Research Article

Effect of Injection Flow on Conductive Network in Polypropylene-carbon-filler Composite Bipolar Plates

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Abstract
Bipolar plates have been manufactured by different techniques, such as high performance drilling, compression molding, metal stamping, and injection molding processes. The bipolar plates should be produced via a standard mass production technique in a one-step process, since this can reduce the cost structure of fuel cell stacks, significantly contributed by the bipolar plates. Polypropylene/three-carbon-filler composites were selected for bipolar plate production through an injection molding process for this research work. Although the conductive injection moldable composites can be produced for a bipolar plate application, their electrical conductivity, especially through plane conductivity, has not yet achieved a commercial target. For that reason, a simulation of fiber orientation in an injecting plaque using the finite element simulation program Moldex 3D was carried out with the support of Compuplast Canada Inc. to investigate the effect of an injection flow on fiber orientation in conductive networks. Even the simulation output cannot clearly elucidate the orientation of carbon fibers in the composites containing hybrid fillers as the experimental results showed. Further improvements in the development of conductive networks in injected composite bipolar plates can be achieved, for example, through tailoring of a particular injection mold geometry for the bipolar plate production.

Keywords: Injection flow, Polypropylene/carbon filler composites, Bipolar plates, Fiber orientation, Conductive network, Electrical conductivity, PEMFC, Through-plane electrical conductivity

1 Introduction

Nowadays many companies around the world prioritize fuel cell utilization for niche applications. Low-temperature fuel cells, for instance, Polymer Electrolyte Membrane Fuel Cell (PEMFC) and Direct Methanol Fuel Cell (DMFC), are mainly used for portable apparatuses. The low temperature fuel cells are, therefore, useful for caravanning, camping, boating, communicating in areas without electricity, and medical units in rural areas. The PEMFC stack is not only used as the primary source, but it is also used for charging batteries that provide load balancing [1]. Utilizing a PEMFC stack for charging batteries in remote areas needs a maintenance engineer to visit the site around one time per month that causes a huge saving in operation expenses [2]. One of the concerns for PEMFC's to be widely used in the commercial market place is to produce inexpensive Bipolar Plates (BPs) passing through convenient and high volume fabrication.

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Electrically conductive polymer-based composites have the capability to provide the advantage of good processability simplicity in forming processes, low cost, and low weight. Although compression molding process has been mostly applied for polymeric composite BPs in current markets, scientists and engineers have become interested in BP production via an injection molding process [3]. The need for injection molded bipolar plates in future commercialization as demand increases, is due to its capability for high-volume-production in a one-step process and high geometrical freedom of gas-flow channel design. Minke *et al.* presented research providing an analysis and modeling of bipolar plate productions; compression molding and injection molding processes [4]. The research team created model data for manual compression molding and semi-automated injection molding processes for bipolar plate production. The studied BPs have 25 cm × 25 cm of dimensions and 1–9 mm of thicknesses. With the same material, energy consumption, maintenance cost, and staff payment, the injection molding process causes higher investment of a machine and tooling than the compression molding does, but it provides higher annual production and much faster cycle time. The annual productions of two-mold cavities are 36,000 plates for compression molding and 192,000 plates for injection molding [4]. The cycle time of injection molding is 90 s, while compression molding provides 600 s per cycle [4]. The Zentrum für Brennstoffzellen Technik GmbH, Germany (ZBT) has also produced injection molded bipolar plates. The representative plates were 100 cm^2 in size with a thickness of 2.5 mm and 50 S/cm of electrical through-plane conductivity [5]. The ZBT reported that if manufacturers produce more than 300,000 plates the production cost will be in the range of 0.30–0.35 euros per plate. Note that the price of BPs is competitive depending on mold design and mold production costs [5]. An injection molding is not applicable for all polymer composites, since material viscosity and rheology limit its processability [6], [7]. This problem exists during the process when high filler loading is applied to a polymer matrix (>50 vol%) [8]. On the other hand, the high conductive filler contents correspond to conductive network creation according to percolation theory [9], [10]. The volume fraction of conductive fillers forms the continuous conducting paths referred to as the percolation threshold. A compression molding process becomes a better choice of processing techniques than an injection molding, when high filler loading is used for a desired the electrical conductivity up to 100 S/cm [11]. Polypropylene composites are often formulated for injected BP applications that require a balance of processability, mechanical rigidity, and material cost. The cost of polypropylene is on average 1.20 euros/kg which is cheaper than the cost of phenolic resin (1.4 euros/kg) [4]. The phenolic resin is one of preferred polymers that are selected for commercial BP fabrication via a compression molding process [12]. A comparison of production costs between polypropylene BPs and phenolic BPs through mass production indicated that polypropylene BPs have the production cost of 1.50–2.50 euros/kg, while phenolic BPs need the cost of 4.00–8.00 euros/kg [4]. Superior properties of carbon fillers, such as carbon fiber carbon black, graphite, carbon nanotubes, and graphene over metal powder fillers provide the improvements of electrical and thermal conductivity along with the mechanical property enhancement. The carbon fillers do not corrode, and they also do not encourage an oxidative degradation of a polymer matrix [13]. Very few researches have been focusing on the injected thermoplastic/carbon filler composite BPs, especially for marketable productions. As knowledge of the authors, the best work about injected BP production happened in 2006. SGL Technologies GmbH launched injected BPs that are made from polypropylene/ phenolic bonded graphite compounds [14]. The injection molded BPs were identified as the most promising and cost-effective manufacturing. As known, to create polymer composite BPs giving the desired electrical resistivity (500 μΩm for through plane), the electrically conductive network formation has to be enabled. In an experimental scenario, some researchers were interested in using thermoplastic composites, such as polyethylene terephthalate/ polyvinylidene fluoride blend and carbon fillers [15] or Nylon-6 and S316L stainless steel alloy fibers [16], for injected BP fabrications. Imperative influences of conductive network creation are synergetic effects of different carbon filler sizes, shapes, and multiple filler ratios on the electrical conductivity of bipolar plate materials [17], [18]. Many other factors; processing conditions and mold design, may affect the conductive network in polymer composites. Examples the effect of the processing conditions on electrically conductive paths are given as follows. Pressure during the process leads to an increase in contact areas between conductive fillers, and more connections enhance the conductivity [19]. Small air voids which can arise during polymer processing may decrease the conductive paths in composites [20]. If materials absorb moisture from environment, the conductivity will significantly increase [21]. Filler dispersion, filler orientation, and polymer flow characteristics resulting from the process also directly influence the conductive paths produced in polymer composites. Injection parameters, such as injection speeds, pressure and melt temperature, strongly affect a filler orientation, particularly carbon fibers.

According to the aforementioned literatures, the presented research is aiming to study the effects of injection flow on filler orientation and dispersion in polypropylene composites containing carbonaceous-fillers: carbon fiber; carbon black; and graphite. Experimental activities are presented into two main parts. First, a simulation of fiber orientation in an injecting plaque using Moldex 3D was carried out with the support of Compuplast Canada Inc. to an investigate the effect of an injection flow on fiber orientation. Second, electrical conductivity of composite plates was observed by measuring the conductivity in different locations of the plaques.

2 Experimental Activities

2.1 *Polypropylene composite preparation*

Materials: Equistar® polypropylene (PP35FU01), with 20 g/10 min of a melt flow index, was chosen as the polymer matrix. Note that the PP35FU01 contains a nucleating agent and mold release for improved processing. These particular characters of PP35FU01 are important properties in order to achieve high filler loading while ensuring that the complete mold cavity is filled. Three types of fillers: Carbon Black (CB); Synthetic Graphite (SG); and Carbon Fiber (CF) were used in this study. The CB is XC-72 carbon black (size: <25 ppm of 325 mesh residue with density of 264 kg/m^3) supplied by Cobot corporation. The synthetic graphite named SG 4012, from Asbury, possesses 99% of carbon content, 44×256 μm in size, and 1.5 m^2/g of surface area. Fortafil 243 of Fortafil Fibers Inc. used in the research has a filament diameter of 6–7 μm of diameter and an average length of 5 mm.

The preparation: There are two main steps of composite preparation. A master batch of carbon black filled PP was prepared prior to composite formulations. The master batch was prepared through a twin-screw extruder with a side stuffer (L/D = 40, D = 27 mm; ZSE 27 Leistritz). The mixing of carbon black filled PP master batch with SG and CF was carried out in a 270-mL mixing chamber of Haake Rheomix batch mixer with internal roller-rotors. Operating conditions for all mixing processes were a melt temperature of 210ºC, screw speed at 80 rpm, and a mixing time of 25 min. After the mixing, the composite was ground into powder by a stainless steel rotary grinder (Thomas Wiley Laboratory Mill Model 2) with a feed aperture localized on the top of the rotary cutter.

All formulated composites consisted of 55wt% of filler loading and 45wt% of PP loading. This filler loading was used according to the results of previous work in our research group [22].

Table 1: Formulations of composites

Composites	PP Loading (wt%)	Filler Loading (wt%)		
		CB	CF	SG
COM1	45	0	55	0
COM2	45	36.67	9.17	9.17
COM3	45	18.33	18.33	18.33

Three composites were formulated with different filler ratios as displayed in Table 1. To confirm that the composites contain a desired filler concentration, the actual filler concentrations were determined using Thermal Gravimetric Analysis (TGA).

2.2 *Composite plaque fabrication*

Composite plaques for investigations in this article were injected by Engel 85-ton injection molding machine at 200ºC, 240 rpm of screw speed. The temperature of the mold was maintained around 65ºC by a water cooling system. To address the influence of injection flow on bipolar plate electrical conductivity, electrical conductivity values for a composite plaque were assumed to vary by a region and a direction of applied current. Electrical conductivity values were, therefore, measured for different regions of the same plaque as well as with current being applied in different directions. Specimens for measuring conductivity were prepared according to Figure 1 (a) to (c).

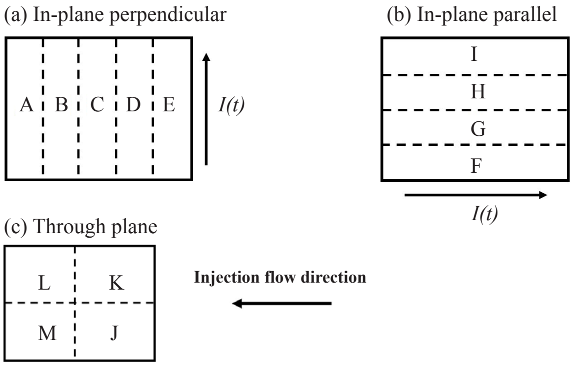

Figure 1: Electrical conductivity testing sample preparation.

2.3 *Injection molding simulation*

The injection molding simulation was performed from the basic plaque geometry used in this research, and dimensions of the plaque were 10.0 cm of width, 20.3 cm of length, 3.0 cm of thickness. An imposed process condition (Table 2) for the injection molding simulation related to the real operating condition that was used for PP-composite BP and PP-composite plaque fabrications in other research activities.

Table 2: The setting process condition for injection molding simulation

Parameters	Values
Stroke Time	2.914 sec
Actual Fill Time	2.914 sec.
Melt Temperature	200°C
Mold Temperature	65°C
Maximum Injection Pressure	350 MPa
Mold Thermal Boundary Condition Type	Heat Transfer Coefficient
Heat Transfer Coefficient	500 W/m^2.K

2.4 *Electrical conductivity measurement*

In-plane electrical conductivity: A four-point probe set was the apparatus chosen for measuring the conductivity of composite samples in this work. By passing a current through two outer probes and measuring the voltage through the inner probes allows the measurement of the substrate conductivity. This in-plane conductivity test procedure follows the procedure outlined in ASTM D-991 and the concept of a four-point probe method.

The In-plane electrical conductivity test indicates electrical conductivity measurements at the surface and near-surface of a bipolar plate, but they cannot provide the same insight into the electrical characteristics deep inside the bipolar plate.

Through-plane electrical conductivity: volumetric electrical conductivity or through-plane electrical conductivity was measured by a procedure followed by the US Fuel Cell Council [23]. The conductivity was determined by compressing a composite plaque between two gold-plated-copper plates and then a constant current was passed through the two plates. The potential difference between the plates was measured.

For further experiments, images from Scanning Electron Microscope (SEM) were used to determine a number of filler particles (SG and CF), a number of connection points, and filler contact areas using UTHSCSA ImageTool Version 3.0. Micrographs (with 3kX of magnification) having an area of approximately 4,872 μm^2 were used for the determination. Note that five areas were snapped for each SEM specimen, and ten specimens were required to determine those values.

3 Results and Discussions

3.1 *Fiber orientation in an injection plaque*

The orientation and dispersion of conductive fillers, especially carbon fibers, in composites are typically influenced by the geometry of injection flow. This simulation procedure addressed a single-filler system composite, which is PP/CF composite (COM1, Table1).

This simulation gave a guideline for further understanding the effect of conductive filler dispersion on conducting paths. The simulation outputs are illustrated in the following images, and the definitions of the output are explained as follows. In the post-processing of fiber orientation, the biggest eigenvalue and its corresponding eigenvector are plotted together to illustrate the complex fiber orientation phenomena. The orientation of the vector shows the most favorable orientation direction, while the magnitude of it (displayed in color) shows the degree of orientation. Figure 2 shows the simulation output filling pattern, and it can be explained that the molten composite flows into a mold due to injection pressure at different times. The blue zone represents the region to which a molten

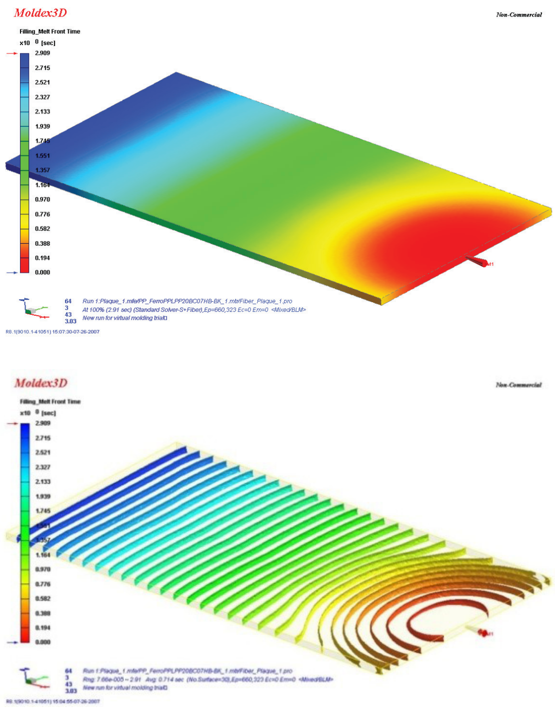

Figure 2: Simulation output filling pattern.

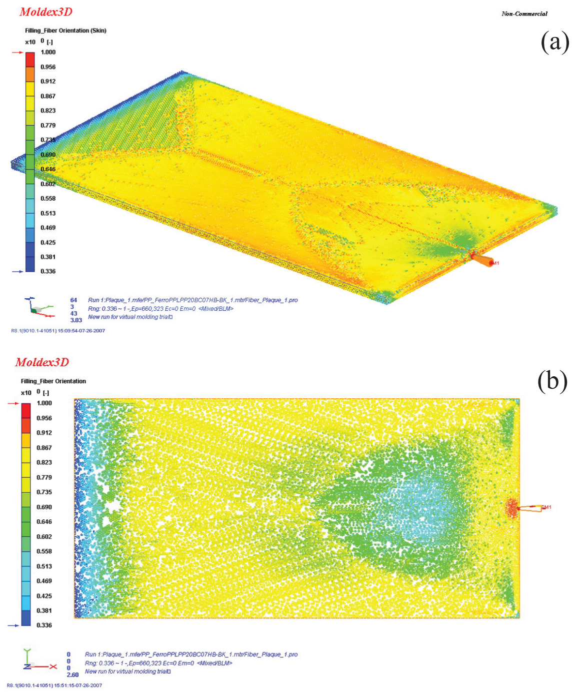

Figure 3: Simulation output: (a) fiber orientation (skin) and (b) fiber orientation (bulk).

composite flows over the longest time (2.909 s), whereas the composite takes the shortest time for the red zone (0.000 s). The Moldex3D analysis outputs are fiber orientation (skin) and fiber orientation (bulk), as illustrated in Figure 3. "Fiber orientation (skin)" is the fiber orientation on the skin layer near the surface of the plaque, while fiber orientation (bulk) is the three-dimensional fiber orientation distribution across the plaque. Therefore, users can use the slicing function to visualize its details. In summary, for a random orientation, the maximum eigenvalue would be 1/3 (blue); for a fully aligned orientation, the maximum eigenvalue would be 1 (red).

The molten composite flows into an injection mold with two main flow phenomena during the mold filling step of an injection molding process. The two different flow phenomena are shear and elongation flows. The shear flow is located near the mold wall, while the elongation flow takes place at the front flow (Figure 4). According to the simulation outputs in Figure 3 (a), the cavity area which is opposite to the injection gate shows fiber random alignments, since the elongation flow results in an orientation perpendicular to the injection flow direction. At the wall locations, a molten composite layer is mainly characterized by shear stress. Therefore, shear flow leads to a fully aligned orientation of fibers (orange to red zone). The fiber alignment exists in the injection flow direction owing to the arising shear flow [24].

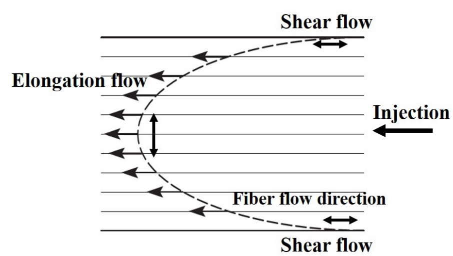

Figure 4: Flow phenomena of skin-shear-core layering.

Besides this, the lower temperature of the mold wall than temperature at a core layer and fast cooling of the molten composite in the vicinity of the mold wall also has an effect on uniformity and high fiber orientation. Figure 3 (b) shows the simulation output in a core layer or the center of the molded part. The fiber orientation pattern in the core layer depend upon the elongation of the flow. It leads to a perpendicular alignment to the injection flow direction. Then, the larger green area can be seen in this simulation output of fiber orientation (bulk). It implies that fibers randomly orientate in the center of the molded part. If the filling time and melt temperature are increased, the skin layer (yellow zone) will be increased [25]. Specimens for measuring conductivity were prepared according to Figure 1. For each prototype plaque, electrical conductivity values for regions A to M were measured. Note that four specimens from four composite plaques for each sample were required to determine the effects of current direction on electrical conductivity values. For in-plane samples, current was passed along the direction of the plaque plane. The arrows in Figures 1 (a) and (b) indicate the direction through which current was applied. Perpendicular and parallel designations refer to the direction of the applied current relative to the direction of injection flow during the injection molding process. In-plane parallel samples were cut along the direction of injection flow, while in-plane perpendicular samples were cut perpendicular to the injection flow. Lastly, for through-plane samples, current was passed directly through the plaque plane.

3.2 *Through-plane electrical conductivity*

Three injection plaques were cut into four areas (J, K, L, and M) as shown in Figure 1 (c). The through-plane electrical conductivity values of three composite systems were measured in different locations the results of which are shown in Figure 5.

The electrical conductivity ranking of COM1 plaques, containing 55wt% of carbon fiber loading, is M > L > J > K, and the resulting discussions are related to the simulation output pictures [Figure 6(a) and 6(b)]. As the experimental results show, a specimen from area M had the highest electrical conductivity, and the fiber orientation patterns can be seen in Figure 7. The M specimen covers area 1 of slice 7 and half of slice 6; it also covers half of area 2 in slice 7 and half of slice 6. It can be seen that the fibers randomly oriented in the middle and the end of slices 7 and 6 (area 1). This orientation is in the highest disorientation range, represented by dark blue color. In area 2, which is the center region of an injection plate, more orientation appears in the middle of slices 6 and 7. Most fibers align quite orderly along the flow direction on both edges of slices 6 and 7. To sum up, a conductive network can be formed in which the fiber orientation ranges from green (~0.690) to dark blue (~0.381) [26]. The electrical conductivity of the L specimen was slightly lower than that of M. The result corresponds to the simulation output, since the degree of fiber disorientation in area 1 of slice 5 is slightly lower than that of slice 7.

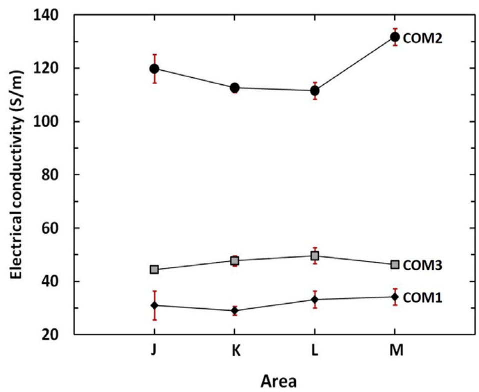

Figure 5: Through-plane electrical conductivity of composite plates in different locations.

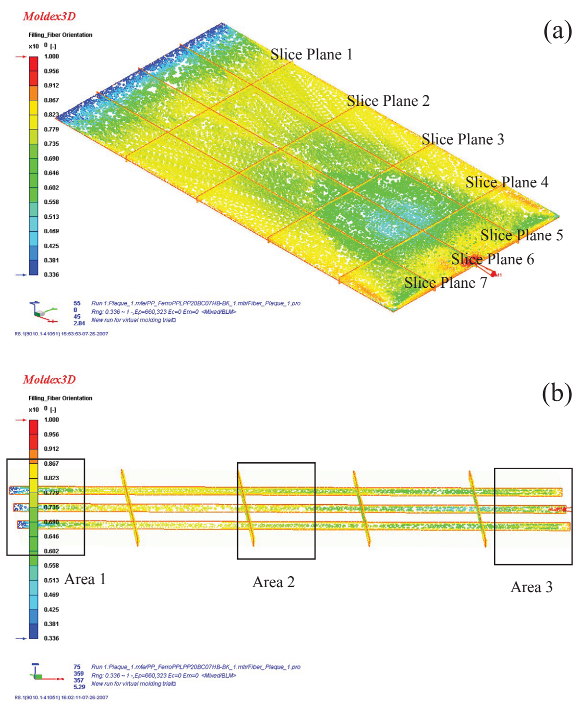

Figure 6: Various areas of the fiber orientation simulation output.

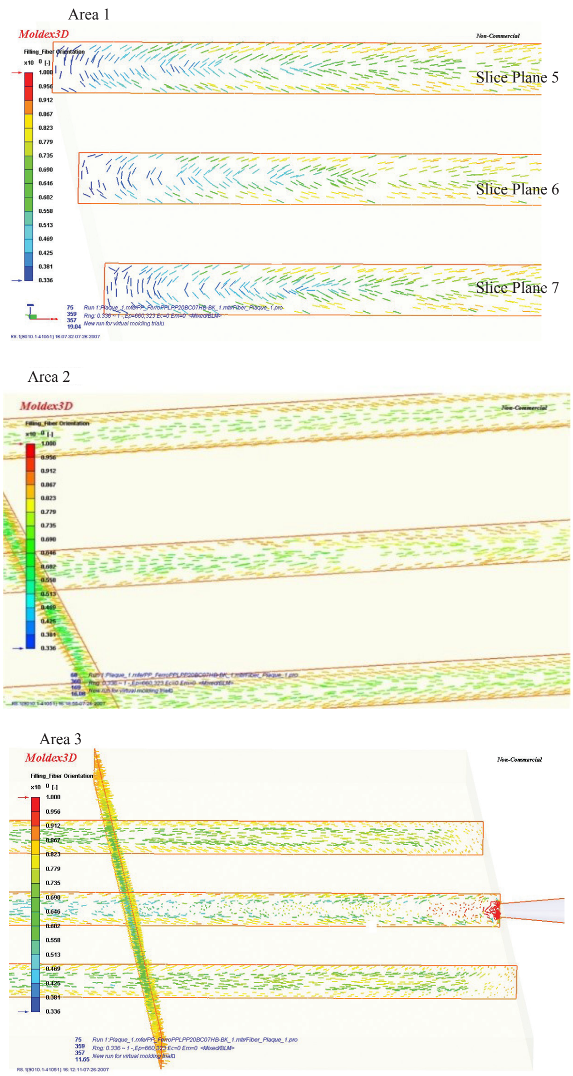

Figure 7: Zoom in on the three investigating areas.

According to Figure 7, the presence of aligned fibers along with the parabolic distribution of fibers validates the combined impact of shear flow and elongation flow in the bulk of a composite plaque. The parabolic flow pattern presents a higher degree of transverse orientation with respect to the injection flow direction at the end-plaque. The transverse orientation is affected by the elongation (or extensional) flow. Different angles of the fiber alignment make fiber connections, and the connections among carbon fibers construct a conductive network. Quantities of conductive paths in slice plane 5, 6, and 7 are not equal, since the asymmetric state of viscosity results in asymmetric patterns of fibers in the flow plane [27]. It could be concluded that the quantity of conductive network depends upon fiber orientation, filler dispersion and distribution. A good filler dispersion in composites typically has lower electrical conductivity than relating poorly dispersed composites [26]. J and K specimens mainly represent area 3, the location near an injection gate. The carbon fiber orientation in both sides of the injection gate (Figure 6) is quite alike. The carbon fibers orientated slightly on both sides of the injection gate, but with disorder alignment in the middle region along the flow line from the injection gate (the light blue color), is probably due to a fountain flow effect which happens during injection molding, pushing composite layers at the melt front that entered the cavity outward [28]. In comparison with an end plate area, the area near the gate exhibits better fiber orientation. The fibers in the area close to the injection gate were induced to align by injection and melt pressure more than the fibers at an end of filling area. The distribution in fiber connection at the area close to the gate may cause the composites to lose conductivity. The wide error bar of specimen J's conductivity shows the electrical conductivity distributions in the area adjacent to an injection gate. In terms of COM3 composites, the three filler system, the through plane electrical conductivity ranks L > K > M > J. This order of electrical conductivity does not correspond to the simulation output. The result tendency cannot provide proper information about the state of filler orientation. During injection molding of composites, mechanical shear induces dispersion and distribution of SG and CB particles in the matrix. SG and CB distribution or SG agglomerates may disrupt fiber orientation. The electrical conductivity values of COM3 in different locations did not show a drastic change. In the case of COM2, the electrical conductivity measured from the area near the gate (J and K) shows lower values than at the end of the filling area. In any case, the results of the three composites indicates that co-supporting conductive percolation networks with a synergistic effect with different filler shapes results in these composites having an enhanced conductivity and lower anisotropy. The three-filler system composites (COM2 and COM3, without simulation) provide higher through-plane conductivity than the one-filler system composites (COM1). Different physical transport mechanisms can contribute to the electrical conduction. The mechanisms consist of hopping, tunnelling, Schottky barrier transport, and Frenkel emission [29]. The hopping mechanism typically dominates for current flow in polymer composites [30]. Regarding to the hopping mechanism, inter-particle connections are important for current transport between neighbouring filler particles. The increasing conductivity can be attributed the CF acting as long distance charge transporter, and the CB and SG aggregates may serve as interconnections between the fibers by forming local conductive paths. The distribution of CB aggregates strongly influences the orientation of carbon fibers as well as the conductivity.

3.3 *In-plane electrical conductivity*

The in-plane electrical conductivity values were measured parallel (Figure 8) and perpendicular to the injection direction (Figure 9). The specimens were cut as described in Figure 1. The electrical conductivity of COM1 plaques, from Figure 8, shows two levels of conductivity values. Electrical conductivity values can correspond to the simulation output fiber orientation-skin in Figure 10 (a) to (c). The simulation output indicates that the fibers are highly orientated, notably on the surface of composite plaques.

The fiber orientation prevails in the injection flow direction on the plaque surface, because of the mentioned reason elucidated in section 3.1. The four-probe technique was utilized for the in-plane electrical conductivity measurement. When fillers (especially CFs) orientate near the skin, high possibilities exist for having contacts between the probes and fillers. Thus, the orientation on the skin is a reason that in-plane electrical conductivity is higher than through-plane electrical conductivity. The reason for the conductivity difference in two directions corresponding to the direction of the filler alignment and measurement direction. The fiber orientation powerfully affected in-plane electrical conductivity, since the current was applied in the same direction as the orientation. High conductive paths are provided for the flow of electrons in this direction. The in-plane electrical conductivity of the samples vertically cut to an injection flow direction has overall values lower than the values of samples cut in the parallel direction. That is because of lower numbers of fiber interconnections in the direction of electron flow. The lower number of the interconnections could be due

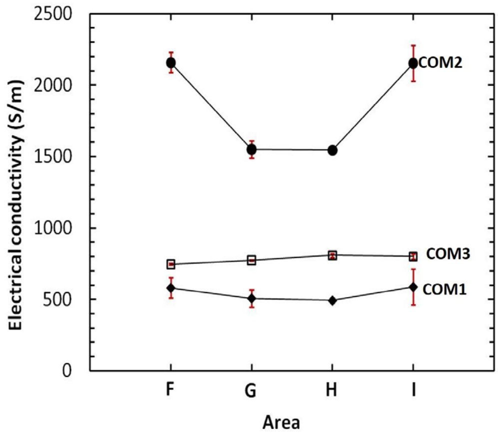

Figure 8: In-plane electrical conductivity of composite plaques in different locations (parallel).

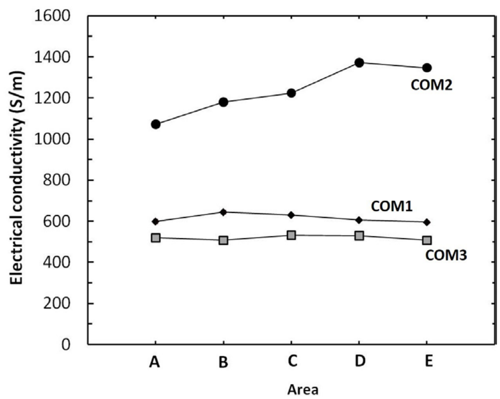

Figure 9: In-plane electrical conductivity of composite plaques in different locations (perpendicular).

to the effect of shear rate. The high shear rate leads to the rupture of conductive networks and a cooling step is too short to allow dynamic percolation [31]. Higher electrical conductivity values of the F and I specimens are due to the carbon fibers orderly orientated on both sides of the plate skin layer, and they are aligned well in the mid-zone along the injection flow from the gate. As results show, the electrical conductivity of the G and H specimens was slightly decreased, because fibers become disordered in the layer near the filling gate.

The high ratio of carbon black in COM2 composites enhances a poor filler arrangement, especially in the area near the injecting gate. Almost of the results indicate that the combination of carbon fillers has no significant effect on filler orientation at the surface of the composite plates. Therefore, this simulation has

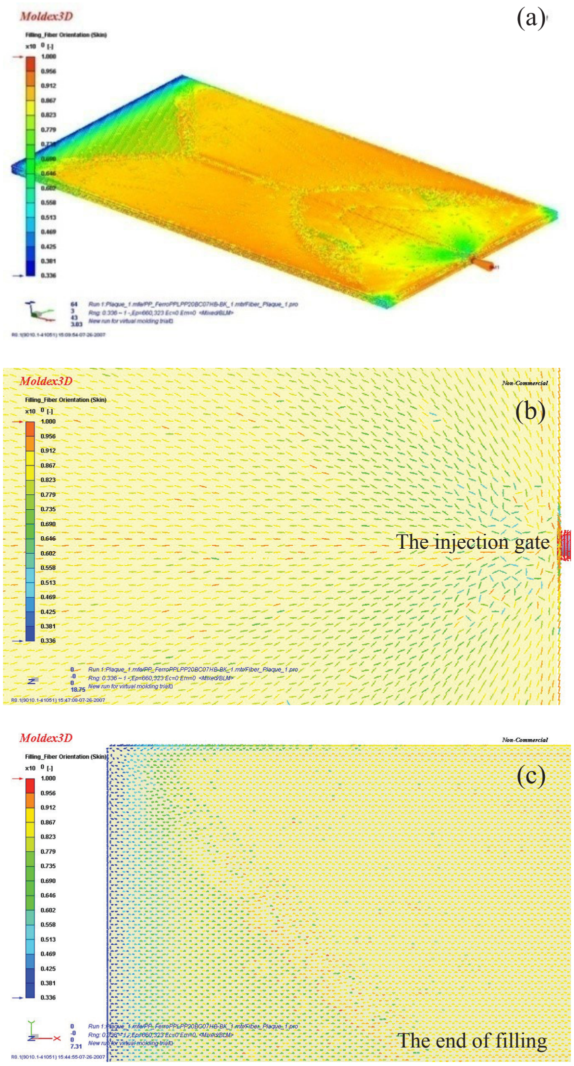

Figure 10: Simulation output fiber orientation-skin.

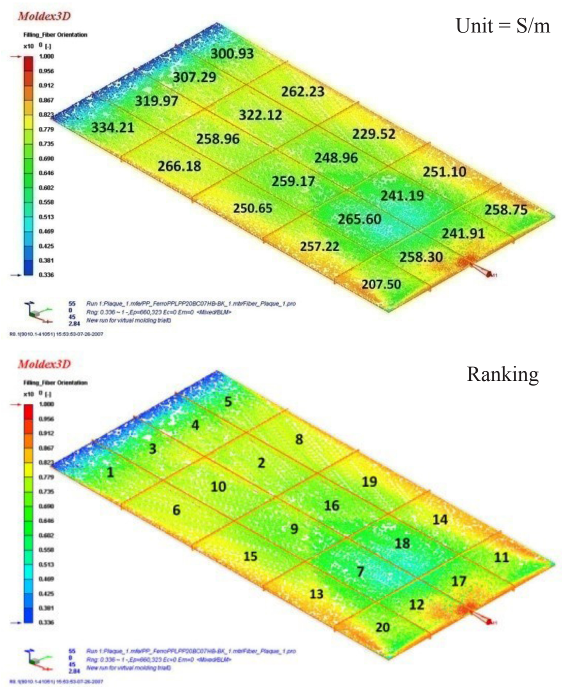

Figure 11: Through-plane electrical conductivity of composite plates in twenty locations.

potential to be used for the investigation of the change in carbon fiber interconnections. There was little variance in the electrical conductivity of composites measured from area A to E, and this result was unexpected. The electrical conductivity determined from areas A and E should be higher than that of the other zones, since the carbon fiber is randomly distributed. For that reason, more conducting paths would be created in the direction of the measurement. In the case of the COM2 composite, the conductivity increased from the area at the end of filling to the area near the gate. A feasible reason for this phenomenon is poor fillers dispersion at the end of filling; thus connecting paths may be broken. From Figure 10 (b), near the gate, a large quantity of fiber contacts can be observed. If there are good filler distributions around that area, more conductive filler networks will be associated. For further study, COM2 composite plaques were cut into many pieces as depicted in Figure 11, and those specimens were tested for through-plane electrical conductivity. The electrical conductivity of the composite diverged in various areas (Figure 11) as expected, because carbon fillers are randomly distributed in a polymer matrix. It is hard to determine the actual pattern of filler network formation to give each a conductive value.

To summarize the results, the highest electrical conductivity (334.21 S/m) was found from an end filling area (marking red circle) and the last row of the end filling area gave the highest conductivity compared to other zones. The results positively correspond to the previous discussion describing a relation between the simulation output and the through-plane electrical conductivity. As described previously, the degree of orientation is represented by the degree of orientation in different colors.

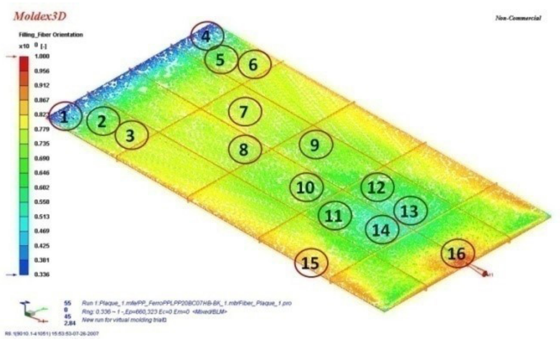

Figure 12: The areas in a composite plate observed by their morphology by SEM.

Composite specimens from each color shade were prepared to observe the morphological characteristic of composites in that area by SEM images (Figure 12). For further experiments, the SEM images were used to determine a number of fillers (SG and CF), a number of connection points and filler contact areas using UTHSCSA ImageTool Version 3.0. As the results in the table show, the total number of filler contacts in a dark blue zone is highest, and the overall values from a light green zone to a dark blue zone are higher than a red zone. Results in Table 3 can be related to the electrical conductivity values in Figure 11. The middle degree of fiber orientation gives fillers a higher opportunity to form more conducting paths, however; the area at end of plaque indicates the highest electrical conductivity. It implies that CB dispersion may significantly impact on the electrical conductivity of the composite.

Table 3: The results from ImageTool

Area Number	Number of SG (particles)	Number of CF (particles)	Total Number of Contacts Between Fillers (SG and CF)	Total Number of Contact Area (mm^2)
1	10	6	12	19.08
2	22	3	9	19.82
3	10	10	6	22.53
4	17	5	6	16.03
5	17	3	9	25.19
6	10	7	4	10.780
7	5	6	5	10.50
8	4	4	5	27.65
9	8	7	4	34.15
10	19	6	6	34.28
11	11	7	8	15.59
12	11	9	8	13.64
13	9	5	9	16.68
14	21	5	7	11.17
15	13	13	4	14.43
16	8	11	4	9.46

4 Conclusions

The orientation of carbon fibers in composites is affected by the injection flow geometry. It was determined that the electrical conductivity values of injected specimens cut from different areas of an injected plaque varied, because the electrical conductivity depends largely on the carbon fiber alignment, filler dispersion, and filler distribution. The simulation of fiber orientation in an injected plaque using the Moldex 3D was used to investigate the effect of injection flow on fiber orientation in a conductive network. Injection composite samples were cut from different areas and different directions of an injection molded plaque to measure in-plane and through-plane electrical conductivity. The both electrical conductivity of the composite containing only carbon fibers as a filler has a positive correlation with the simulation output; however, the final distribution and dispersion of the filler are believed to be caused by complex interactions among many factors during injection molding. Therefore, the simulation output could not explain the orientation of carbon fibers in the composites containing hybrid fillers. Most of the in-plane electrical conductivity results, from the specimens cut in the flow direction, indicate that the combination of carbon fillers does not show any significant effect on filler orientation at the surface of composite plaques. Using the simulation of flow injection to describe the conductive network pattern for the combination of fillers in a hybrid filled system and various operating parameters is recommended to perform for a further study with a suitable simulation program.

Acknowledgments

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