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Effect of Fiber Length on Mechanical Properties of Injection Molded Long-Fiber-Reinforced Thermoplastics

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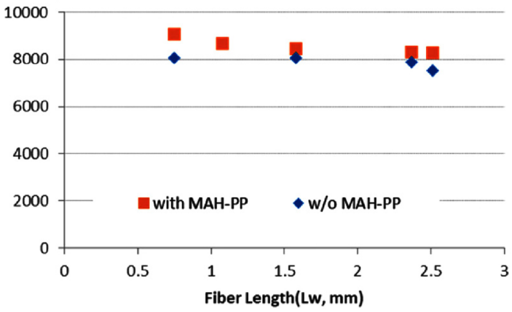
Abstract: Fibers of long-fiber-reinforced thermoplastic (LFT) pellets are longer than those of short-fiber-reinforced thermoplastic (SFT) pellets produced by extrusion. To overcome the fiber length limitations of the SFT pellets, LFT pellets were prepared by a pultrusion process using continuous fibers, which afforded longer fibers. Currently, long glass-fiber-reinforced polypropylene (LGF-PP) materials, which are one of the growing markets of the plastics industry, are typically used, particularly for applications in the automotive industry where lightweight performance and cost savings are required. The LFT pellets are primarily converted into the final product by injection molding. During the injection molding process, the LFT pellets are broken and the fiber length decreases as a consequence. In this study, glass and carbon-fiber-reinforced polypropylene of various pellet lengths (3-16 mm) were prepared by impregnating pultrusion process to evaluate the effect of mechanical properties according to fiber length. The length of the residual fibers recorded after injection molding were observed to decrease in proportion to the pellet length. Even with LFTs having the same material composition, the mechanical properties was different after injection molding according to the residual fiber length. In this injection molded LFT, the flexural modulus was higher as the residual fiber length was shorter. The impact strength was larger in samples without adhesive resin and the observed differences were larger for longer fiber lengths. From these results, the mechanical properties of LFT can be improved by understanding the properties of long fibers.



Keywords: LFT, fiber length, fiber orientation, interfacial adhesion.

1. Introduction

Fiber-reinforced plastics (FRP) have been increasingly used for structural materials, which is partly due to their high mechanical properties and strength-to-weight ratio. Recently, injection-moldable glass-fiber-reinforced thermoplastic composites have attracted considerable attention due to their superior mechanical properties and facile production using a cost reduction for automotive industry.[1,2] Fiber-reinforced thermoplastics (FRTP) have been synthesized by compounding and pultrusion processes. Various manufacturing technologies of FRTP are utilized depending on the desired application and required properties, although there is a difference in the lengths of the reinforcing fibers. Glass-fiber-reinforced polypropylene (GFRPP) composites including short fiber thermoplastics (SFT), long fiber thermoplastics (LFT), glass mat thermoplastics (GMT), and continuous-fiber-reinforced sheets are typically used in industrial applications and are commercialized technologies. The mechanical strength of GFRPP has previously been reported to increase with increasing fiber length. LFT gives significant improvements in same fiber diameter tensile and flexural strength and impact resistance than SFT.[3] In addition, the impact strength of GFRPP improved as the length and content of the glass fiber increased.[4] By using a coupling agent that improves the interfacial bond between glass fiber and polypropylene, the physical properties of LFT and FRTP were further improved.[5]

SFT compounded pellets are produced by extrusion compounding using short chopped fibers that are introduced into the extruder together along with the matrix resin. Typically, 4-mm-long chopped fibers are used, and the fiber length is shortened to less than or equal to 0.5 mm in the pellet while passing through the extrusion screw. Hence, due to the limitation of short fibers, SFT exhibits a limited fiber-reinforcing performance on the physical properties of the injection-molded product.

Thus, the LFT pellet manufacturing technique, which combines pultrusion, impregnation and compounding, has been developed to afford an increase in fiber length. As the fibers do not pass through the extrusion screw but are pelletized, the fiber length of the original pellet length is retained (Figure 1). Typically, 10-12 mm length of long glass-fiber-reinforced polypropylene (LGF-PP) pellets have been commercialized and widely used for injection molding products. To successfully impregnate continuous fibers, a matrix resin with low viscosity and that is compatible with the fiber material is required. Furthermore, the fiber surface should be treated to contain specific reactive radicals that may become interfacial-bonded to the matrix polymer. A coupling agent is adding according to the fiber surface siz-

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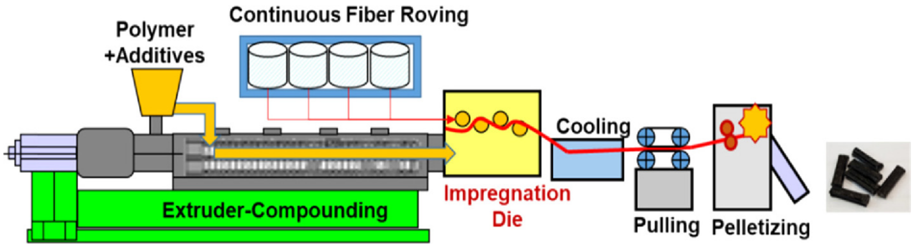


Figure 1. Manufacturing of LFT by Compounding, Impregnation and Pultrusion.

ing and the chemical characteristics of matrix polymer. Maleic anhydride graft PP (MAH-PP) is widely used commercially as a coupling agent in LGF-PP, and it is known that the higher the MAH content, the stronger the interfacial adhesion.[6] The bond strength between fiber and resin is measured and described by interfacial shear strength (IFSS). In addition, MAH-PP can increase the interfacial bonding and mechanical strength of carbon fiber reinforced polypropylene (CFRPP).[7]

In recent years, carbon-fiber-reinforced plastics (CFRP) have been utilized in high performance engineering fields. However, the cost of carbon fibers and the processing costs of carbon-fiber-reinforced thermoplastics (CFRTP) are considerably greater than glass-fiber-reinforced thermoplastics (GFRTP). Hence, use of these carbon-fiber reinforced products are limited to the aerospace and defense industries via curing and cast molding techniques using carbon fiber prepreg with a thermosetting resin such as an epoxy, acryl and phenol. Therefore, to achieve the effective application of carbon-fiber thermoplastics to industries that require continuous mass production, such as in the automotive industry, pellets of long-carbon-fiber-reinforced thermoplastics (LCFTP) produced by the LFT process are required to be manufactured.[8]

In this study, long carbon-fiber-reinforced polypropylene (LCF-PP) of various pellet lengths (3-16 mm) were prepared by same LGF-PP pultrusion process to evaluate the effect of mechanical properties according to fiber length. The final fiber length was able to be controlled within a certain range by controlling for the LFT pellet length. Furthermore, the fiber length and mechanical properties of the injection molded LGF-PP and LCF-PP were investigated. The residual fiber length of the injection molded LFT is not homogeneous and has a length distribution.[9,10] It is expected that long fibers and short fibers are remained together, and that the more the long fibers are, the higher the mechanical strength. However, even if the residual fiber length was longer after molding, stiffness was not increased.[11] This is because there is a difference in fiber orientation due to long fibers. In addition, the interfacial bonding force between the fibers and the resin can be controlled by an adhesive resin (MAH-PP). The higher the interfacial bonding strength, the higher the mechanical strength. Since the rigid fibers are strongly bonded to the resin, the reinforcing effect of the strength of the matrix resin is increased.[5] However, when the interfacial bond was weak, the impact strength was higher.[7] The mechanical properties of the injection-molded LFTs were affected by the length, distribution, and orientation of the fibers. Differences in the fiber orientation and mechanical properties were observed to be affected by the fiber length.[12,13]

Depending on the conditions of the injection machine and the mold characteristics, there may be differences in the residual fiber length. When subjected to high shear stresses on injection process, more of the fiber will be broken, resulting in a shorter residual fiber length. Therefore, even if an LFT having the same material composition is produced and injection-molded, ultimately different physical properties can be obtained depending on the fiber length.[12,14]

The mechanical strength and the coefficient of linear thermal expansion (CLTE) due to the fiber orientation difference were measured using specimens which were injected so as to have a difference in fiber orientation. Longitudinal to mold direction (MD, 0 degree) and transverse (90 degree) of injection specimens, the strength and the coefficient of linear expansion differ by more than 2 times. This can be used to estimate the fiber orientation in the injection specimen. The difference in impact strength according to fiber length and interfacial bonding force depends on the break mechanism of the long fibers, and it is possible to analyze the fiber length and cross section on the resin fracture surface through microscope.

2. Experiments

2.1. Materials

To examine whether the properties of fiber lengths were dependent on the type of resin and fiber used, two types of LFT were prepared, including polypropylene reinforced with long glass fiber (LGF-PP) and long carbon fiber(LCF-PP). Preparation of the LGF-PP specimens employed continuous glass fiber roving using a commercial product SE4121 (2400 tex, 4000 filaments, OCV) and were sizing treated with a silane-type coupling agent applied throughout the glass surface. The matrix polymers used were PP (J-190H) and maleic-anhydride graft polypropylene (MAH-PP, CM-1120H) from LOTTE CHEMICAL. Preparation of the LCF-PP was via reinforced continuous carbon fiber roving using a commercial product T700SC-24K-50C (24,000 filaments, TORAY) were sizing treated by an epoxy-type coupling agent applied throughout the CF surface.

2.2. Manufacturing of LFT

The LFT pellets were manufactured by the pultrusion process using impregnation die designed by author. An impregnation die design was used to impregnate the continuous fibers with complete dispersion. The continuous fiber filaments were impregnated with molten polypropylene and cut into pellets of various lengths. The base resin and additives were compounded by using a twin extruder (screw diameter of 40Φ-L/D 40, UNEEPLUS, Korea). By adjusting the rotation speed of the rotary knife in the pelletizer, the length is able to be adjusted from 3 to 20 mm. The impregnated LFT pellets were then processed using an injection molding machine in order to examine the physical properties.

2.3. Measurement of mechanical properties

To examine the physical propertie, the specimens were processed using an injection molding machine for LFT (LGE-110, electric injection machine, Ls Mtron Ltd.) according to ISO-3167 Type 1A. Tensile tests were carried out according to ISO 527 using a universal testing machine (4466 model, Instron Co.) at a test speed of 5 mm/min. Flexural tests were carried out according to ISO 178 using a universal testing machine (466 model, Instron Co.) at a test speed of 2 mm/min. The Izod notched impact test was carried out according to ISO 180 using the impact tester for plastics (258 model, Yasuda-seiki Ltd.). This process measured the physical properties using at least 10 specimens.

2.4. Analysis of fiber length (Microscopic image analysis)

The fiber length analysis is very important because the properties of LFT injection specimens are affected by the fiber length. Various analysis techniques have been developed for objective and reliable fiber length analysis, but each analysis method has advantages and disadvantages.[15] In this study, we used the method of directly measuring the length of the remaining fiber after pyrolysis of the actual specimen and using a microscopeTo measure the length of the residual fibers in the injection molded LFT specimen, the specimen was treated in a furnace at 500-600 °C for 2 h, causing the polymer to decompose, leaving only the fibers and ash. The residual fibers were sampled and dispersed on a microscopic slide. A stereo microscope (SZH-10, Olympus) employed in transmission mode was equipped with a charge-coupled device camera, which was coupled to a computer to obtain and record images of the fibers. These images were then analyzed using image processing software. The fiber length is not constant but has a length distribution, and usually represents the fiber length as an average value of the remaining fiber length. The average fiber length are measured from at least 500 fibers obtained from the injection specimen.

2.5. Scanning electron microscopy (SEM)

Scanning electron microscopy (SEM) was employed to examine the surface and fracture sections of the LFT fibers after impact testing. The fracture surfaces of the samples were sputter-coated with a gold layer before SEM imaging, and SEM (SU8220, Hitachi) was employed to record micrographs showing the fiber and polymer morphology at 500-2000× magnification.

2.6. Thermal mechanical analysis (TMA)

The coefficients of linear thermal expansion (CLTE) were determined between -30 and 80 °C using a TA Q400 system operating under nitrogen atmosphere at a heating rate of 5 °C/min. CLTEs were calculated from the second heating scan and averaged over two samples. Specimen dimensions were 10 (length) × 3 (width) × 3 (thickness) mm.

The CLTE measured for the LFT specimens, which was found to be considerably less than that of neat polymers, varied between the longitudinal (parallel to the flow direction) and perpendicular directions due to the fact that LCFT reduced the shrinkage considerably more than for the short fibers, and the fibers were orientated in the flow direction. Therefore, when sampling on specimen including fiber, specimens should be precisely prepared considering the fiber orientation.

3. Results and discussion

3.1. Fiber length by fiber breakage during LFT injection molding

The fiber length of the LFT pellets decreased during the injection molding process. Long fibers were broken during interactions with the cylinder, nozzle, runner, and cavity, whereby the length of the majority of the residual fibers decreased to less than 1 mm (Figure 2). To achieve the optimal mechanical properties of LFT materials, the average length of residual fibers is required to be greater than 2 mm as a minimum.[4] Although long fibers are mandatory to achieve maximized mechanical properties, severe fiber breakage often occurs during injection molding due to the high shear stresses generated during the process,[16] thereby affecting the mechanical performance of the molded parts. Fiber breakage leads to a decrease in the tensile strength and impact resistance of long and short fiber-reinforced thermoplastics.[9,17] In injection molding, several factors contribute to the final fiber length, including mold geometry, fiber content, and processing conditions. To achieve the desired performance for the final molded product, the manufacturing process must be optimized in order to establish a satisfactory correlation between the processing parameters and fiber characteristics.[10] In particular, the majority of fiber breakage is related to the plasticizing process in cylinder.[18-20]

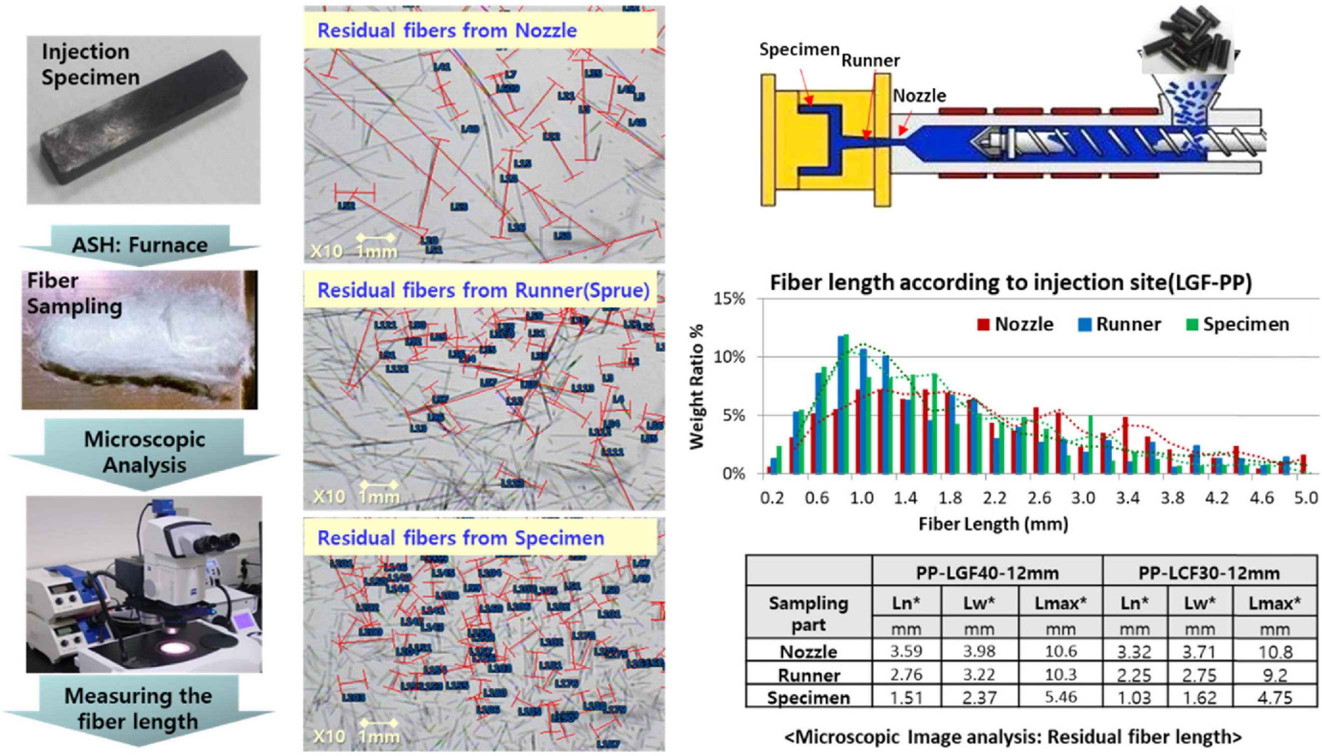
After injection molding, the fiber length distribution (FLD) of residual fibers were analyzed. The FLD is a value that reflects the range of fiber length, and is crucial to examine not only the average length of fibers but also the mechanical properties of injection molded LFT, which is dependent on the fiber length. The average length by number (L_n), the average length by weight (L_w), and FLD were calculated by the following equations:

$$L_n = \frac{\sum niLi}{N} \tag{1}$$

$$L_w = \frac{\sum niL_i^2}{\sum niLi} \tag{2}$$

$$FLD = \frac{L_w}{L_n} \tag{3}$$

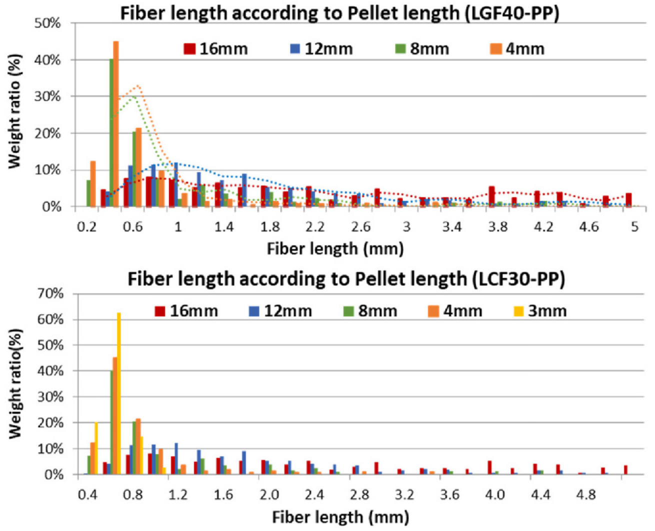
For the samples used in this experiment, the length of fibers were analyzed during injection process. The fiber length grad-



Sampling part	PP-LGF40-12mm Ln*	PP-LGF40-12mm Lw*	PP-LGF40-12mm Lmax*	PP-LCF30-12mm Ln*	PP-LCF30-12mm Lw*	PP-LCF30-12mm Lmax*
	mm	mm	mm	mm	mm	mm
Nozzle	3.59	3.98	10.6	3.32	3.71	10.8
Runner	2.76	3.22	10.3	2.25	2.75	9.2
Specimen	1.51	2.37	5.46	1.03	1.62	4.75

<Microscopic Image analysis: Residual fiber length>

Figure 2. Analysis process of fiber length and Fiber breakage during injection molding process.



Pellet	LGF40-PP Ln*	LGF40-PP Lw*	LGF40-PP FLD*	LCF30-PP Ln*	LCF30-PP Lw*	LCF30-PP FLD*
	mm	mm	Lw/Ln	mm	mm	Lw/Ln
3mm	0.45	0.75	1.67	0.24	0.4	1.67
4mm	0.63	1.08	1.71	0.35	0.61	1.74
8mm	0.94	1.58	1.68	0.61	0.83	1.36
12mm	1.51	2.37	1.57	1.03	1.62	1.57
16mm	1.86	2.51	1.35	1.58	2.25	1.42

Figure 3. Residual Fiber length and FLD for the injection specimen according to pellet length.

ually decreased through passing the injection screw, the narrow nozzle, runner and gate of specimen inlet (Figure 2). The average length of the fiber passing through the screw zone from the 10 mm pellet was 2-3 mm, and the final specimen exhibited length (L_n) values ranging from 0.5 to 2.0 mm (Figure 3).

The residual lengths of the fibers after injection was measured by utilizing the pellet length of each sample. As expected, the fiber length was confirmed to exhibit a residual fiber length proportional to the pellet length. The residual fiber lengths (minimum to maximum fiber length) of the long pellets exhibited a wide range, but the FLD was not proportional to its pellet length. Hence, long pellets were observed to break more during injection molding. It is difficult to maintain long fiber lengths during injection molding because of the flow path through the injection screw cylinder and narrow flow path. In order to maintain long fiber lengths, it is recommended that LFT pellets are used, along with an injection machine that possesses a large cylinder nozzle, a wide pitch screw and a mold with a wide flow path.

3.2.1. Mechanical properties of LGF-PP

The stiffness of the LGF-PP specimen was improved according to the glass fiber content, Both the strength and notched impact performance show a maximum in performance in the 40-50 wt% fibre content range. %.[11] The tensile, flexural, impact properties and property balance of thermoplastic material specimens subjected to injection molding were investigated. Figure 4 shows the mechanical properties of the final injection product with respect to the length of the pellet injected into the injection machine. In this experiment, the LGF-PP pellet reinforced with 40 wt% of glass fiber was prepared using a prescribed ratio of 0-8 wt% of MAH-g-PP, respectively. The length of the pellet was controlled at 3-16 mm. Furthermore, the longer the pellet length, the better the observed overall balance of mechanical properties. Depending on the pellet length (3-16 mm) of the LGF40-PP, the average residual fiber length (L_w) increased from 0.75 to 2.5 mm.

Within this fiber length range, tensile and flexural strengths

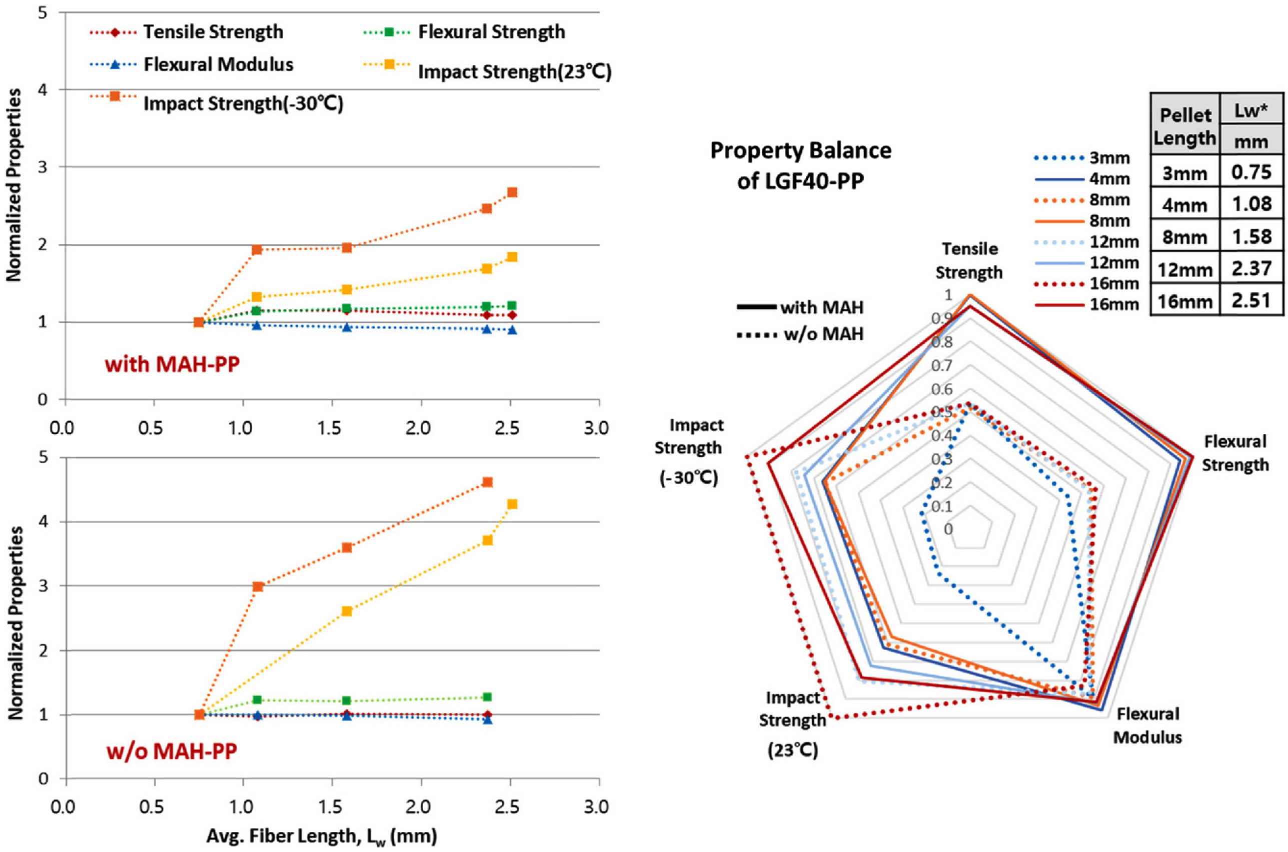


Figure 4. Change of mechanical properties according to fiber length (L_w): by pellet length of LGF40-PP.

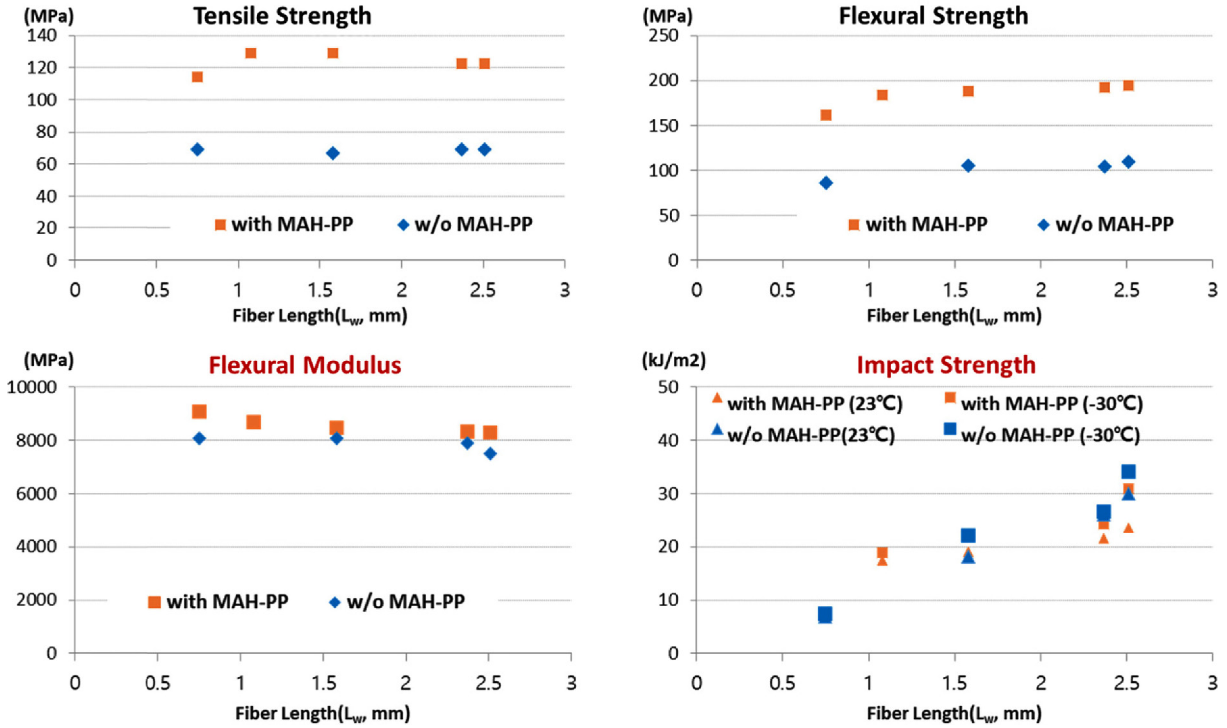


Figure 5. Mechanical properties of LGF40-PP according to the average residual fiber length (L_w).

did not change significantly. The impact strength increased significantly with increasing residual fiber length. On the other hand, flexural modulus tended to decrease slightly as fiber length increased (Figure 5).

Essentially, the better the interfacial adhesion between the polymer and the fiber, the higher the interfacial shear strength (IFSS) of LFT.[5,21] As the MAH content increased, the graph (Figure 6(a)) was observed to shift towards an increase in the ten-

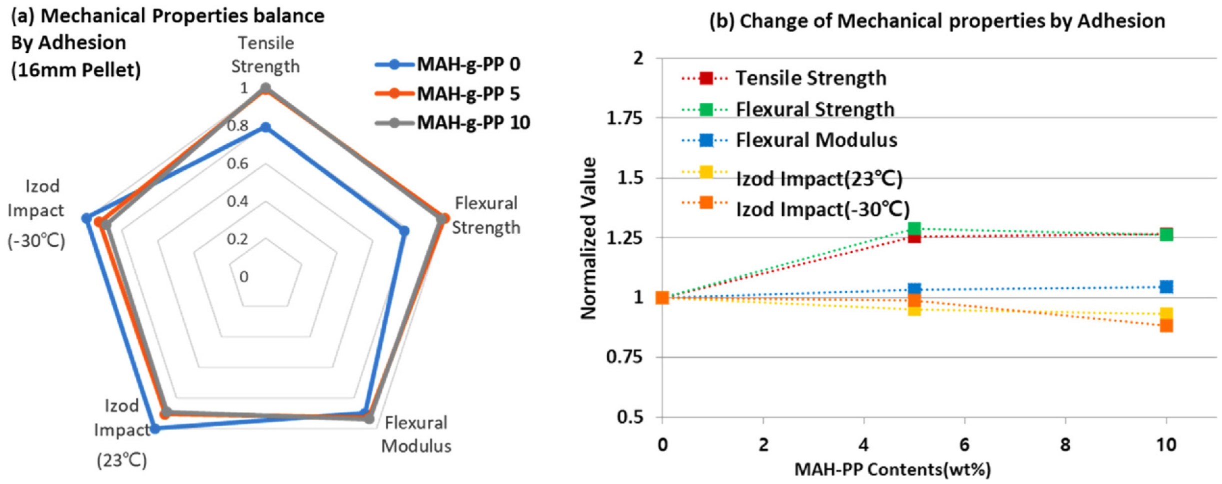


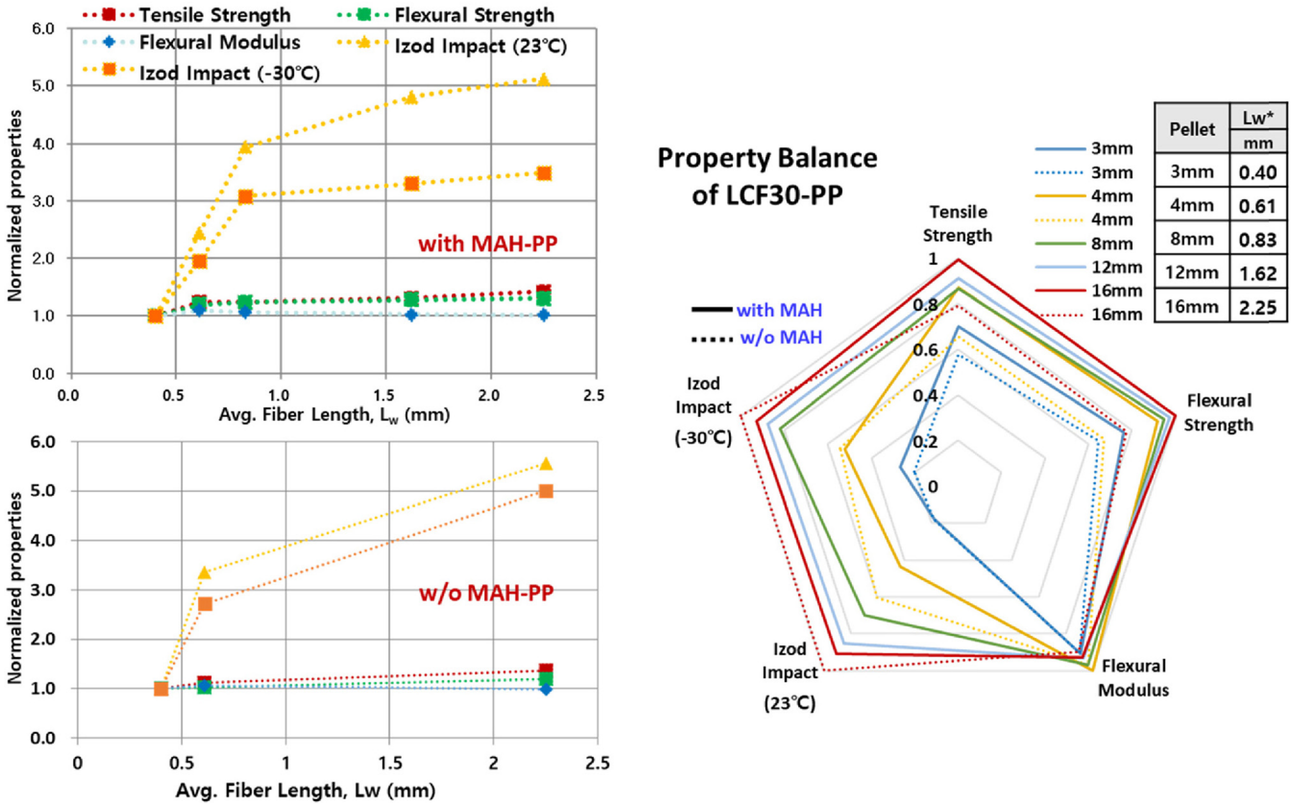
Figure 6. Mechanical properties of LGF40-PP: by the adhesive resin.

sile and flexural strength. The tensile and flexural strength tended to increase with increased the content of MAH-PP as the tensile strength shifted in the direction aligned with the fiber orientation. Notably, the impact strength was greater for the sample without the adhesive resin, and the difference observed was larger for the longer fiber lengths (Figure 6(b)).

3.2.2. Mechanical properties of LCF-PP

The LCF-PP pellet reinforced with carbon fiber (30 wt%) was prepared using the prescribed ratio of 0-10 wt% of MAH-g-PP, respectively, and the physical properties of each specimen were examined. he length of the pellet was controlled at 3-16 mm. Furthermore, the longer the pellet length, the better the observed overall balance of mechanical properties. Depending on the pellet length (3-16 mm) of the LCF30-PP, the average residual fiber length (L_w) increased from 0.4 to 2.25 mm. As the pellet length increased, the physical strength of the specimen was also observed to improve. For the LCF-PP, the strength was observed to increase in proportion to fiber length, with the mechanical property balance optimized for the 16-mm pellet. However, the flexural modulus was inversely proportional to the residual fiber length, which was the same trend as that observed for LGF40-PP (Figure 7-8).

The tensile and flexural properties of the LCF30-PP increased with adhesion, and at MAH-PP content of 5%, it increased enough. However, the impact strength tended to decrease with an increase



Pellet	Lw* mm
3mm	0.40
4mm	0.61
8mm	0.83
12mm	1.62
16mm	2.25

Figure 7. Change of mechanical properties according to fiber length (L_w): by pellet length of LCF30-PP.

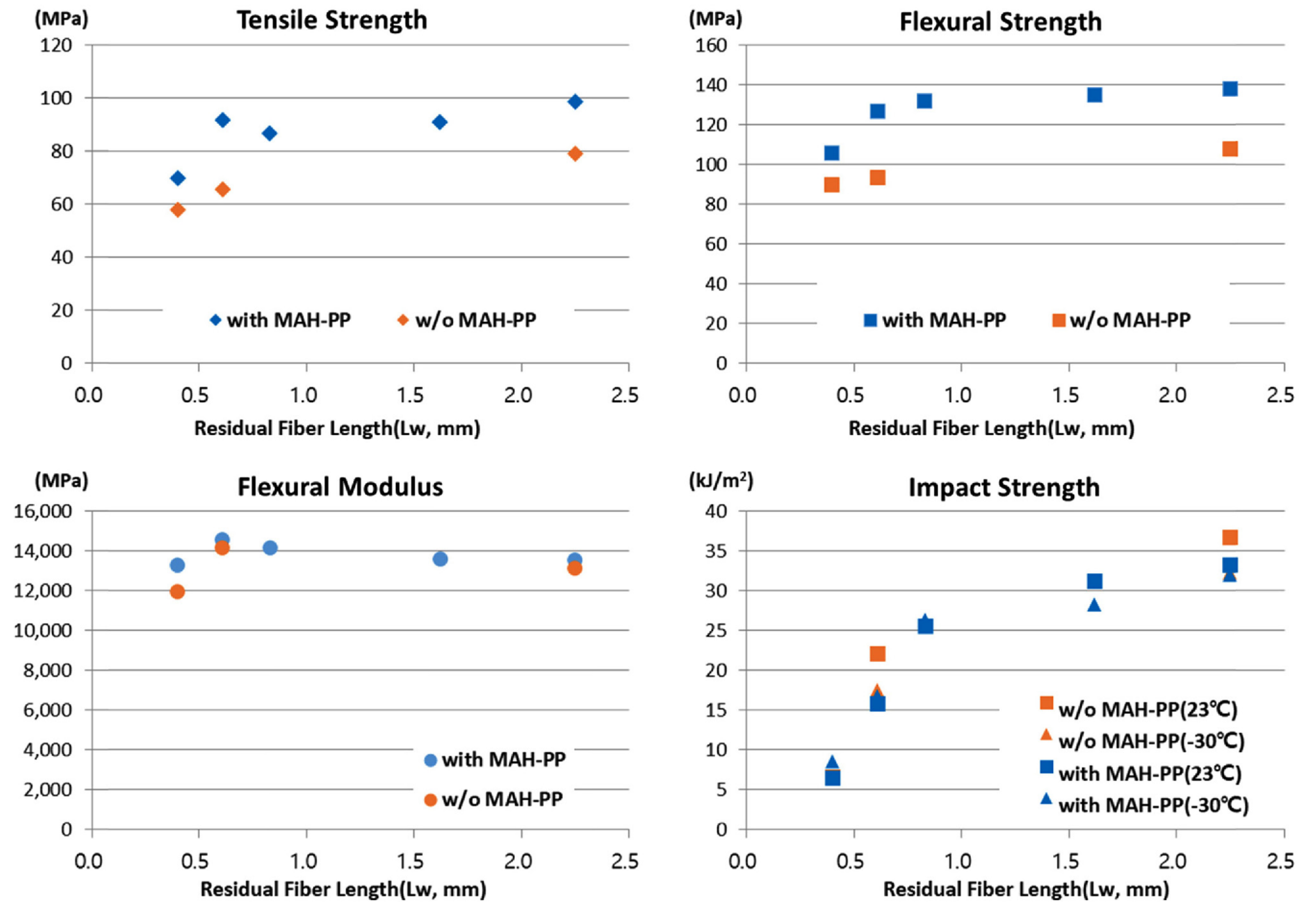


Figure 8. Mechanical properties of LCF30-PP according to the average residual fiber length (L_w).

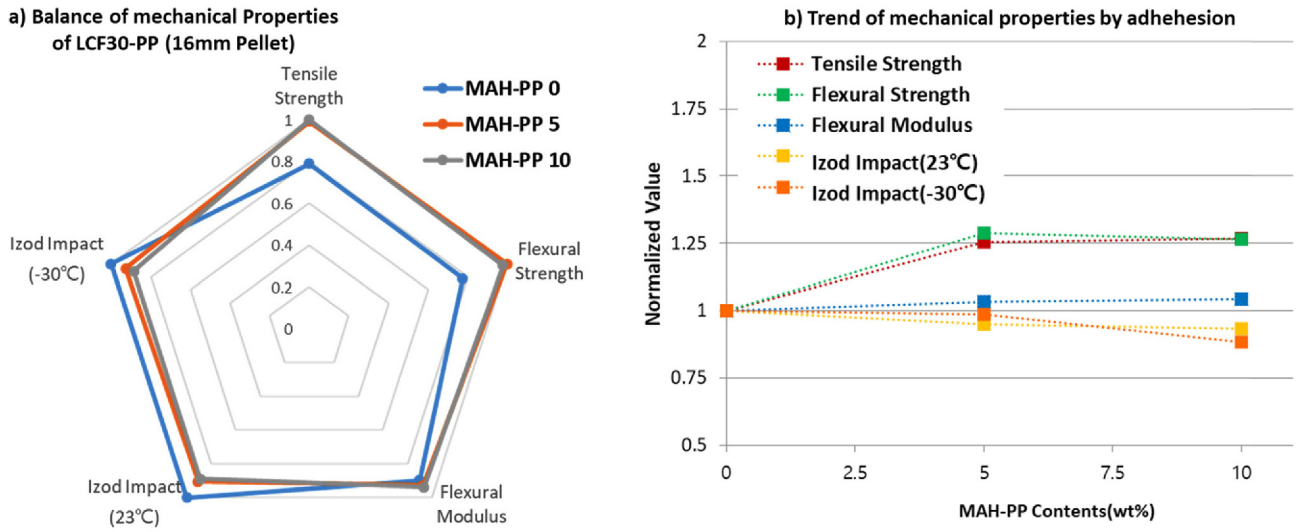


Figure 9. Mechanical properties of LCF30-PP: by the adhesive resin.

in the amount of the adhesive resin (Figure 9). The overall trend of the mechanical properties was similar to that observed for the LGF-PP specimens.

In general, the mechanical properties of LCF-PP and LGF-PP are expected to enhance with increasing fiber length and interfacial adhesion. The flexural modulus and impact strength of the injection-molded LFTs exhibited different tendencies. It can be assumed that this is influenced by factors other than fiber length.

3.3. Impact strength by the fiber length and interfacial adhesion

Increases in the interfacial bonding strength between the fibers and resin led to a clear increase in the strength of matrix polymer, but the impact strength exhibited different trend.

Generally, to increase the impact strength of polypropylene (PP), modified by mixing the rubber and elastomer, affording a flexible molecular structure that can absorb the impact. PP exhibited a low impact strength at temperatures of less than or equal to -10 °C because PP exhibited high crystallinity at less than or equal to the glass transition temperature (T_g), which is weak to impact of high speed.

However, when the long fibers were reinforced the impact strength at low temperature (-30 °C) was considerably enhanced than at room temperature. In fiber-reinforced composites, the fibers enhance the impact strength by different mechanism. The impact strength of the LFTs increased significantly in proportion to the fiber length, whereby longer fibers considerably improve the impact strength because the long fibers are able to resist the impact at the breaking moment.

The interfacial bond between fiber and resin is mainly expressed in interfacial shear strength (IFSS).[5,21] Tensile strength and flexural stiffness of composites increase with higher IFSS but have different characteristics in toughness such as impact strength. Fibers having high IFSS are broken together on the surface where the resin is fractured, On the contrary, non-adhesive fibers remained longer length.

In carbon fiber reinforced PP (CFRPP), when the fiber length is long, the impact strength of samples with low IFSS tends to be higher.[7]

Also in carbon fiber thermoplastic composites based on polyaryletherketones (CFR-PAEK), it was reported that the fiber breaks easily at the fracture surface in the specimen with improved IFSS.[22] In the long fibers and short fibers, there are differences in the impact strength of the reinforcing effects of the IFSS. When the residual fiber length was short, the higher IFSS, the higher the impact strength. When the residual fiber length was long enough, the lower IFSS, the higher the impact strength.

The impact strength was higher for all of the LGF-PP and LCF-PP specimens without the adhesive resin, and the difference was greater for longer fiber lengths (Figure 10).

Figure 11-12 shows a magnified image of the fracture section after impact test. Less adhesion with PP was observed on the fiber surface in the low IFSS specimens. Additionally, a narrow space was observed at the root of the fiber in the low IFSS specimen. These might be caused by low interfacial adhesion between the fiber and the matrix resin. In the high IFSS specimens (Figure 12(a),(c)), some matrix resin sticking was observed on the fiber surface, and the resin was observed to rise around the root of the fiber.

As the impact strength of the sample without adhesive resin was high, the physical reinforcement effect was greater than the chemical bond between the resin and fiber. The higher the interfacial bonding force between the matrix resin and the fibers in the LFT, the more easily the fiber is broken during the impact strength test under the application of an instantaneous high-speed impact. When the specimen with a high interfacial bonding force was fractured by using MAH-PP, the fibers strongly bound to the resin were broken at the fracture surface of the resin. On the other hand, fibers with a weak interfacial bonding strength increased the impact resistance while simultaneously

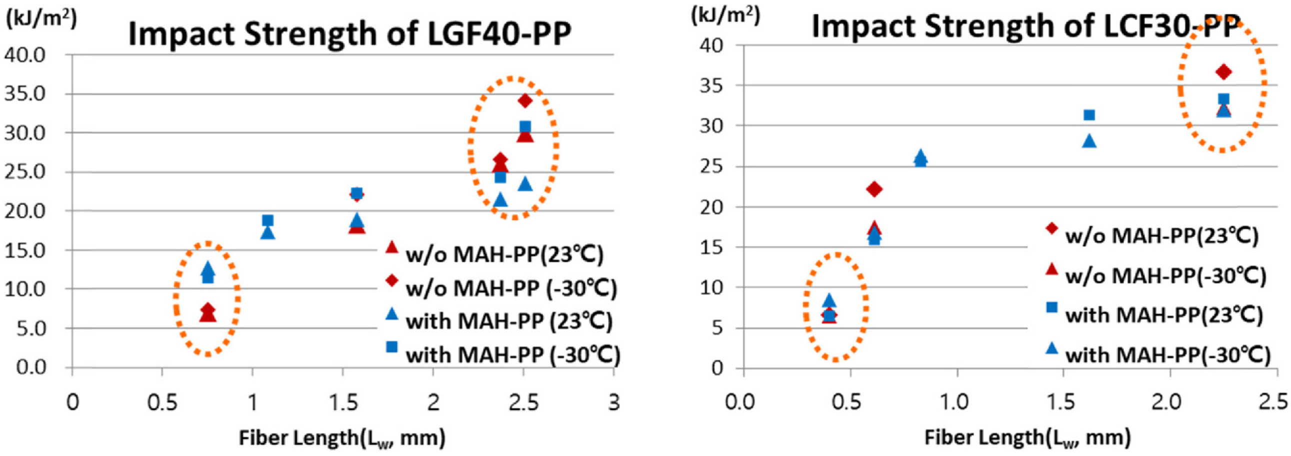


Figure 10. Change of impact strength by fiber length and adhesion.

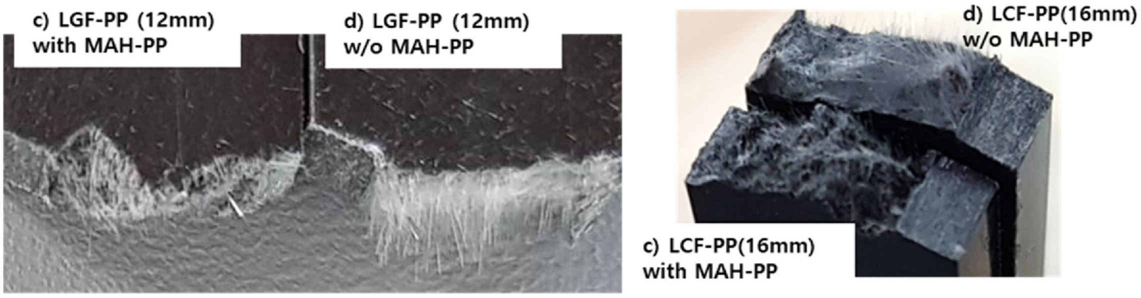


Figure 11. Fracture section after the izod impact test: (a) LGF40-PP with MAH-PP, (b) LGF40-PP without MAH-PP, (c) LCF30-PP with MAH-PP, and (d) LCF30-PP without MAH-PP.

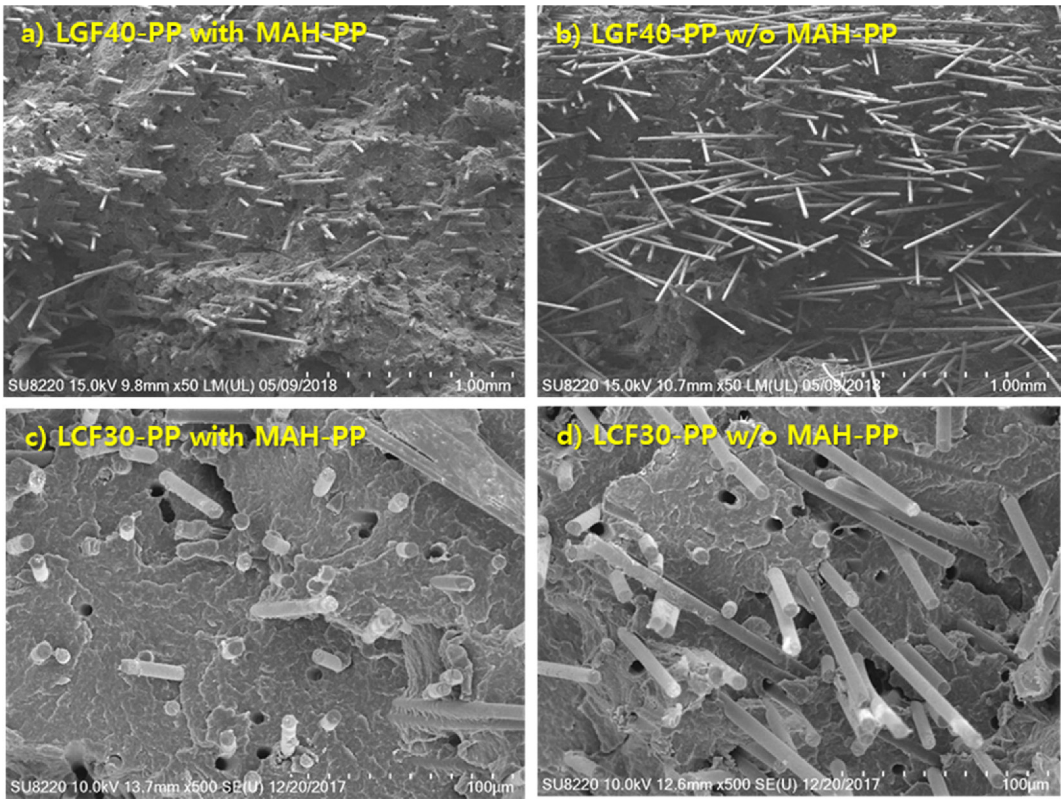


Figure 12. SEM image of fracture section after the izod impact test: (a) LGF40-PP with MAH-PP, (b) LGF40-PP without MAH-PP, (c) LCF30-PP with MAH-PP, and (d) LCF30-PP without MAH-PP.

maintaining the long fibers without breaking at the same fracture surface.

3.4. Effect of fiber length on the stiffness

The flexural modulus of the LFT specimen slightly decreased with an increase to the fiber lengths of the LGF and LCF-PP specimens. Regardless of the addition of the adhesive resin, the flexural modulus tended to decrease with an increase in the pellet length (Figure 13). Therefore, it can be considered that is more influenced by other factors compared to the influence of fiber length and interfacial bonding. In the flexural test, stress was exerted in the perpendicular direction, not in the uniaxial stretching test as per the tensile test method. Along the upper, lower, and central portions of the thickness of the test specimen, stressors such as compression, elongation, and shear stress were applied in different directions (Figure 14(a)).

As a result of the injection molding used LFT, the fibers were oriented according to the resin flow (Figure 14(b)). The skin layer, which was mainly in contact with the mold surface, exhibited the same fiber orientation as the resin flow in the mold direction (MD), and the resin flow in the core layer was in the transverse direction (TD) or a random direction (RD). The core layer thickness was observed to vary depending on the fiber length.

Where the longer the fiber, the larger the random orientation layer (Figure 14(b)). Hence, the flexural modulus of the specimen

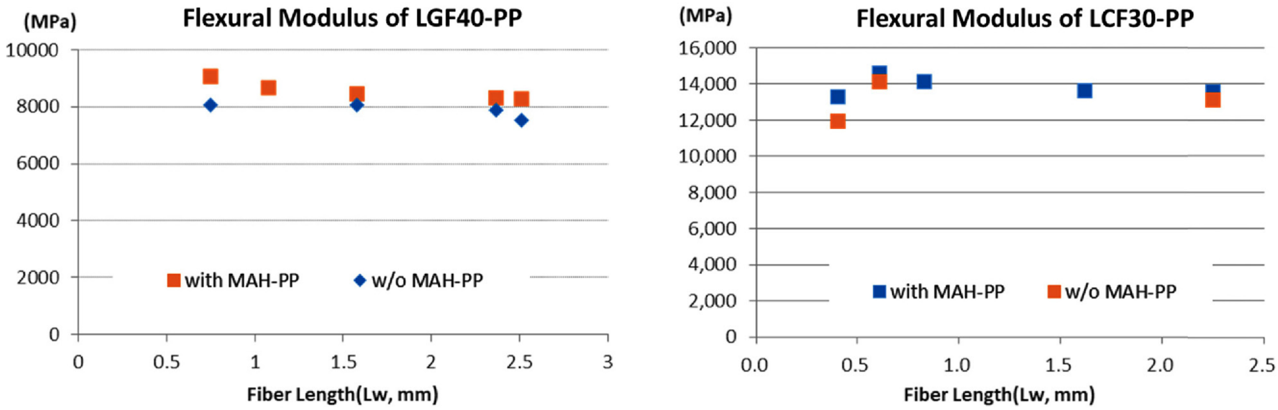


Figure 13. Flexural modulus of the LFT-injection-molding by the fiber length.

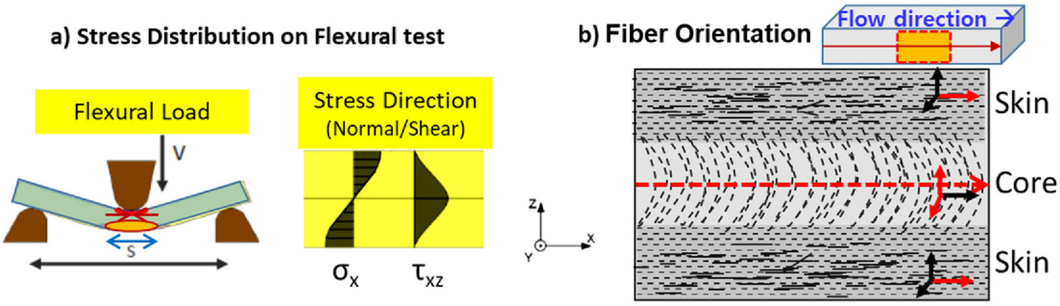


Figure 14. Flexural test and fiber orientation of the injection-molded specimen: a) stress distribution on the flexural test, b) fiber orientation according to the injection flow.

with high random orientation would be low. In addition, it can be assumed that the shorter the fiber, the denser the fiber structure, and the elastic modulus value corresponding to the initial strain in the flexural direction increases. The mechanical properties of the fiber-reinforced composites depended not only on the elastic properties and volume fraction of the constituent materials, but also on the fiber orientation and fiber length distribution from the molding. By inserting the orientation and length distribution of the long fibers into the components of the stiffness constant, the modulus of the fiber-reinforced injection molding plates can be predicted on the basis of a generalized laminated plate theory. By using a simulated laminated plate model, an analytical method was presented for predicting the stiffness of fiber-reinforced injection moldings, including the effects of fiber orientation and fiber length distribution.[13,23]

To confirm the difference in the orientation of the fibers, sections of the injection molded specimens with a thickness of 4 mm were observed by SEM. The 12-mm LGF-PP pellets recorded an L_n value of ~1.8 mm, with a core layer thickness of ~1.5 mm. The 4-mm pellets retained an L_n value of ~0.8 mm, and the intermediate layer was reduced to ~1 mm. For comparison, short-glass fiber compounded polypropylene (SGF-PP) was examined, which exhibited the extremely short residual fiber length and thin core layer. The fiber orientation distribution was found to differ according to fiber length. In the case of 12 mm pellets, the thickness of the core layer was greater than that of 4 mm pellets because of long fibers, and the ratio of MD orientation was relatively lower.

The physical properties of the LFT specimens potentially varied depending on the fiber orientation. The properties were measured according to the different angles of fiber orientation arising from the injection flow direction (Figure 16). Hence, there is a large difference in the stress-strain behavior between the different flow directions (0°, 45°, and 90°). Therefore, for a thick core layer with random orientation of fibers a low modulus was achieved.

In computation modeling for LFT injection molding, accurately predicting the fiber orientation is a critical issue, which supposedly leads to the anisotropy on the mechanical properties of the FRP parts. The predicted orientation distributions obtained by micromechanical material modeling computation of the mechanical properties may aid in understanding the reinforcing ability

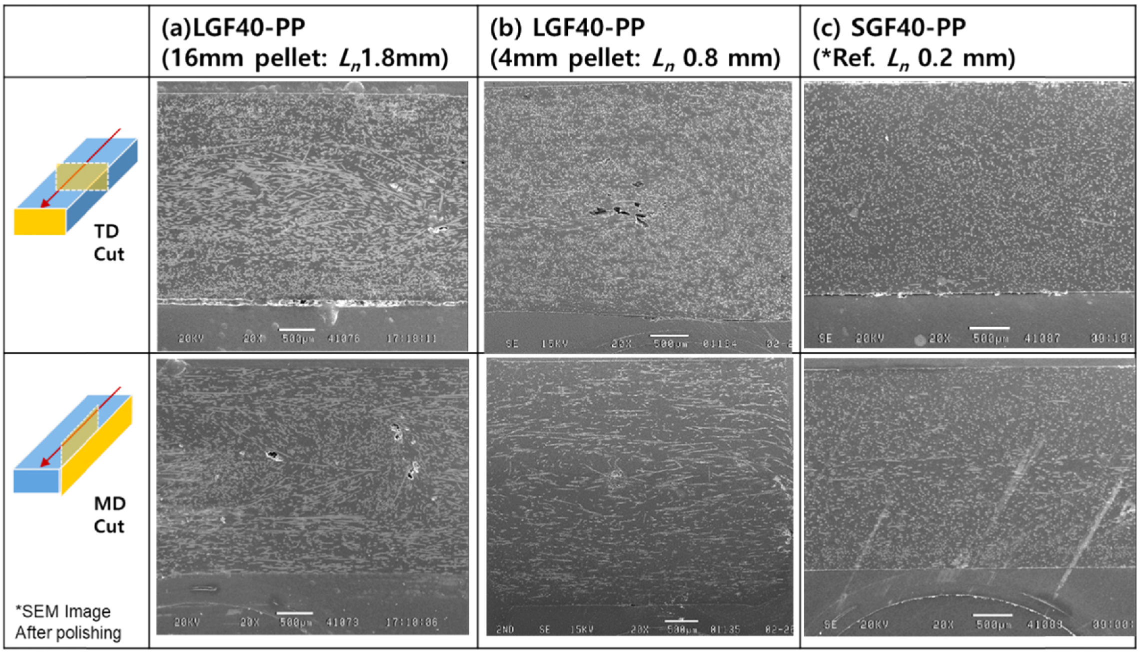
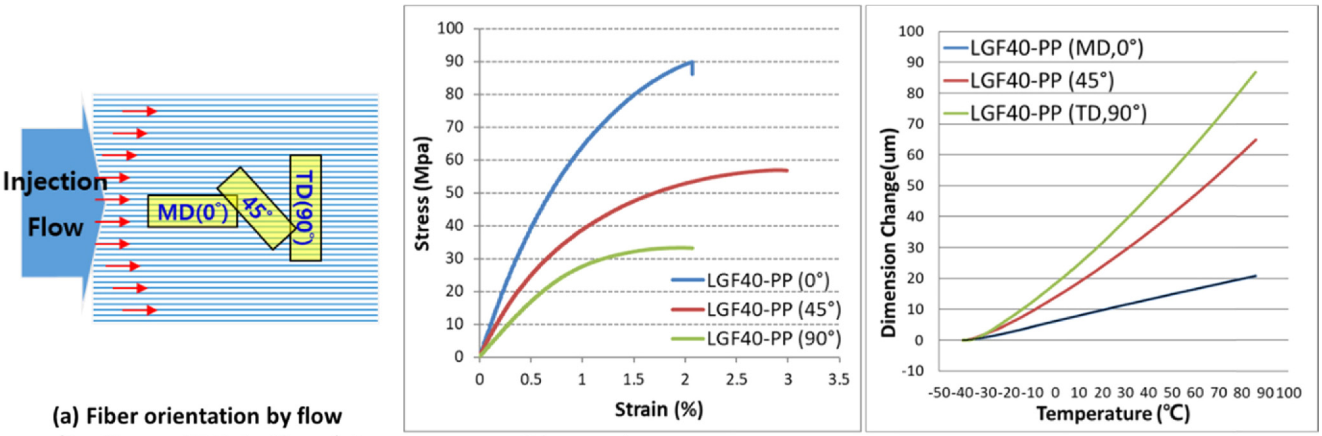


Figure 15. Fiber distribution and orientation over thickness by the fiber length.

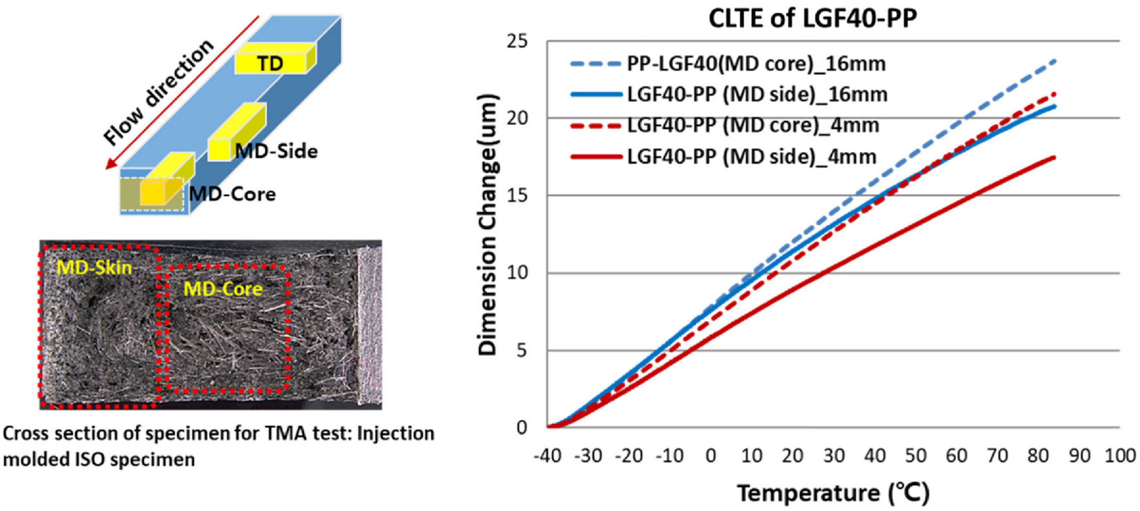


(a) Fiber orientation by flow direction on LFT injection plate

(b) Stress/strain curve

(c) CLTE curve

Figure 16. Effects of the fiber orientation according to the flow direction on the LFT injection plate: (a) fiber orientation, (b) stress-strain curve, and (c) CLTE curve.



Cross section of specimen for TMA test: Injection molded ISO specimen

Figure 17. CLTE changes according to fiber orientation on specimen made by different fiber length.

of short/long fibers and glass/carbon fibers based on the numerical simulation results. Under extreme conditions of high concentration (50 wt%) of LCF and SCF reinforced Polyamide (PA), a thick core region and narrow skin were always observed as a typical orientation pattern associated with injection-molded specimens. And results obtained from the experimental data were compared with the modeling computation results.[13]

Fiber orientations could also be confirmed by the measurement of the CLTE using TMA. The range of variation to the CLTE values according to fiber orientation was greater for the LGF-PP materials (Figure 16(c)). The CLTE for the mold direction (MD, 0°) was less than that of the LFT injection plate, and the CLTE of the core layer increased for different mold directions (45° and 90°), permitting the differences in the fiber orientation to be estimated.

For the LGF40-PP injection specimen, the CLTE curve of the core layer was observed to shift upwards when compared to that of the skin layer (Figure 17). Thus, the fiber orientation ratio of

Table 1. Technical data of materials

Material	Commercial grade (Supplier)	Specifications
Polypropylene (H-PP)	J-190H (LOTTE CHEMICAL)	T_m: 164 °C MFR: 80 g/10 min (at 230 °C)
Maleic anhydride graft PP (MAH-PP)	CM-1120H (LOTTE CHEMICAL)	T_m: 160 °C MAH graft ratio: 0.5-1 wt%
Glass fiber (GF Roving)	SE4121 (OCV)	Single End Roving Tex: 2400 g/1000 m Filament diameter: 17 μm
Carbon fiber (CF Roving)	T700SC-24K-50C (Toray)	Tex: 1650 g/1000 m Filament diameter: 7 μm

the core layer is estimated to be lowered. The difference in CLTE for the core layer is more prominent in the long pellets because the long fibers cause the core layer to be thicker. Owing to the effect of the long fibers, the fiber orientation in the core layer was randomly oriented, and it is confirmed to be associated with a lowered modulus.

Finally, for the LFT injection molding, the longer the pellet length, the lower the flexural modulus and strength. To enhance the balance of the mechanical properties for LFTs, the fiber orientation and FLD need to be optimized by controlling the fiber length during the LFT manufacturing process or controlling the injection conditions.

4. Conclusions

The mechanical properties of LFTs reinforced with glass and carbon fiber were examined, with unusual property variations observed. Even LFT specimens manufactured using the same materials and processes exhibited different mechanical property balances depending on the fiber length. Several compound materials prepared by injection molding exhibited an inversely proportional relationship between the stiffness and impact strength. A similar trend was observed for the injection-molded LFT. Typically, as the fiber length increased, and the interfacial adhesion performance improved, the mechanical strength also increased.

LFT pellets with a length of 4 mm to 16 mm were used to adjust the average residual fiber length to about 0.5-2 mm. In this range, the flexural modulus decreased with a increase in the fiber length, which is related to the fiber orientation arising from the injection molding. At the core layer of the injection specimen, fibers of increased length exhibited a more random fiber direction orientation, which thereby decreased the modulus.

Within the same fiber length range, the impact strength was proportional to the fiber length. Notably, the LFT with the weak interfacial bonded, without adhesive resin, exhibited high impact strength properties. In particular, the longer the residual fiber length, the higher the impact strength of the specimen with the weaker interfacial adhesion, because apart from the resin the fiber was not broken by the momentary impact, and it was not broken while maintaining the original strength of fibers.

The mechanical properties of the LFT were changed by the length and orientation of the fibers in the injection molding process. It is adjustable by pellet length and adhesive resin in the LFT manufacturing process. To improve the impact strength and flexural modulus of the LFT injection product, the fiber length and interfacial bonding strength need to optimize by controlling the fiber length and adhesive resin during the LFT manufacturing process. Further studies related to the injection molding technology for optimizing the fiber length distribution and fiber orientation are currently underway.

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