British Journal of Applied Science & Technology
7(2): 186-194, 2015, Article no.BJAST.2015.136
ISSN: 2231-0843

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An Approach for Predicting Fiber Orientation Distribution in Plastic Injection Molding of Composites

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Authors' contributions

This work was carried out in collaboration between all authors. Author XP designed the study, performed the analysis, and guided the whole study. Author JQ wrote the first draft of the manuscript and managed literature searches. Authors XP and YJ revised the manuscript, and managed the analyses of the study. All authors read and approved the final manuscript.

Article Information

DOI: 10.9734/BJAST/2015/15765
Editor(s):
(1) Yu Hai-Liang, School of Mechanical, Materials and Mechatronic Engineering, University of Wollongong, Australia.
Reviewers:
(1) Anonymous, Belgium.
(2) Anonymous, USA.
(3) Syed Altaf Hussain, Department of Mechanical Engineering, Rajeev Gandhi Memorial College of engineering & Technology, India.
Complete Peer review History: http://www.sciencedomain.org/review-history.php?iid=771&id=5&aid=7984

Original Research Article

Received 17th December 2014
Accepted 21st January 2015
Published 2nd February 2015

ABSTRACT

Aims: This paper presents an approach for predicting the fiber orientation distribution in plastic injection composites.
Methodology: By introducing fiber orientation tensor, the average distribution of fibers in the composite is acquired through injection molding simulation with Autodesk Moldflow Simulation Insight version 2014. Quantitative fiber orientation distribution along thickness at specific spot is obtained by image analysis on microscopic photos of samples. The proposed approach is demonstrated by a car instrument panel made from injection molding of thermoplastics with glass fibers. Tensile test samples are cut from the instrument panel with an angle of 0º, 45º, 90º to the fiber orientation at sites where fibers are highly aligned for measuring tensile modulus. The fiber orientation distribution and its effect on the tensile modulus are investigated.
Results: It is shown that the car instrument panel is heterogeneous in mechanical properties. The fibers are roughly distributed into three layers along the thickness with each layer having roughly

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aligned fibers.
Conclusion: It is necessary to consider the effect of fiber orientation and thickness layer distribution on the mechanical properties during numerical analysis of plastic injection composites.

Keywords: Composite; plastic injection; tensile modulus; fiber; orientation.

1. INTRODUCTION

Fiber orientation distribution is a variable significantly affecting the overall physical properties, such as stiffness, thermal conductivity of fiber reinforced composite parts [1]. Injection molded parts with complex surfaces such as car instrument panel usually has discrete distribution of fiber orientation, resulting in strong anisotropy and heterogeneity in mechanical properties [2]. The accurate prediction of fiber orientation distribution is vital on the selection of material parameters in finite element analysis of composite parts from injection molding [3].

Mechanical property prediction of fiber reinforced composites has attracted significant attention in the last decades, starting from unidirectional composites to general fiber reinforced products. Gusevet et al. [4] proposed a finite-element-based numerical procedure to predict the mechanical and thermal properties of highly aligned continuous fibre composites. By building a probability density function based on fiber length and orientation distribution, Nguyen et al. [5] developed a methodology to predict the stiffness matrix of aligned long-fiber injection-molded thermoplastics. They then extended the approach to the elastic-plastic regime [6]. Kaleemulla and Siddeswarappa [7] experimentally investigated the effect of fibre content and orientation on the in-plane tensile and compression strengths of laminated hybrid polymer composites. A model was then proposed to describe the contribution of these parameters by regression analysis. An accurate measurement of fiber orientation and contents is a prerequisite for the effectiveness of models developed for the mechanical property prediction of fiber reinforced composites.

Numerical simulation was applied in the fiber orientation determination of composites. By modelling fibers as chains of connected rigid beads, Londoño-Hurtado et al. [8] simulated the suspension of fibers in molding and proposed a mathematical model for predicting final orientation distribution in molded composites. Kim et al. [9] calculated the fiber orientation of fiber-reinforced polymeric composites from injection molding simulation. Various experimental approaches were developed in the past decades for fiber orientation measurement. Among them, the most often used one is image analysis technique, starting from the 1980's [10-12]. Gadala-Maria and Parsi [13] used digital image processing technique to measure orientation distribution of fibers in a plane of a short-fiber composite. By using a transputer-controlled image analysis system, Hine et al. [14] measured the fiber orientation from polished sections of well-aligned continuous or short fiber reinforced composites. The effects of fibre shape, sample orientation and manufacturing procedure on the orientation measurement accuracy were investigated. Mlekbusch et al. [15] presented a computer-aided image analysis approach to quantify fiber orientation in thermoplastic polymers reinforced by short glass fibers. A specimen preparation treatment technique was proposed for identifying the interface between the matrix material and fibers in reflected light microscopic images. Eberhardt et al. [16] proposed a method for correcting the systematic measurement error of fiber orientation in short-glass fiber composites using a confocal microscope for 2D image analysis of polished cross-sections. By using a 2D optical technique, Vincent et al. [17] measured fiber orientations in a rectangular plaque of short fiber reinforced thermoplastic from injection molding. Except the mainstream technology of digital image analysis, other techniques such as microwave [18], wide angle X-ray diffraction [19], scanning acoustic microscopy [20], X-ray micro-computed tomography [21] etc were applied in the measurement of fiber orientation in composites.

However, the measurement of number of fibers and their individual orientation in large injection molded fiber reinforced composites is still unresolved. This paper presents an approach for predicting the fiber orientation distribution in plastic injection composites. By introducing fiber orientation tensor, the average distribution of fibers in the composite is acquired through injection molding simulation with Autodesk Mold flow Simulation Insight version 2014. Quantitative fiber orientation distribution along thickness at specific spot is obtained by image analysis on microscopic photos of samples. The proposed approach is demonstrated by a car instrument panel made from injection molding of thermoplastics with glass fibers. Tensile test samples are cut from the instrument panel at sites where fibers are highly aligned for measuring tensile modulus. The fiber orientation distribution and its effect on the tensile modulus are investigated.

2. MATERIALS AND METHODS

2.1 Theoretical Basis

The spatial orientation of a single fiber in fiber reinforced composites can be described by a directional unit vector which is parallel to the fiber [22], as shown in Fig. 1. The Cartesian components of $\boldsymbol{p}$ are

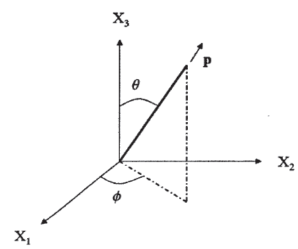

Fig. 1. Fiber orientation vector

$$\boldsymbol{p}=\begin{pmatrix} sin\theta cos\varphi \\ sin\theta sin\varphi \\ cos\theta \end{pmatrix} \quad (1)$$

Where θ and φ are the angles between the fiber and the z- and x-axes, respectively.

For injection molded fiber reinforced plastic parts, the global mechanical properties are usually heterogeneous and are mainly dependent on fiber orientation and distribution. A fiber orientation tensor is applied to describe the fiber orientation state. It is described by forming dyadic products of a number of fiber directional vectors $\boldsymbol{p}$ and integrating over all directions, weighting the product with a distribution function $\psi(\boldsymbol{p})$.

$$a_{ijk...l}=\int_P p_i p_j p_k \boldsymbol{...} p_l \psi(\boldsymbol{p}) d\boldsymbol{p} \quad (2)$$

The number of subscripts *i*, *j*, *k*, …, *l* indicates the rank of the fiber orientation tensor. The distribution function $\psi(\boldsymbol{p})$ denotes the probability of a fiber being oriented between the angles θ_1 and ($\theta_1+\mathrm{d}\theta$) and φ_1 and ($\varphi_1+\mathrm{d}\varphi_1$). Since one end of a fiber is indistinguishable from the other end, the distribution function is even, i.e., $\psi(\boldsymbol{p})=\psi(\boldsymbol{-p})$. So the result of integrations over the multiplication of odd number of fiber directional vectors $\boldsymbol{p}$ is zero. Consequently, only integrations over the multiplication of even number of fiber directional vectors $\boldsymbol{p}$ are used in the definition of the fiber orientation tensor. Take a second-rank tensor as an example, the fiber orientation tensor $\boldsymbol{a_{ij}}$ is a second order symmetric tensor [22] which can be defined as

$$a_{ij}=<p_i p_j>=\int_P p_i p_j \psi(\boldsymbol{p}) d\boldsymbol{p} \quad (3)$$

The orientation tensor can be diagonalized and its state is described in Fig. 2 [23]. Fig. 2(a) represents a plane uniaxial arrangement in which fibers are aligned along a single direction; Fig. 2(b) represents a biaxial arrangement in which fiber are evenly distributed and oriented along two principle directions. It also represents the state of a random distribution in the plane. Fig. 2(c) represents that fibers are evenly distributed and oriented along three principle directions or the state of a 3D random distribution.

2.2 Structure and Materials

Fig. 3 shows a car instrument panel made from PP-LGF20 (Polypropylene +20% long glass fiber) by injection molding. The overall dimension of the instrumental pane is 650 mm × 1450 mm × 350 mm with a basic thickness of 2mm. The shape of the instrumental panel is irregular with local curvature changing significantly. The material properties of the PP-LGF20 related to injection molding are listed in Table 1. The diameter and length of glass fibers in the grains are 16 µm and 15 mm, respectively.

2.3 Plastic Injection Simulation with Autodesk Moldflow Simulation Insight Version 2014

The fiber orientation of car instrument panel is calculated by the fiber orientation module in Autodesk Moldflow Simulation Insight version 2014 with Midplane mesh. The gate number, location and process parameters in the simulation are set to be identical to the real injection molding process.

Table 1. Physical properties of PP-LGF20

Property (units)	Value
Melt density (g·cm^{-3})	0.8539
Solid density (g·cm^{-3})	1.0276
Ejection Temperature (°C)	101
Maximum shear stress (MPa)	0.25
Maximum shear rate (s^{-1})	100000
Melt Temperature (°C)	230
Mold Temperature (°C)	55

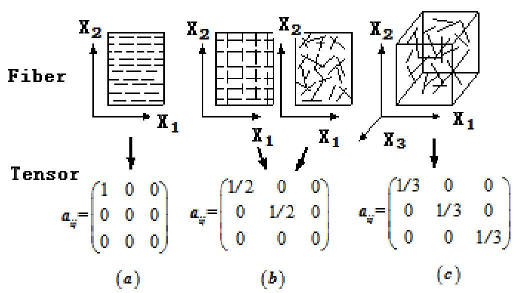

Fig. 2. Geometric description of orientation tensor [23]

Fig. 3. The instrument panel structure

2.4 Sample Preparation and Tensile Test

Three instrument panels are cut into 26 rectangular pieces with size of 80mmx15mm, in which the strong fiber orientation is according to the model in Autodesk Moldflow Simulation Insight version 2014. The rectangular pieces are cut with an angle of about 0º, 45º and 90º to the fiber highly aligned orientation as shown in Fig. 3 with white rectangles. Panel surfaces where ribs and mandrel grooves lie are avoided. Then the rectangular pieces are cut into S3A (DIN 53504) standard tensile testing samples. The samples are kept in an incubator for 80 hours to eliminate internal stresses.

The samples are tested by a tensile testing machine (INSTRON-5567) with a speed of 1mm/min. The strain in the gauge length is measured by a video extensometer (INSTRON 2663-821).

2.5 Microscopic Metallographic Observation Method

Due to the small feature size of glass fibers and the tremendous number of fibers in each cross-section along the thickness of the tensile testing samples，it is impractical to count the number of fibers in the cross-section by hand and to record the cross-section area of each fiber. The fiber orientation can be predicted based on its projection cross-section area on the plane. In this study, the gauge length of samples are mosaiced along the vertical direction, and then grinded, polished, and photographed under a microscope (ZEISS). Based on a home-made program and by using image processing software Image Pro Plus, the microscope photos are analyzed to calculate the number and cross-sectional area of fibers, which quantitatively represent the distribution of glass fibers along the thickness in the samples.

3. RESULTS AND DISCUSSION

3.1 The Average Fiber Orientation in the Instrument Panel

Fiber orientation is the main factor affecting the global mechanical properties of fiber reinforced composites. Autodesk Moldflow Simulation Insight version 2014 can predict the movement of fibers in the entire molding process and thus the distribution of average fiber orientation through thickness. The large surface of the glass fiber reinforced instrument panel is the major part that provides support and endures impact. To implement CAE (Computer Aided Engineering) analysis on the instrument panel, it is necessary to provide an accurate material parameters for the large surface as inputs. Fig. 4 shows the distribution of average fiber orientation through thickness of a sample sliced from the large surface region.

In Fig. 4, each element has a cross, which represents the average fiber orientation in the element. The longer the edge of the cross, the larger the possibility of the fiber orienting along the direction of that edge. The color scale from blue to red in Fig. 4 denote the degree of fiber alignment. The blue color, green, yellow and red color represent that the fibers' distribution is random, slight alignment, mild alignment and high alignment, respectively. It can be seen from Fig. 4 that in regions (a), (b) and (c), the fiber orientation alignment is very high with a degree of fiber orientation about 0.95. So samples can be cut with an angle of 0º, 45º or 90º to the direction where fibers are highly aligned; on contrast, the degree of fiber orientation in region (d) is only about 0.5, which stands for a random fiber orientation distribution.

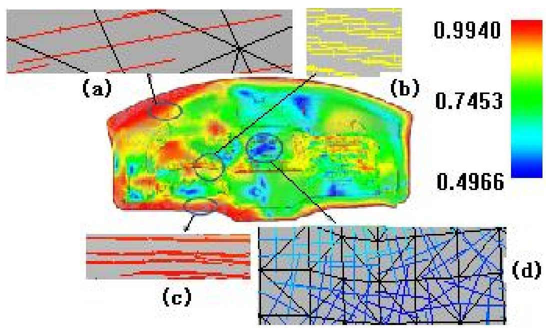

Fig. 4. The average fiber orientation tensor

3.2 Influence of the Thickness on the Fiber Orientation Stratification

Observations on fiber reinforced plastic injection parts show that along the thickness, there exist two skin layers in which fibers have a preferential orientation parallel to the flow direction, and a core layer in which fibers prefer to an orientation perpendicular to the flow direction. It is known that in a pure shear flow, fibers orient mainly in the flow direction, whereas in extensional flows, they orient in the direction of extension [24,25]. Vincent et al. [17] studied short-fiber reinforced injection products. Their results show that when the thickness is greater than 3mm, there will be a three layer distribution with regard to fiber orientation, and when the thickness is less than 1.7 mm, the stratification is not obvious. There are few reports regarding fiber stratification in long glass fiber reinforced plastic injection parts. Figure 5 shows the half cross section of a sample cut from the instrument panel. It can be seen from Fig. 5 that there are two layers: a skin layer and a core layer. In the skin layer, the area of each fiber is very small, so the fiber orientation is about perpendicular to the cross section plane of the sample. In the core layer, the area of each fiber is very large and with long strip shape, so the fiber is in the cross section plane and along the strip direction.

Totally 26 samples are cut from each panel at various locations resulting three samples at the same location of the three panels. Measured values such as thickness and elastic modulus of the three samples are averaged to represent the respective value at that location. It shows that the maximum thickness of the panel is 2.38 mm and the minimum thickness is 1.68 mm. Figure 6 shows part of the thickness measurements In Fig. 6, the total height of the column is the total thickness of the sample. The number of sub-columns represents the fiber stratification along the thickness. As can be seen in Fig. 6, with regard to fiber orientation distribution, most samples can be divided into three layers along the thickness. A few can be divided into five layers. Some of the samples have no obvious stratification (see sample 1 and 6 in Fig. 6). It can also be seen in Fig. 6 that most of samples have a core layer with large thickness. In injection molding, when encountering with the cold mold, the surface layer of fluid quickly cools down to solidification and thus generates a great shear force which aligns the fiber to the flow direction and results in a relatively consistent fiber orientation in the skin layer. However, the shear force is limited to the place near the mold surface only, so the sample's skin layer is thin. In the core layer where shear force is small, the fiber is easy to randomly deflect its direction and brings out unobvious fiber stratification. This can be verified by microscopic images of some samples' cross section.

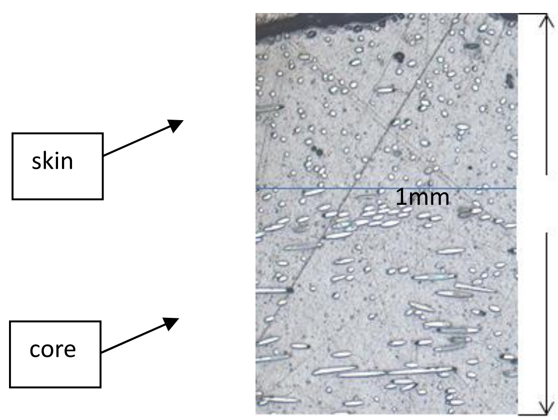

Fig. 5. Microscopic image of sample section

3.3 The Relationship between Fiber Orientation and Elastic Modulus

It is shown in the tensile tests that most samples from the instrument panel have a very small fracture strain of about 0.03. Only a few can reach to 0.06. The experimental stress-strain curves vary greatly with the highest modulus of elasticity achieving 4683MPa and the minimum being 1962MPa. Fig. 7 shows the averaged elastic modules of the 26 samples from various locations. It can be seen from Fig. 7 that most of the elastic modules fall into the medium region. Representative stress-strain curves with maximum, medium and minimum elastic modulus, respectively, are shown in Fig. 8.

Image Pro Plus software is used to identify the number of glass fibers and their individual cross-section areas on the plane by analyzing the microscope images, as shown in Fig. 9. The fiber orientation, which is defined by the angle between the fiber and the plane, can be determined from its cross-section area on the plane. For example, a cross-section area approximating the fiber sectional area represents that the fiber is perpendicular to the plane. Table 2 shows some typical cross-section areas corresponding to specific angles between the fiber and the plane. Table 3 lists the elastic modulus of some samples along with the number of fibers and cross-section area distribution in each sample. Fiber numbers are counted in a sample region of 10 mm^2. As demonstrated in Table 3, the elastic modulus of the glass fiber reinforced plastic panel changes greatly with locations and directions. The maximum value is 2.39 times of the minimum value.

Table 2. Area of fiber cross section

Fiber orientation	Area /μm^2
90°	200
45°	282
30°	340

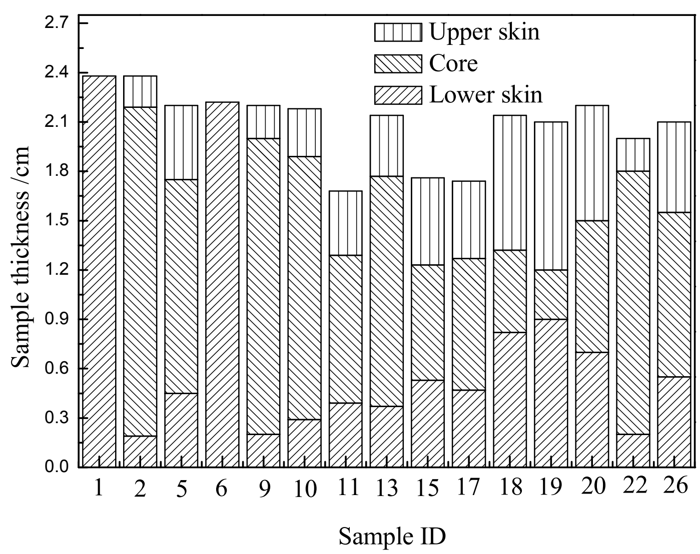

Fig. 6. Layer thickness distribution of samples

Table 3. The measurements of elastic modulus and fiber distribution

Sample	Elastic modulus MPa	Area<200/μm^2 Number	Percent	200/μm^2< Area <340/μm^2 Number	Percent	Area >340/μm^2 Number	Percent
1	2266.7	306	0.48024	161	0.25308	170	0.26666
2	1962.2	218	0.36704	132	0.22222	244	0.41073
5	4683.3	1241	0.76426	242	0.14884	141	0.08689
9	3145	776	0.70188	157	0.14250	172	0.15561
10	2809.1	846	0.64367	232	0.17624	237	0.18007
15	3571.4	1254	0.74074	241	0.14231	198	0.11695
18	2766.7	787	0.69928	145	0.12857	194	0.17214

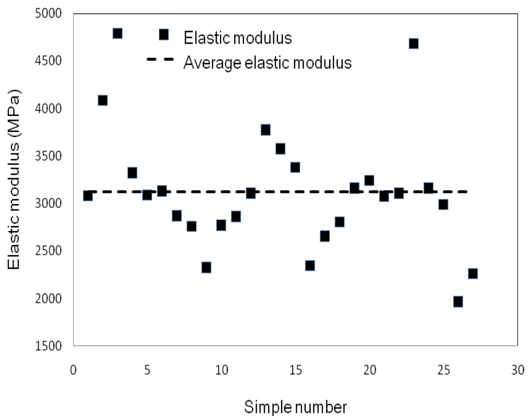

Fig. 7. The elastic modulus distribution

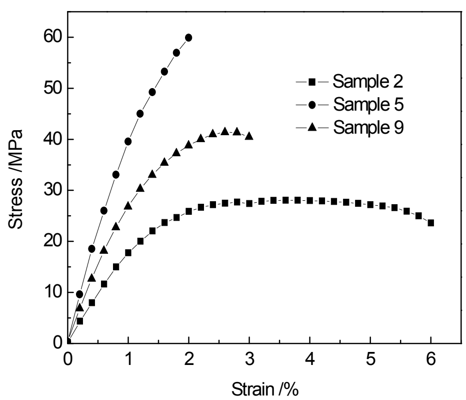

Fig. 8. Representative stress strain curves

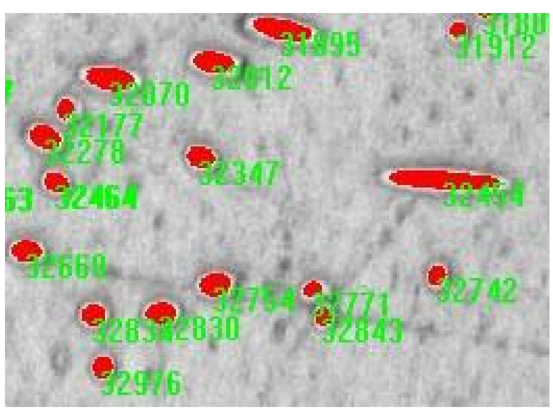

Fig. 9. Software recognition region

In glass fiber reinforced injection molding parts, the orientation and distribution of fibers are usually not uniform, depending on the shape of the part as well as gate design and processing parameter selection for molding. The elastic modulus of a certain location in the finished part is significantly affected by the number and orientation of fibers at that spot. Hence, it is particularly necessary to considering the heterogeneity of elastic modulus in CAE analysis of injection molding products reinforced with long fibers.

4. CONCLUSION

By combining fiber orientation tensor and image analysis technique, an approach for predicting fiber orientation distribution in fiber reinforced plastic injection composites is proposed and demonstrated on a car instrument panel. It is found that most regions of the panel have three layers of fiber stratifications along the thickness. Fiber orientation can be measured base on the cross-section area of the fibers on the thickness plane. The car instrument panel is heterogeneous in mechanical properties with elastic modulus of a certain location significantly affected by the number and orientation of fibers at that spot. The method presented is meaningful to parameter selection in the constitutive model of glass fiber reinforced materials for structural CAE analysis.

ACKNOWLEDGEMENT

The supports from the National Nature Science Foundation of China (11172171), Research Fund for the Doctoral Program of Higher Education of China (20130073110054) and the Scientific and Technological Innovation Foundation of Shanghai, China (12521102203) are gratefully acknowledged.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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