Turkish J. Eng. Env. Sci.
30 (2006) , 23 – 34.
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A Review of the Effect of Moulding Parameters on the Performance of Polymeric Composite Injection Moulding

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Received 07.03.2005

Abstract

A review of the effect of changes in moulding parameters on polymeric composite injection moulding is presented in this paper. The emphasis of this work is on the use of short fibre reinforced polymer composite in the injection moulding process. The behaviours of fibres that influence the performance of the injection moulding process, like fibre orientation and distribution, fibre concentration and fibre length, are initially reviewed. The effects of mould design such as the effect of gate design, the effect of the runner system and the effect of cooling channels are then studied. The effects of processing parameters, particularly the effect of injection speed, are also discussed. Finally the use of mould flow simulation software is reviewed.

Key words: Injection moulding, Simulation, Fibre orientation, Mold flow analysis.

Introduction

The application of plastics in the automotive world has been rising steadily since the 1950. They were initially used as electrical components and interior fittings as a convenient low cost alternative to traditional materials. Maxwell (1994) described a consensus from the motor industry on the merits of plastics usage as economy, weight reduction, styling potential, functional design, new effects, reduced maintenance, and corrosion resistance.

However, designers that contemplate the use of plastic as a solution to automotive application problems often feel a lack of confidence. Thus, to combine the very best of both metals and plastics, they resort to composites. In order to increase the stiffness and deformation resistance of plastics, reinforcement such as fibre (glass), carbon, aramid and asbestos are used. Today, polymeric composites are used extensively as metal replacements for automotive parts such as valve covers, power steering reservoirs, fuel pumps, fan shrouds, spoilers, and car pedals.

Composites are defined as solid materials that are composed of a binder or matrix that surrounds and binds together fibrous reinforcements. A commonly found matrix is polymeric (plastic) and to a lesser extent ceramics and metal are used. According to Strong (1996), polymeric composite materials represent about 90% of all composites. The matrix's main function is to hold all reinforcements together, thus allowing the applied force to be transmitted to the reinforcement. Other functions of the matrix include protection and prevention of the composite fibres from damage such as crack propagation within the material.

All polymers (plastics) can be divided into 2 groups, thermosets and thermoplastics. Thermosets can be either liquids or solids at room temperature that are placed into a mould and then heated to cure (harden), thus giving the desired shape and solid properties (Strong, 1996). Thermoplastics are solids at room temperature that are melted or softened by heating, placed into a mould or other shaping device, and then cooled to give the desired shape (Strong, 1996). Unlike thermoset polymers, thermoplastics can be reheated and shaped into new parts.

There are generally 14 types of common fillers for plastics, namely glass, carbon, cellulosics, starch, chalk, metallic oxides, metallic powders, powdered polymers, silica products, silicates, inorganic compounds, ceramic powders, chopped cloth and magnesium carbonate. These fillers are commonly used to improve dimensional stability, lower shrinkage and post-mould distortion, increase production cycle time, improve bearing properties and abrasion resistance and improve fire resistance, due to decreased heat of combustion (Waterman and Ashby, 1991).

Short Glass Fibre Reinforced Polymeric Composites

Polymeric materials are often reinforced with short glass fibres to improve the structural properties (stiffness and strength) and to reduce the shrinkage and warpage of the final product. The properties change from isotropic to anisotropic as the fibre orientation becomes less random. Short fibre composites are aptly used in applications that require moderate stiffness, moderate loads, and high volume production.

Mayer (1993) explained that properties determined by the fibres differ in 2 fundamental ways from those dominated by the resin. They depend upon both its orientation and amount of fibres (volume fraction).

Fibre orientation and distribution

An important characteristic that all composite parts have in common is the effect of fibre orientation on the final properties of the part. The properties of the part in the direction of fibre orientation and transverse to it are significantly different (Davies et al., 2002). The graph in Figure 1 demonstrates this effect. It is clear that the elastic modulus is much higher when a stress is applied in the direction of fibre orientation than when it is applied transverse to it. Mayer (1993) claims that there is progressive damage to the material at stresses below the ultimate. The first sign of damage is transverse fibre debonding through separation between the resin and fibre perpendicular to the load direction. This occurs typically at 0.3% strain and a stress level of about 30% of the tensile strength.

Thomason (1999) elucidated the general features in studies of fibre orientation distribution. As the melt fills the mould there is a fountain flow (Figure 2). Fountain flow causes the melt to be deposited on the mould wall with the alignment direction parallel to the mould fill direction. Here it solidifies rapidly and this alignment is retained in the solid particle. Further behind the melt front, shear flow dominates and produces fairly uniform levels of fibre alignment. In the very centre of the melt, the rate of shear is low

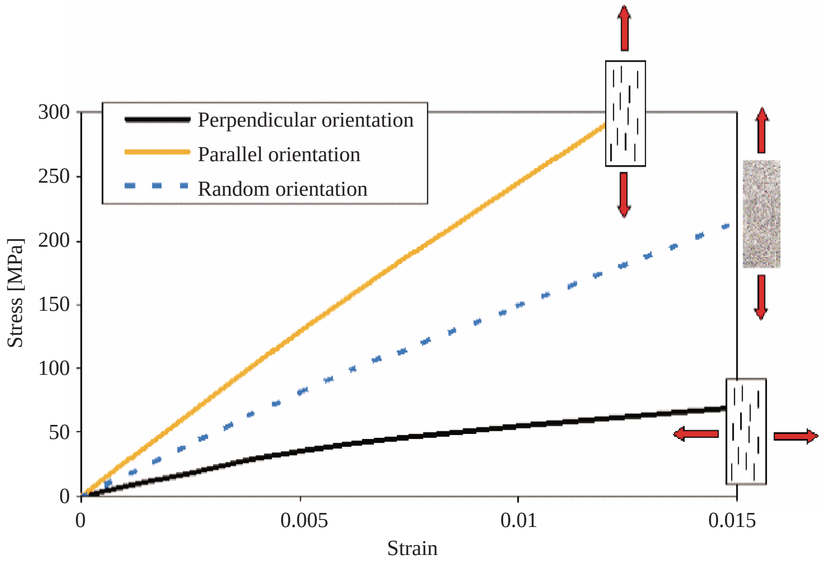


Figure 1. Stress-strain graph with fibres oriented in the direction of strain and transversal to strain (Davies et al., 2002).

and flow behaves extensionally; thus the transverse fibre alignment present at the gate is retained. The fountain flow behaviour resulted in a shell-core structure of fibre reinforced injection moulded parts (Figure 3). It is apparent from the graph that the centre of the part is strongly oriented transverse to the flow and fibres at the edges of the part are strongly oriented parallel to the flow.

Anon (1999) provided 2 basic guidelines for flow-induced alignment:

- Shear flows align fibres in the direction of flow.
- Stretching aligns fibres in the direction of stretch.

Such a condition is exemplified in the case of converging and diverging flow (Figure 4). In diverging flows, the fluid is stretched bi-axially in the plane perpendicular to the flow direction and the fibres tend to be aligned in the cross flow direction. While in converging flows, the fluid is stretched along the flow direction and the fibres tend to be aligned in the flow direction.

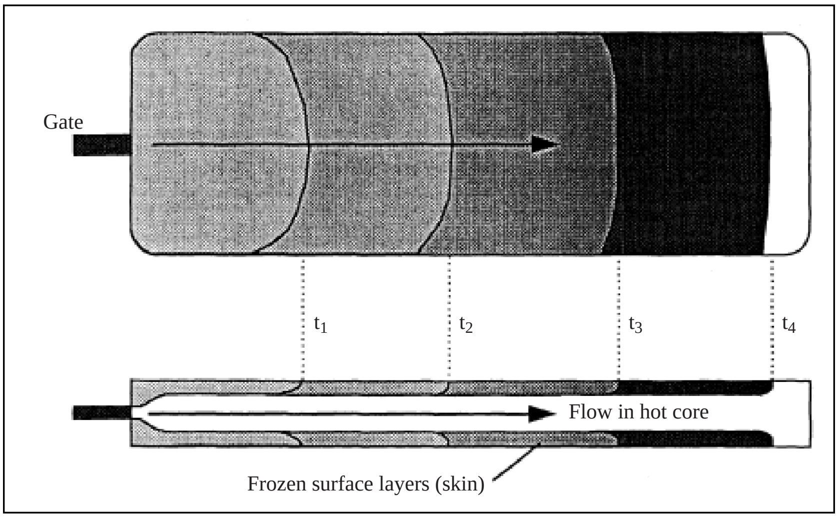


Figure 2. Fountain flow in injection moulded part (Anon., 1999).

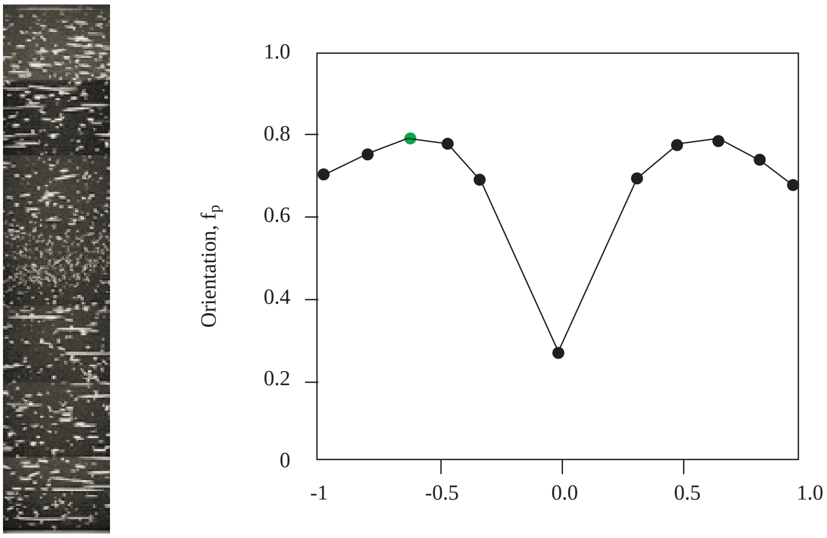


Figure 3. Shell core structure (Anon., 1999)

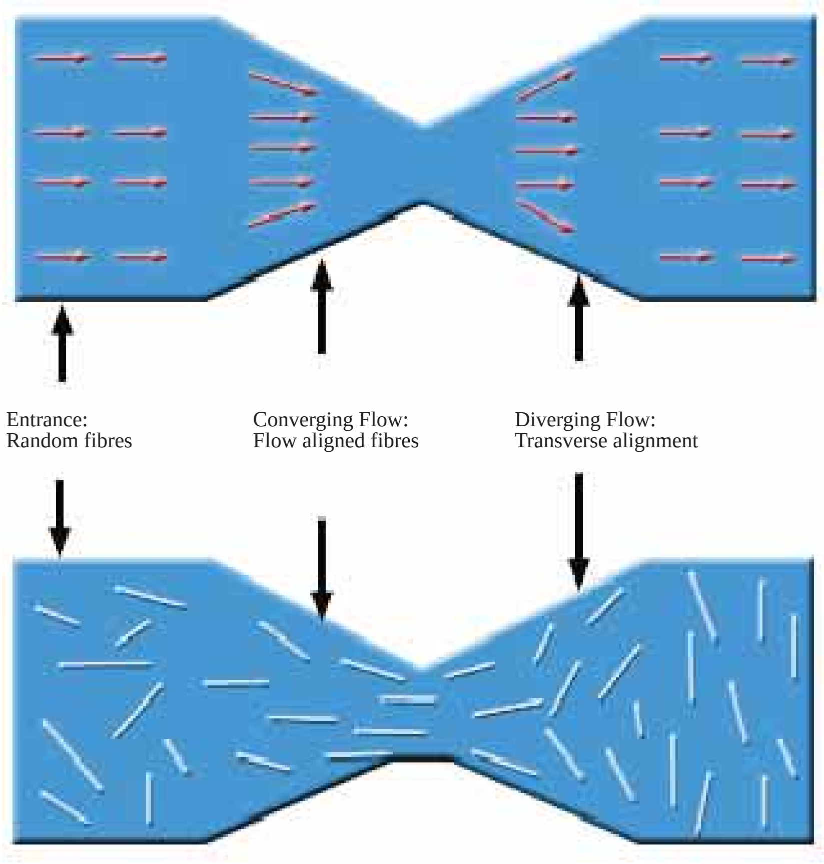


Figure 4. Converging and diverging flow (Anon., 1996).

A single parameter f_p can be used to present the distribution of fibre orientations. This condition holds true when all the fibre are all in parallel planes as in thin layers. When all orientations are equally likely, this parameter becomes 0 and when all the fibres are perfectly aligned along a reference direction, f_p becomes 1. When the fibres are all aligned at right angles to the reference direction, f_p is -1 (Anon, 1999). The variations of f_p properties from 0 to 1 are represented in Figure 5.

Matthew and Rawlings (1994) describe factors that affect fibre orientation distribution:

Geometrical properties of the fibre

Viscoelastic behaviour of the fibre-filled matrix

Mould design

The change in shape of the material produced by the processing operation.

Effects of fibre concentration

Generally, the mechanical strength of the composite depends on the amount of glass or other reinforcing agent it contains (Richardson, 1987). Variation with fibre volume in the fibre direction is illustrated in Figure 6.

Brunings et al. (1989) compares 2 main types of the PA family, PA 6,6 (30%) and PA6 (40%). He concluded that the stiffness of pedal PA6 in the dry state is higher than that of the pedal made from PA66 due to higher glass content.

Effects of fibre length

Thomason's (1999) study on fibre properties in glass fibre reinforced polyamide 6,6 revealed that the average fibre length is reduced in all aspects of the processing, i.e. chopping of the fibres, the compounding and the moulding, and finer fibres end up shorter in the composite.

The Effects of Mould Design

An assembly of moulds consists of a sprue, runner, gate, fixed half and moving half, core and cavity,

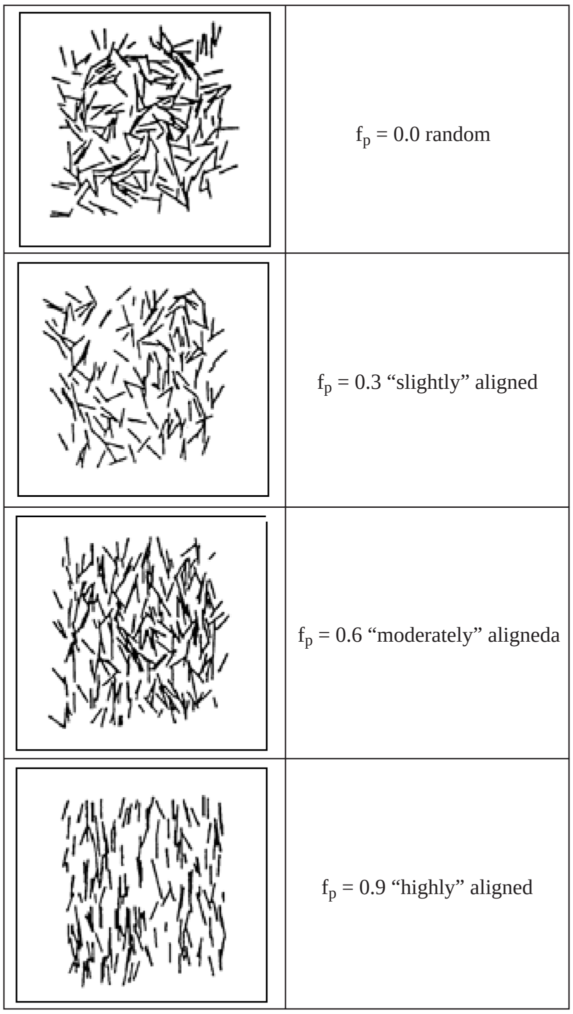


Figure 5. Variation of f_p properties correspondingly from 0 to1 (Anon., 1999).

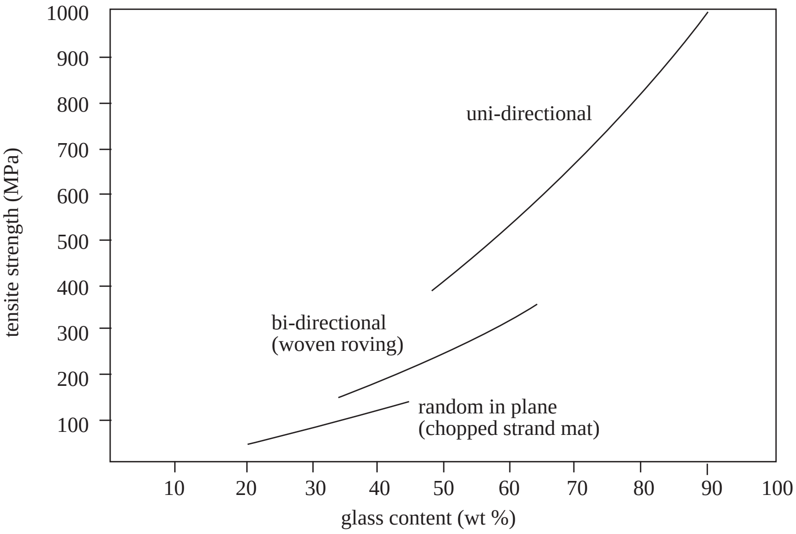


Figure 6. Tensile strength of a glass reinforced plastic versus glass content (by weight) in the fibre direction (Mayer, 1993).

ejector pins, return pins, cooling channels, ejector plate/rod, sprue puller, guide pins, locating plugs, backplate and spacers. In the injection moulding process the placement of gates, runners and cooling channels can dramatically alter fibre orientation. Gating is perhaps the most important aspect of the tooling design (Richardson, 1987).

The types of material to be used for the mould cast depend on production volume. For instance, in high production volume, steel is favourable due to its wear resistance and durability. While for low volume production or prototype applications, it is common to cast moulds from low melting point metals, such as aluminium and zinc, since they are less expensive and are faster to build.

Effects of gate design

The placement of the gate is an important consideration that can often affect shrinkage, moulding efficiency, and part performance (Strong, 2000). Studies by Davies et al. 2002) and O'Regan and Akay (1996) agreed that the gate design plays an important role in predicting average fibre orientation and resultant fibre length. Additional fibre attrition occurs when the gate dimensions are decreased and, with larger gate arrangement, average fibre length can be found longer in the core region (O'Regan and Akay, 1996). Primary considerations in designing the gate are its number, size and location. Generally, the gate thickness is 40% to 60% of the part thickness (Beck, 1980).

There are no exact rules for the number of gates for a polymer injection mould. However, 2 factors that can be considered are material flow length and part volume. Flow length refers to how far the polymer must flow from the polymer injection location. Parts with thicker walls cause the material to flow easily in the thick region compared to parts with thinner walls, hence a long flow path. Thus, for thinner parts (shorter flow length) additional gates are needed to fill the part. Generally, larger parts, thinner walled parts and higher viscosity materials require more gates to fill a part. An additional gate acts to reduce fill pressure, especially when the flow length is long for the wall thickness and material used. This produces a lower injection pressure, lower shear rate and lower shear stress levels.

An intensive study by Akay and Barkley (1985) on the effects of jetting for short glass fibre polypropylene revealed that jetting is most emphatic with decreasing mould gate dimension. This causes a weld line to develop in which only the polymer melt mixes adequately, while the fibres align themselves with the flow along the weld line. Jetting results when plastic flows through a gate and into a cavity without sticking to the mould walls and produces a rope-like flow or "jet", which is then compressed into the part (Anon., 2003).

Kim et al. (2003) investigated flow patterns and the occurrence of defects that varied with 4 different gate locations (cases 1-4) for an automobile junction box with integral hinges using numerical analysis (Figure 7). That study revealed that a properly determined gate location leads to better resin flow, thus avoiding defects such as short shot and hesitation marks due to the hesitation effect. The hesitation effect occurs in parts of varied thicknesses where the flow moves preferentially into a thicker area. This causes the adjacent thin area to freeze off while the thicker area fills. Such an effect occurs in cases 3 and 4 in Figure 8.

Effects of runner system

In injection moulding, melt polymer flows through a delivery system consisting of a sprue, a runner system and gates into individual cavities. A proper runner-system is important, especially for a multiple cavities mould since it dictates the filling pattern, prevents overpacking, diminishes faulty moulded product parts and increases productivity. Li and Shen (1995) provided 2 main design criteria that should be kept in mind while designing the runner system:

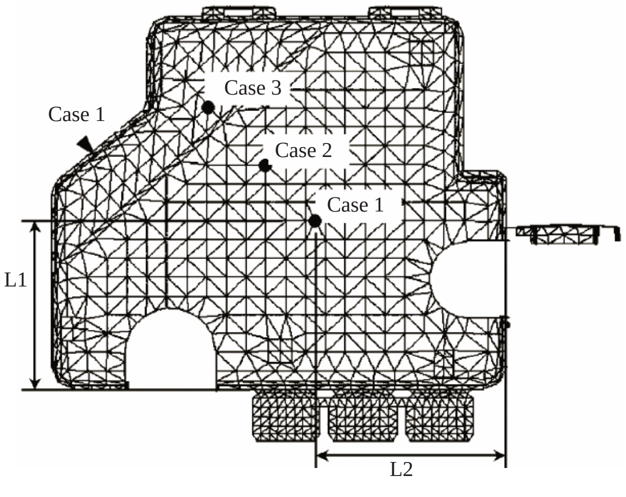
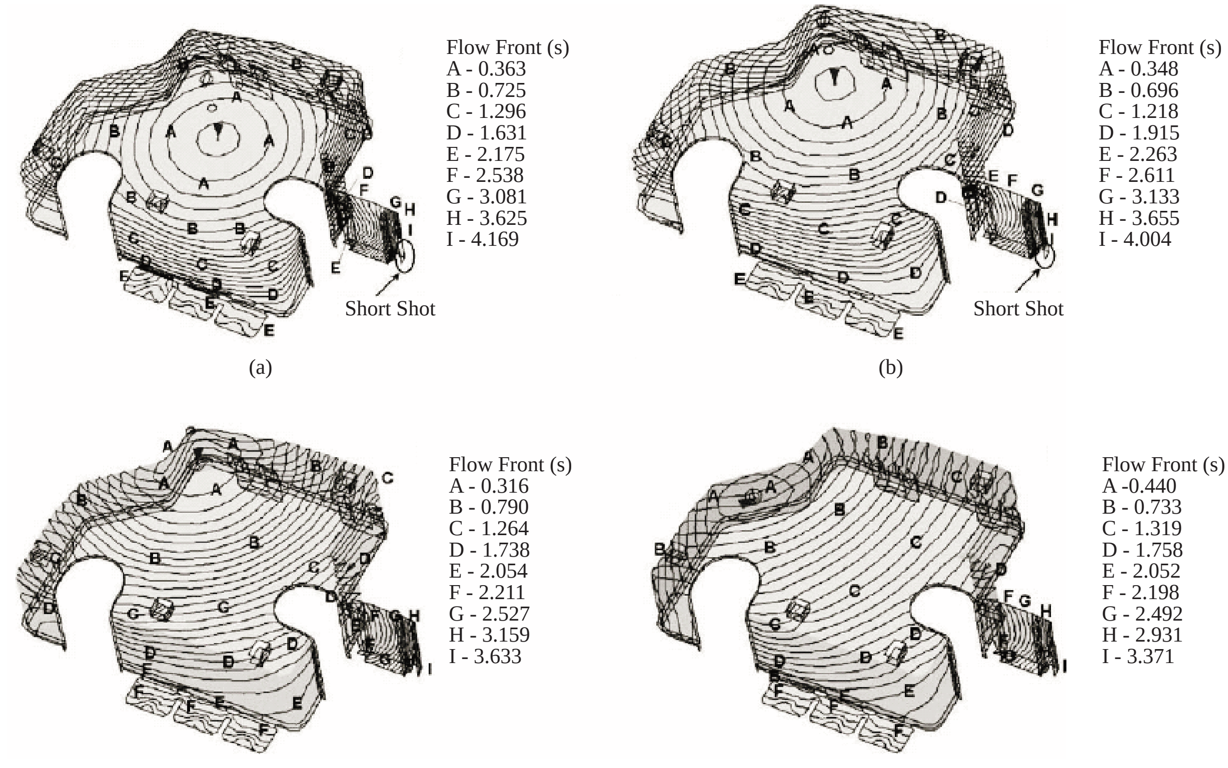


Figure 7. Analysis model and gate locations (Kim et al., 2003).



(a) (b) (c) (d)

Figure 8. Predicted flow front for each gate location: (a) Case 1, (b) Case 2, (c) Case 3, (d) Case 4 (Kim et al., 2003).

- The pressure loss and total volume in the runner system should be as small as possible,
- The viscous heating generated by the flow in the runner system must be eliminated to avoid degradation of the polymer material.

Effects of cooling channel

A method of cooling is usually incorporated into the mould to speed the solidification of the plastic. Thus, holes are usually bored in each half of the mould through which a heat exchange fluid, usually water, can circulate. For parts requiring tight dimensional control or uniform mechanical properties, uniform cooling is essential. If the part does not solidify uniformly in the mould, residual stress will occur as a result of differential shrinkage. An efficient cooling system also aims to minimise such undesired defects as sink marks, differential shrinkage and part warpage.

The Effects of Processing Parameters

The process parameters that affect the quality of injection moulding products include cooling time, injection pressure, injection speed, injection time, filling time, melt temperature, ejecting pressure, mould temperature, mould geometry shape, material property of melt, melt speed and heat transfer action of flow field (Shen et al., 2002).

Processing techniques such as injection moulding have a devastating effect on fibre length (Matthew and Rawlings, 1994). Figure 9 shows a polymer composite sampled after the process of injection moulding. They explained further that the degree of fibre length degradation depends on several process parameters such as screw design, shear rates, and melt viscosity and fibre volume fraction.

Whilst fibres even down to 50 μm in length may retain some ability to reinforce, it is the fact that actual fibre length and its distribution are uncertain that can cause problems.

Strong (2000) describes some factors that affect the temperature of the system (for both the melt and the mould temperature) as:

- Shot size – larger shots take more heat
- Injection rate – faster filling creates higher melt temperatures because of shearing

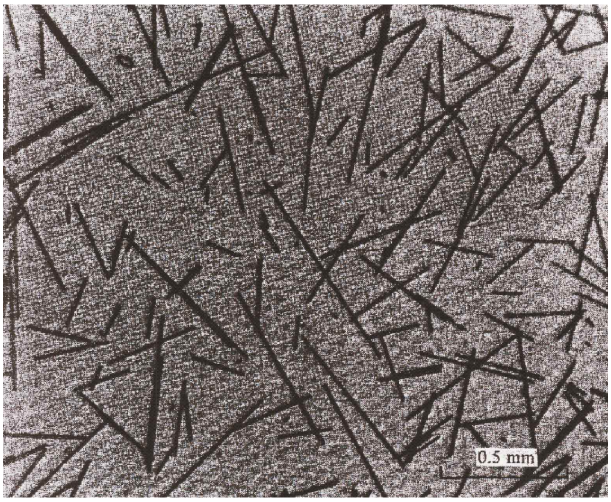


Figure 9. Light micrograph showing the wide variation in fibre length after injection moulding (Matthew and Rawlings, 1994).

- Size of runner – long runners require higher temperatures
- Part thickness – thick parts require more cooling time and are moulded at lower temperatures.

Effects of injection speed

The filling speed is the process parameter that most influences fibre orientation (Anon, 1996). Breitfelder (2003) describes 4 effects of increasing speed:

- Bigger flow duct and wall thickness relationship
- Smaller degree of total orientation
- More constant shrinkage relationship
- Better fusion result of the molten mass.

Lee et al. (1997) studied and compared fibre orientation for slow and fast filling cases. It was found that due to the shear flow more fibres are oriented in the direction of flow for the slow filling case rather than for the fast filling case (Figure 10). Such tendencies occur because larger solid layers are formed near the cold mould surface for the slow filling case where the temperature in the thickness direction is low. As the solid layer becomes thicker, the velocity gradient in the thickness direction becomes sharper, resulting in a more shear dominant flow, which causes higher fibre orientation in the direction of flow. Fung et al. (2003) investigated the effect of injection moulding process parameters on the tensile properties of short glass fibre reinforced polybutylene terephthalate (PBT). He concluded that the strength of PBT depends on the thickness of layer where fibres were oriented in the loading direction.

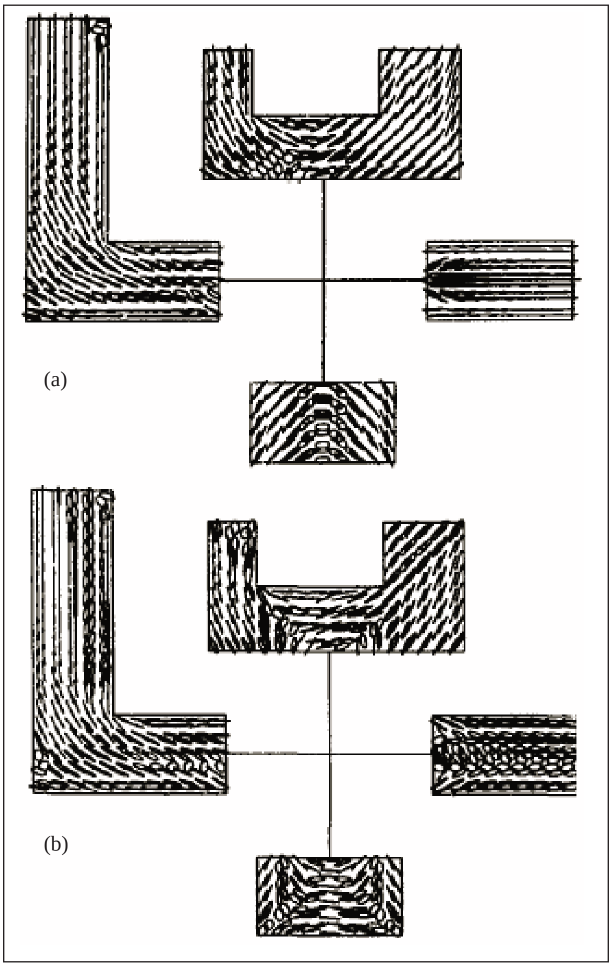


Figure 10. Predicted fibre orientation and distribution for (a) slow filling case and (b) fast filling case (Lee et al., 1997).

Bright and Darlington (1981) explained that a faster injection speed is usually applied to an unfilled melt to achieve a better surface finish. An unglossy surface finish is a common problem with reinforced thermoplastic; thus it is recommended that a higher injection speed, pressure, mould and melt temperature be used during processing.

Mould Flow Simulation Programs

Advances in computer technology have enabled enormous studies to be carried out using simulation programs based on finite element analysis such as Moldflow, C-Mold and Cadmould. Simulation software is used extensively in the design of injection moulds, due to the ability of the Hele-Shaw flow approximation to describe reasonably well the mould filling process (Vlachopoulos and Strutt, 2003). These programs enable the filling, post-filling and cooling phases of the injection moulded product to be studied. By this means, it is possible to encapsulate complicated polymer behaviour and advanced mathematics in algorithms, which model the mould filling process (Mayer, 1985). Hence, the product manufacturability and process feasibility can be optimised. Tucker-Folgar's model has been the best available for fibre orientation modelling in concentrated suspensions. The model (Eq. 1) has been given in this form by Advani and Tucker (1994):

$$\begin{aligned}&\frac{\partial a_{ij}}{\partial t}+v_k\frac{\partial a_{ij}}{\partial x_k}=\\&-\frac{1}{2}(\omega_{ik}a_{kj}-a_{ik}\omega_{kj})+\frac{1}{2}\lambda(\gamma_{ik}a_{kj}+a_{ik}\gamma_{kj}\\&-2\gamma_{kl}a_{ijkl})+2C_I\gamma\delta_{ij}-\alpha a_{ij}\end{aligned} \tag{1}$$

where

α equals 3 for 3D and 2 for planar (2D) orientation

v_k is the velocity component

ω_{ij} and γ_{ij} are the vorticity (whirling) and deformation tensors

λ is a constant that depends on the geometry of the particle, where, for short fibre, $\lambda=\frac{(r_e^2-1)}{(r_e^2+1)}$

where r_e= L/D

δ_{ij} is a unit tensor

C_I is the interaction coefficient

The hybrid closure approximation method by Advani and Tucker (1990) is used for second-order tensor from the fourth-order tensor, and finally, scala measure of orientation, f=1-27det(a_{ij}), equal to zero for 3-D random orientation and unity for fully aligned fibres.

Abundant studies have been conducted to improve various aspects of injection mould designs using simulation programs. Spina (2004) investigated the fabrication of a plastic arm of the body interior of a medium sized car by evaluating different hot runner systems, gating and product configuration. The software adopted was Moldflow Plastic Insight®version 4.1. Nardin et al. (2002) simulated various options for an automotive braking light and then produced the real moulded part based on their findings. The simulations results were consistent with the real moulded part. For instance, the clamp force profile indicated that a short shot would occur for Simulation 6 (Figures 11 and 12). Chun (1999) performed a cavity filling analysis of an injected moulded part for a polystyrene flask using Moldflow software. Various product thicknesses were simulated to eliminate the cause of bubbles and the long visible weld line in the part that often occurs during the manufacturing process.

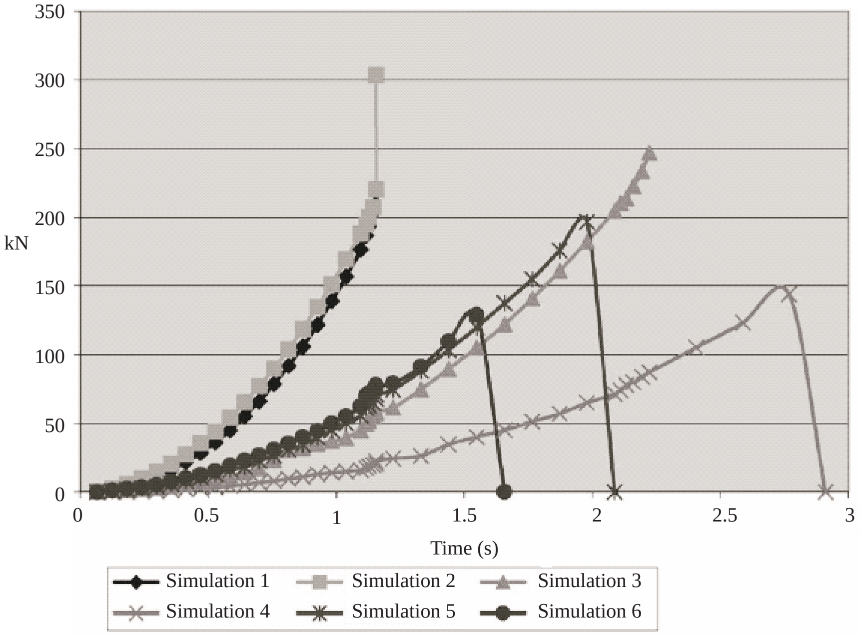


Figure 11. Clamp force profile (Nardin et al., 2002).

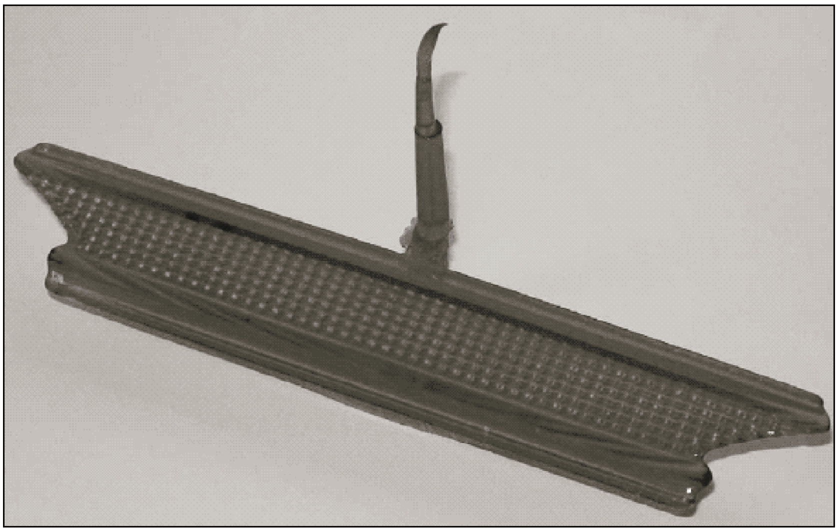


Figure 12. Short shot for Simulation 6 (Nardin et al., 2002).

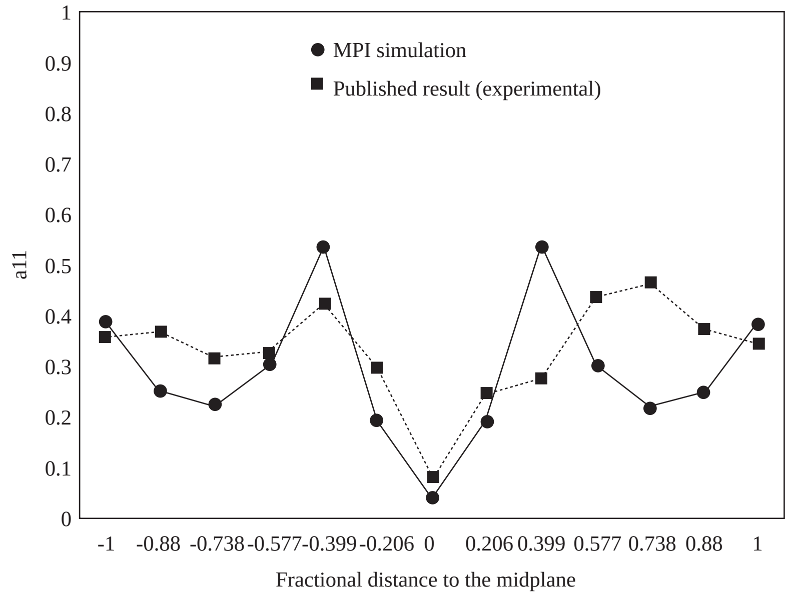


Figure 13. Fibre orientation in flow direction at 20 mm from the gate (Zainudin, 2002).

Zainudin (2002) compares the simulation results of the short fibre orientation distribution (FOD) obtained by Moldflow Plastic Insight (MPI) to published experimental results of fibre orientation of centre-gated disc by Neves et al. (1999). The model used for both studies is a centre-gated disc moulded with 10% by weight glass fibre reinforced polycarbonate composites. Figure 13 indicates that a similar trend clearly exists between published experimental results and the predicted results of the fibre orientation pattern in an injection moulded polycarbonate disc.

However, huge amounts of data compiled by the simulation programs frequently make the identification of the optimal design and process selection very difficult due to the complex non-linear interactions between design and process variables. Furthermore, the accuracy of the simulation results is often doubted in the application of high glass fibre content. Kim et al. (2003) studied and compared the fibre orientation of injection moulded fibre-reinforced composite using image processing and numerical simulation. They concluded that the result of fibre orientation distribution by the numerical simulation (using Moldflow) is consistent with that obtained from the image intensity method for low fibre content (30%). However, the distribution cannot be predicted for high fibre content (50% and 70%) due to the effects of fibre interaction.

Conclusions

From this review, the following conclusions can be drawn:

Fibre orientation and distribution greatly affect the final product property since elastic modulus is much higher when a stress is applied in the direction of fibre orientation compared to it. Its orientation and distribution depend on the geometrical properties of the fibre, viscoelastic behaviour of the fibre filled matrix and mould design.

Gating (size, location and number) is one of the most important aspects in mould design since it affects shrinkage, moulding efficiency and part performance.

One of the processing parameters that affect fibre orientation is the filling speed.

Although many studies have been carried out in the areas of cavity filling for injection moulds, those pertaining to the relationship between the design of the injection mould and the product process and product quality are still scarce, especially for glass fibre reinforced composite automotive clutch pedals.

Acknowledgements

The authors wish to acknowledge the contribution of Associate Professor Dr Megat Hamdan and Associate Professor Dr Shamsuddin Sulaiman of Universiti Putra Malaysia. This work is funded by the Ministry of Science, Technology and Innovations, Malaysia, under IRPA grant scheme project number 09-02-04-0323-EA 001.

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