. The results are shown in Figure 7. An undulating shape with the melt front meeting area as its apex is observed on the surface of the mold product obtained by two-point gate molding without melt flow control [Figure 7 (1)]. On the other hand, the surface of the mold product obtained by two-point gate molding with melt flow control [Figure 7 (2)] is flat and does not have an undulating shape. Similar results are also obtained when the injection molding is carried out without heating the mold, which reveals that heating the mold has no effect on the formation of the undulating shape.

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As discussed above, the exposure of fibers and the generation of a weld line can be prevented by heating the mold. Also, a flat surface without an undulating shape can be achieved by melt flow control regardless of whether or not the mold is heated.

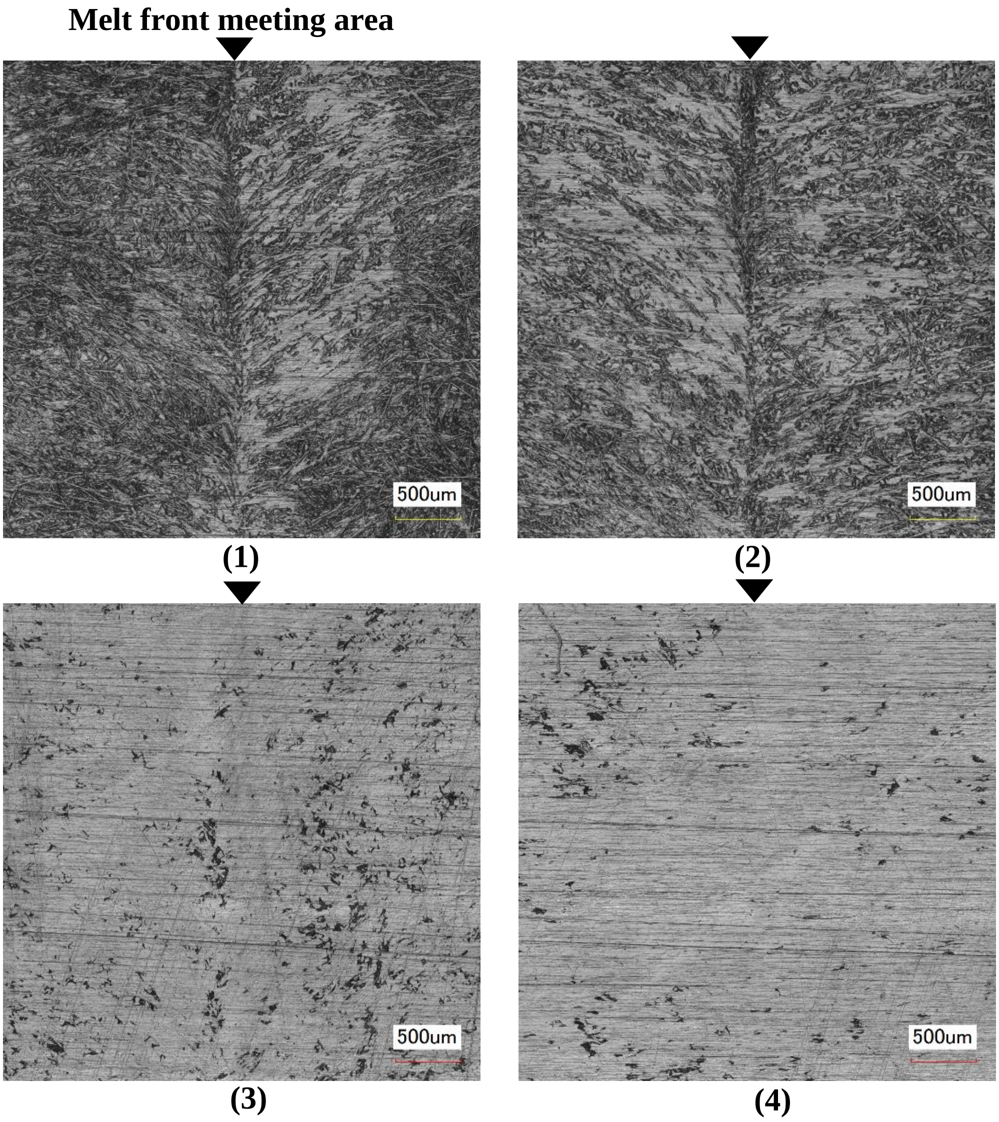

Figure 6. Appearance of surface of molded products: (**1**) Without flow control (95 °C); (**2**) With flow control: 0s (95 °C, melt flow control volume: 15 vol%); (**3**) Without flow control (95→180→95 °C); (**4**) With flow control: 0s (95→180→95 °C, melt flow control volume: 15 vol%).

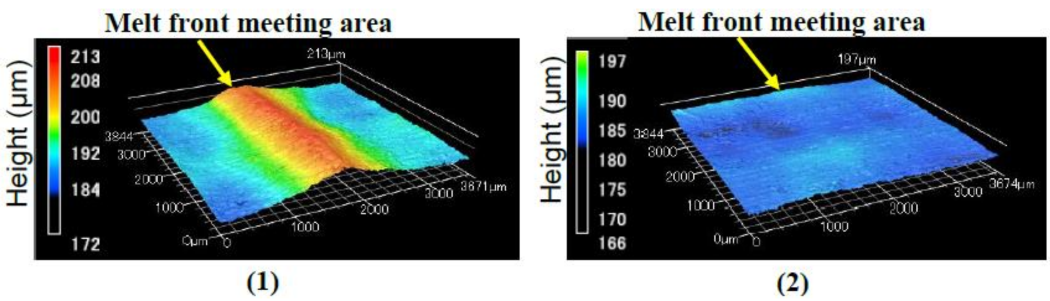

Figure 7. Surface shape around melt front meeting area of molded products (95→180→95 °C): (**1**) Without flow control; (**2**) With flow control (melt flow control volume: 15 vol%).

4.2. Bending strength

A three-point bending test is performed by applying load through the indenter pressed onto line ③ in the melt front meeting area in Figure 5 (2). Figure 8 shows the bending strength properties of the molded products obtained under different molding conditions. The bending strength of the molded products obtained by two-point gate molding without melt flow control slightly decreases as the heating temperature of the mold increases. This result indicates that, although the heating of the mold contributes to the disappearance of the weld line, it does not improve the bending strength in the melt front meeting area when melt flow control is not performed. The bending strength of the molded products obtained by two-point gate molding with melt flow control is nearly threefold that of the molded products obtained by two-point gate molding without melt flow control and is comparable to that of the molded products obtained by one-point gate molding. Also, the bending strength increases as the heating temperature of the mold increases when melt flow control is performed. Moreover, the bending strength increases as the melt flow control volume increases for all heating temperatures of the mold.

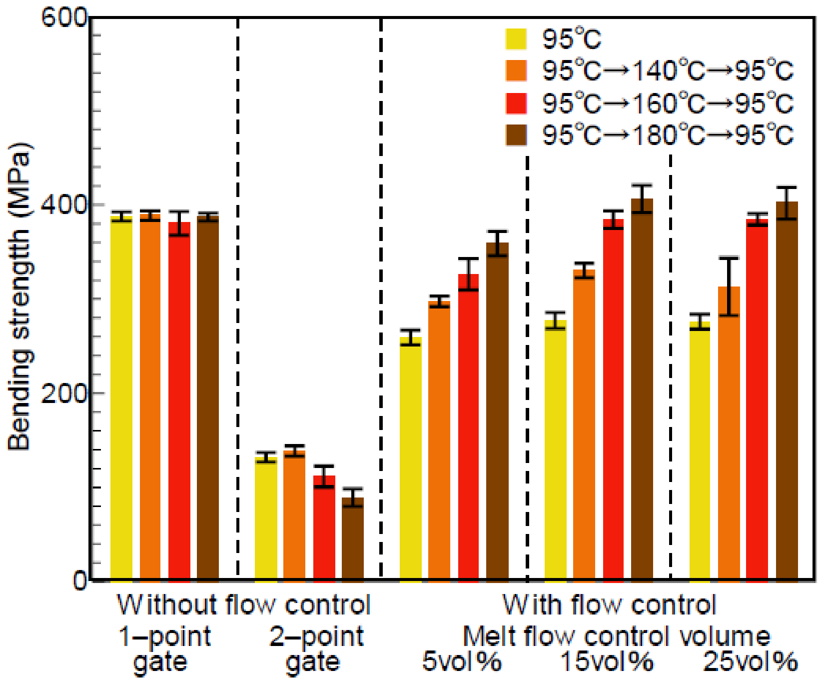

Figure 8. Bending stress of the molded products (indenter position ③).

A three-point bending test is performed by applying load through the indenters pressed onto lines ②, ③, and ④ of the molded products obtained by heat and cool molding (95 °C→180 °C→ 95 °C). Figure 9 shows the bending strength measured by the three-point bending test. On line ③ in the melt front meeting area, the bending strength increases sharply as the melt flow control volume increases. The bending strength on line ③ is close to that on lines ② and ④ when the melt flow control volume is more than 15 vol%. On line ②, the bending strength does not change and remains high even when the melt flow control volume increases. The bending strength is high on line ④. The bending strength on line ④ of the molded products obtained by two-point gate molding and that of the molded products obtained with melt flow control volumes of 5 and 15 vol% are almost the same. The bending strength on line ④ slightly increases when the melt flow control volume is 25 vol%.

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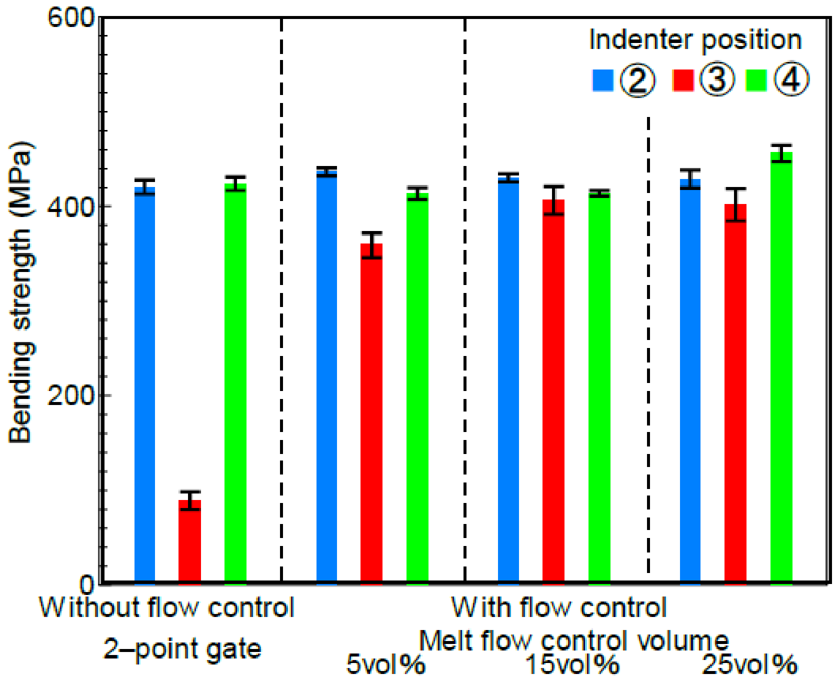

Figure 9. Bending stress of molded products obtained by changing indenter position (95→180→95 °C).

4.3. Cooling conditions of mold and bending strength

The effect of the cooling speed of the mold on the bending strength in the melt front meeting area is examined. The temperature of the cooling water circulating within the mold is changed to 20, 50, and 80 °C. Figure 10 shows the changes over time at the temperatures measured at C in Figure 2 during heat and cool molding (95 °C→180 °C→95 °C). The figure shows only the results of measurement during the cooling process. The temperature drops per unit time, namely, the cooling speed of the mold, decreases as the cooling water temperature increases. Figure 11 shows the bending strength on line ③ in the melt front meeting area when the cooling speed of the mold is changed by changing the cooling water temperature under different heating conditions of the mold. The bending strength increases as the cooling water temperature increases, namely, as the cooling speed of the mold decreases. Also, the bending strength increases as the heating temperature of the mold increases.

The above results indicate that the cooling speed of the mold affects the bending strength.

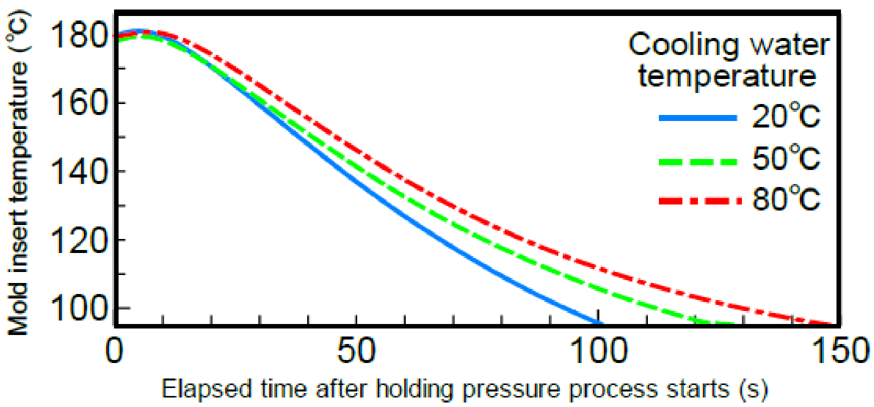

Figure 10. Cavity insert temperature curves for various cooling water temperatures (95→180→95 °C).

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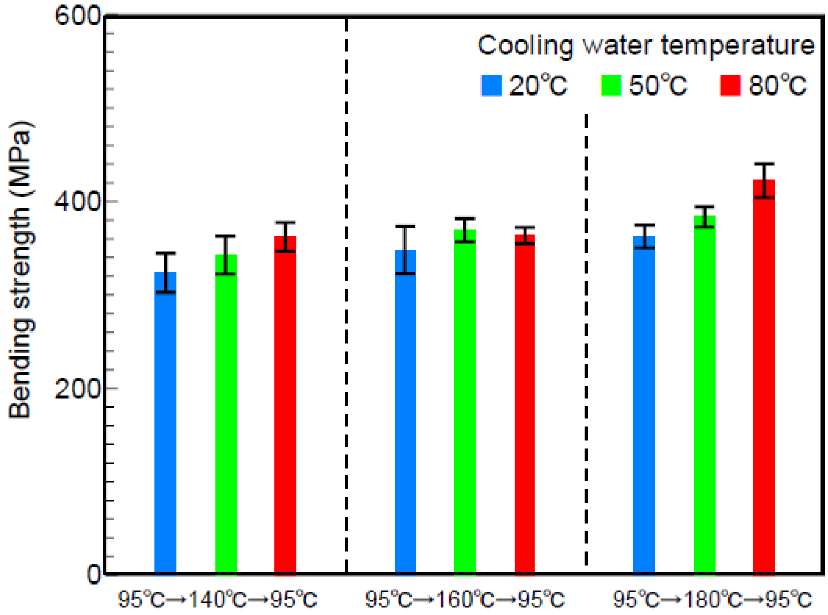

Figure 11. Bending stress for various cooling water temperatures (indenter position ③, melt flow control volume: 15 vol%).

4.4. Observation of cross sections of molded products

Figure 12 shows the results of observing melt front meeting area ③ on cross section E along the thickness direction of the molded products [Figure 5 (1)]. The fibers in and around the melt front meeting area are oriented almost parallel to the meeting area as shown in Figure 12 (1) when the molded product is obtained by two-point gate molding at a constant temperature of 95 °C without melt flow control. On the other hand, three fiber orientation layers (Layers I–III) are formed along the thickness direction of the molded products, as shown in Figs. 12 (2)–(4), when the molded products are obtained with melt flow control. In Layer I, many fibers in and around the melt front meeting area are oriented almost parallel to the meeting area. Namely, these fibers are oriented perpendicular to the melt flow direction and appear as dots. In Layer II, many fibers are oriented almost parallel to the melt flow direction. In Layer III, some fibers are oriented parallel to the melt flow direction while others are oriented perpendicular to the melt flow direction and appear as dots. These three fiber orientation layers are also formed in the molded products shown in Figs. 12 (4)–(6), which are obtained by heat and cool molding (95 °C→180 °C→95 °C) with different melt flow control volumes. Figure 13 shows the thickness of each layer as a percentage of the total thickness of the mold products, which is calculated on the basis of Figure 12. The thickness of Layer I decreases and the thickness of Layers II and III increases as the heating temperature of the mold increases as shown in Figure 13 (1). The thickness of Layer I remains virtually unchanged even when the melt flow control volume increases, but the thickness of Layer II increases and that of Layer III decreases as the melt flow control volume increases as shown in Figure 13 (2).

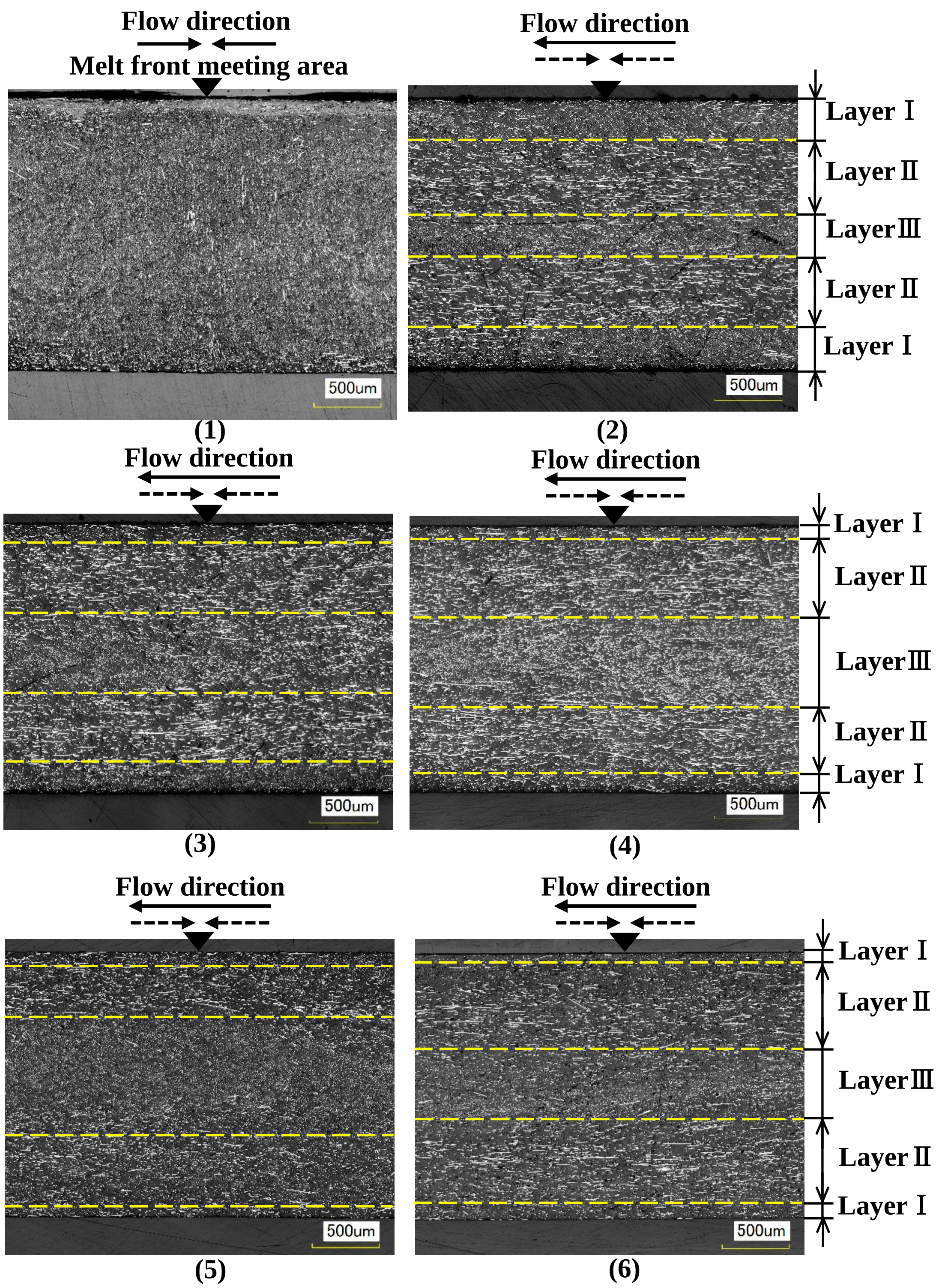

Figure 12. Observation results of fiber orientation along the thickness direction of molded products: (**1**) Without flow control (95 °C); (**2**) With flow control (95 °C, melt flow control volume: 15 vol%); (**3**) With flow control (95→140→95 °C, melt flow control volume: 15 vol%); (**4**) With flow control (95→180→95 °C, melt flow control volume: 15 vol%); (**5**) With flow control (95→180→95 °C, melt flow control volume: 5 vol%); (**6**) With flow control (95→180→95 °C, melt flow control volume: 25 vol%).

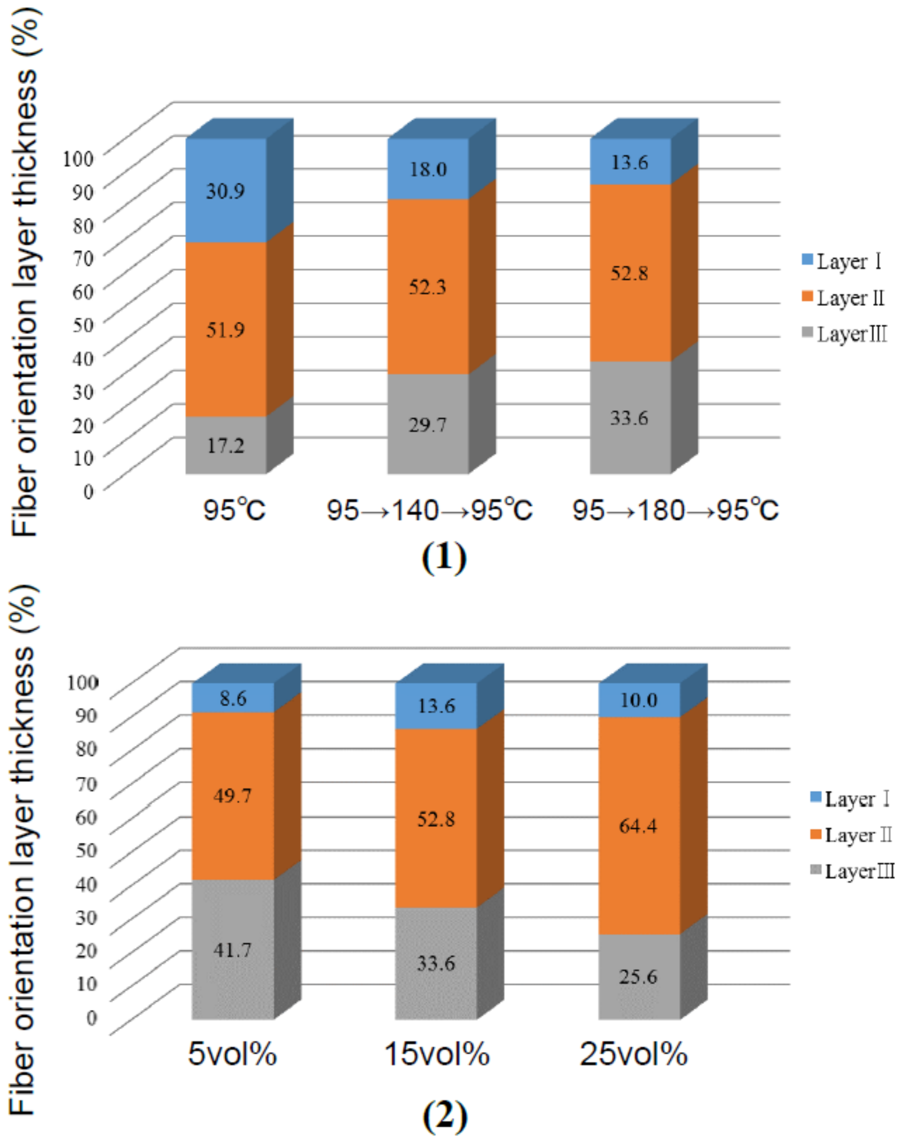

Figure 13. Fiber orientation layer thicknesses as percentages under various molding conditions: (**1**) Effect of heating temperature; (**2**) Effect of melt flow control volume (95→180→95 °C).

Figure 14 shows the distribution of the fiber orientation at each point on lines ①–④ of the molded products, which is measured by the periodic heating and infrared radiation thermometer method. The molded products shown in this figure are obtained by heat and cool molding (95 °C →180 °C→95 °C). The molded product shown in Figure 14 (1) is obtained by two-point gate molding, whereas the molded products shown in Figs. 14 (2)-(4) are obtained with different melt flow control volumes. The ratio of the length of the long axis to that of the short axis of each ellipse indicates the strength of the fiber orientation. To be more specific, the fiber orientation becomes more random when the ellipse approaches a circle. The angle between the X-axis and the long axis indicates the average direction of the fiber orientation. For example, the fiber orientation at point ③-a in Figs. 14 (2)–(4) represents the quantified fiber orientation in the central portion (1.0 mm thickness) of the cross sections along the thickness direction shown in Figs. 12 (4)–(6), which contain part of Layers II and III. Figure 14 shows that the fiber orientation changes to the melt flow direction in the entire molded product as the melt flow control volume increases. On lines ① and ⑤, which are close to Gates B and A, respectively, fibers are oriented in the direction of the gates in all cross sections. This tendency is stronger at points closer to the gates, such as ①-a and ⑤-a. On line ②, fibers are oriented in the upper left direction at point ②-a. However, the direction of the long axis of the ellipses slightly changes at points ②-b and ②-c regardless of whether or not melt flow control is

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performed; the fiber orientation is almost parallel to the melt flow direction. On line ③ in the melt front meeting area, the fiber orientation is perpendicular to the melt flow direction in the molded product shown in Figure 14 (1), which is obtained by two-point gate molding without melt flow control. The fiber orientation gradually changes to the melt flow direction as the melt flow control volume increases. On line ④, the fibers are oriented almost in the upper right or upward direction at point ④-a in the molded product obtained by two-point gate molding without melt flow control and the molded product obtained with 5 vol% of melt flow control. In the molded product obtained with 15 vol% of melt flow control, fibers rotate anticlockwise and are oriented in the upper left direction because of the melt flow from Gate B to the cavity. The rotation of fibers further proceeds and the fiber orientation changes to the melt flow direction in the molded product obtained with 25 vol% of melt flow control.

The above results indicate that the thickness of the fiber orientation layers and the direction of the fiber orientation are significantly changed by the heating of the mold and melt flow control.

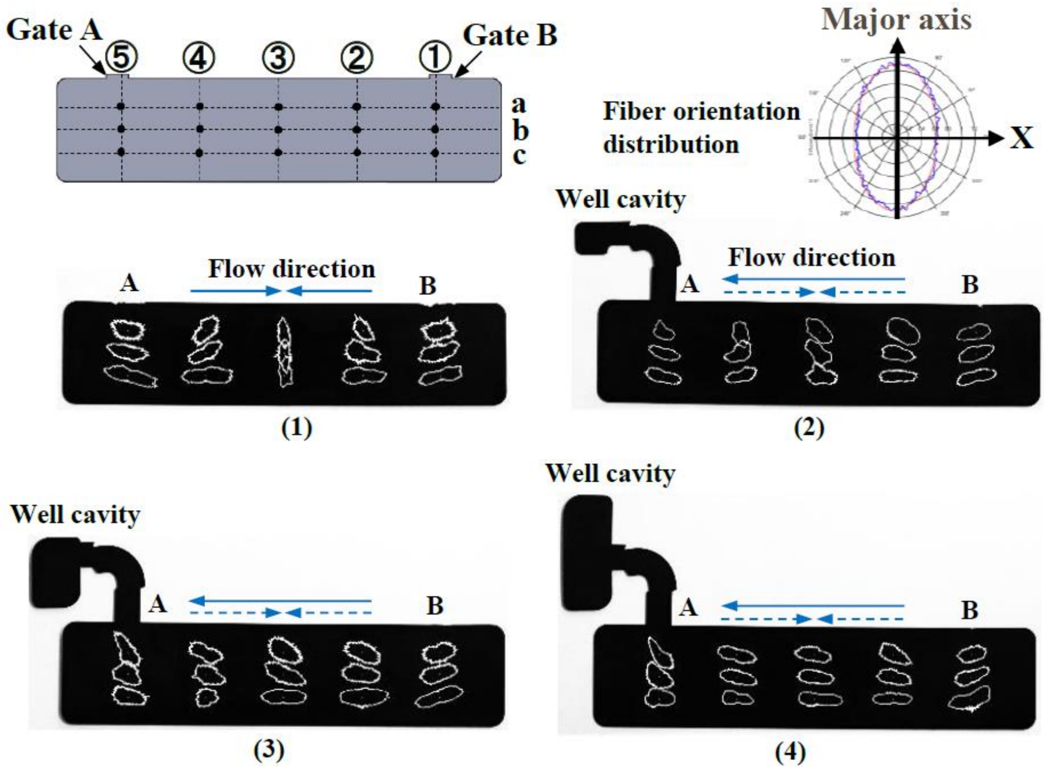

Figure 14. Fiber orientation distribution measured by periodic heating and infrared radiation thermometer method (95→180→95 °C): (**1**) Without flow control; (**2**) With flow control (melt flow control volume: 5 vol%); (**3**) With flow control (melt flow control volume: 15vol%); (**4**) With flow control (melt flow control volume: 25 vol%).

5. Discussion

5.1. Appearance of molded products

A flat and smooth molded product surface with no exposed fibers and no weld line is generated by heating the mold. Possible reasons for this result are as follows. It has been observed in short-shot molded products that fibers at the melt front are projected from the base material, namely, they are exposed on the surface of the melt, during the fountain flow process. In the normal molding carried out at a constant temperature of 95 °C, the melt cools and solidifies to form a skin layer at the moment the melt forms a fountain flow and comes in contact with the cavity wall. This is because the melt at the melt front is deprived of heat by the mold. As a result, the molded product surface with exposed fibers is formed. Once the surface with exposed fibers is formed, the surface conditions cannot be changed and the weld line cannot be eliminated even by melt flow control. On the other hand, in the heat and cool molding, the solidification of the melt near the cavity wall is slowed because of the high temperature of the cavity wall. The melt does not liquefy at the heating temperature in the experiments because the T*m* of the semi-aromatic polyamide used in this study is 243 °C. However, the skin layer softened by the heat of the mold is pressed onto the cavity wall by the internal melt pressure generated by melt flow control. At this moment, the melt surrounds the exposed fibers before it cools and solidifies. As a result, a flat and smooth molded product surface with no exposed fibers and no weld line is generated.

The formation of an undulating shape with the melt front meeting area as its apex is prevented by melt flow control regardless of whether or not the mold is heated. Possible reasons for this result are as follows. In and around the melt flow meeting area shown in Figure 12 (1), fibers oriented along the thickness direction of the molded product have reinforcing effects, which prevent the shrinkage of the molded product in the thickness direction. On the other hand, fibers are oriented parallel to the molded product surface in areas other than the melt flow meeting area, resulting in large shrinkage in the thickness direction. An undulating shape with the melt front meeting area as its apex is formed because the molded product has both the meeting area with small shrinkage and the surrounding area with large shrinkage. An internal melt flow is generated by melt flow control and changes the fiber orientation in the meeting area from the thickness direction of the molded product to the direction parallel to the molded product surface, as shown in Figs. 12 (2)–(6), regardless of whether or not the mold is heated. As a result, a flat surface is formed because the entire molded product shrinks uniformly in the thickness direction.

5.2. Cooling speed of mold and bending strength

The bending strength in melt front meeting area ③ increases as the cooling speed of the mold decreases or the heating temperature of the mold increases. The semi-crystallization time of semi-aromatic polyamide used as the base material is shortest in the temperature range from 150 to 180 °C and, therefore, the crystallization is enhanced. The temperature of the melt decreases slowly in this temperature range when the cooling speed of the mold is low or the heating temperature of the mold is high. As a result, the crystallization of semi-aromatic polyamide is enhanced. It is considered that such enhancement of the crystallization increases the bending strength.

5.3. Bending strength and fiber orientation

Figure 15 shows a diagram of the fiber orientation in and around the melt front meeting area formed by melt flow control, which is created by the observation of the cross sections of the molded products shown in Figure 12. Layer I is formed when fibers and the surrounding melt move toward the cavity wall and solidify during the fountain flow process. Layer I contains many fibers that are oriented parallel to the meeting area. When the bending load is applied from the vertical direction to the molded product surface, as in this study, the bending strength is considered to be low in Layer I, in which fibers are oriented parallel to the direction in which the load acts or the longitudinal direction of the indenter. Layers II and III are formed by the internal melt flow generated by melt flow control. Layer II is mainly formed by the shear flow and contains many fibers that are subjected to shear and oriented parallel to the melt flow direction, namely, the direction perpendicular to the longitudinal direction of the indenter. Therefore, the bending strength is considered to be highest in Layer II. Layer III is subjected to less shear than Layer II and contains fibers oriented both parallel and perpendicular to the melt flow direction. The bending strength in Layer III is considered to be lower than that in Layer II and higher than that in Layer I.

When melt flow control is performed, the bending strength in melt front meeting area ③ increases as the heating temperature of the mold increases. On the basis of the above discussion, the reasons for this result are considered to be as follows. As the heating temperature of the mold increases, the area of the internal melt flow associated with the shear flow near the cavity wall increases because the solidification of the melt near the cavity

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wall is slowed. As a result, the thickness of Layer I having low bending strength decreases, whereas those of Layers II and III having the highest and second highest bending strengths, respectively, increase. The increased thicknesses of Layers II and III as well as the causes of the enhanced crystallization described in Section 5.2 seem to be the reasons for the increase in bending strength with increasing heating temperature of the mold. When melt flow control is performed, the bending strength in melt front meeting area ③ increases as the melt flow control volume increases. Possible reasons for this result are as follows. The internal melt flow occurs for a long duration and the region of shear flow extends to the center of the cavity as the melt flow control volume increases. The extension of the region of shear flow results in the decreased thickness of Layer III and the increased thickness of Layer II, where the latter contains many fibers oriented parallel to the melt flow direction and has the highest bending strength. This seems to be the reason for the increase in bending strength with increasing melt flow control volume.

The bending strength in each area of the molded products is examined. The bending strength on line ② does not change and remains high as the melt flow control volume increases. This seems to be because the fiber orientation on line ② changes negligibly even if melt flow control volume changes. The bending strength in melt front meeting area ③ increases sharply as the melt flow control volume increases, approaching the bending strength on lines ② and ④ when the melt flow control volume is more than 15 vol%. A possible reason is that the fiber orientation in melt front meeting area ③ is significantly shifted to the direction parallel to the melt flow direction as the melt flow control volume increases. The bending strength is high on line ④. The same bending strength is observed on line ④ in the molded product obtained by two-point gate molding and in the molded products obtained with melt flow control volumes of 5 and 15 vol%. The bending strength on line ④ is slightly higher in the molded product obtained with the melt flow control volume of 25 vol%. The fiber orientation on line ④ rotates anticlockwise from the upper right direction to the upper left direction as the melt flow control volume increases. Finally, fibers are oriented along the melt flow direction when melt flow control volume is 25 vol%. There is negligible difference between the bending strength when the fibers are oriented in the upper right direction and that when the fibers are oriented in the upper left direction because the absolute values of the orientation angle are the same. The bending strength increases when the melt flow control volume is 25 vol% because fibers are oriented parallel to the melt flow direction. As discussed above, the bending strength on line ④ seems to vary according to the changes in fiber orientation.

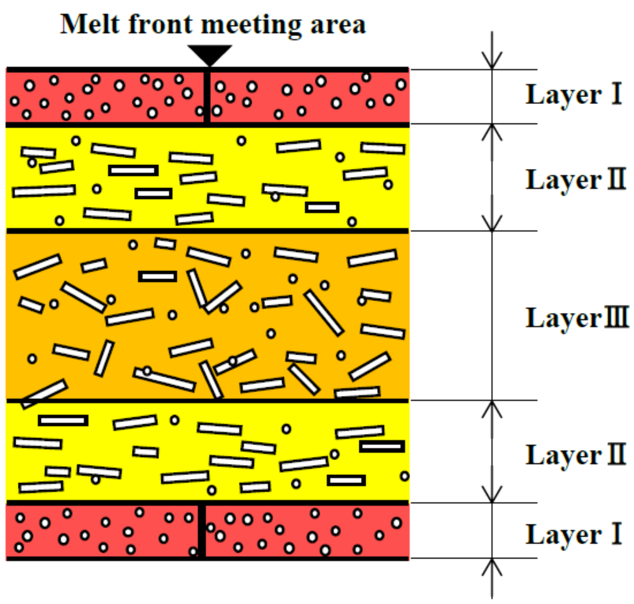

Figure 15. Diagram of fiber orientation layer structure along thickness direction of molded product.

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6. Conclusion

An injection mold capable of melt flow control and induction heating and cooling was used in the injection molding of short carbon fiber reinforced semi-aromatic polyamide. The effects of heating and cooling the mold as well as melt flow control on the appearance, fiber orientation, and bending strength of molded products of the above polyamide were examined. We obtained the following results.

1. A flat and smooth molded product surface with no exposed fibers and no weld line is generated by heating the mold. This seems to be because the solidification of the melt in the surface area of the molded product is slowed down by heating the mold and the softened skin layer is pressed onto the cavity wall by the internal melt pressure generated by melt flow control. Also, a flat surface without an undulating shape is formed by melt flow control regardless of whether or not the mold is heated. This seems to be because the fibers in and around the melt front meeting area are oriented parallel to the molded product surface by melt flow control.
2. The bending strength in the melt front meeting area increases as the cooling speed of the mold decreases or as the heating temperature of the mold increases. A possible reason is that the crystallization of semi-aromatic polyamide used as the base material is enhanced when the melt cools slowly.
3. The bending strength in the melt front meeting area increases as the heating temperature of the mold increases when melt flow control is performed. Possible reasons for this are as follows. The crystallization is enhanced as described in (2) by increasing the heating temperature of the mold. In addition, the increase in the heating temperature of the mold leads to the decreased thickness of Layer I, which has low bending strength because of fibers oriented parallel to the melt front meeting area, as well as the increased thicknesses of Layers II and III, which have the highest and second highest bending strengths, respectively, because of fibers oriented parallel to the melt flow direction.
4. The bending strength in the melt front meeting area increases as the melt flow control volume increases for all heating temperatures of the mold. This seems to be because of the increased thickness of Layer II, which contains many fibers oriented parallel to the melt flow direction and has the highest bending strength.
5. The bending strength is high in areas other than the melt flow meeting area regardless of whether or not melt flow control is performed. The bending strength varies in the entire area of molded products in accordance with the changes in fiber orientation.

As discussed above, the effects of both heating the mold and melt flow control on the appearance and bending strength of the molded products were systematically evaluated using the injection mold capable of melt flow control and induction heating and cooling. This injection mold can be applied not only to glass and carbon fibers but also to filler-filled materials such as cellulose nanofibers. Further studies will be carried out using this injection mold.

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