EFFECT OF VOID CONTENT ON THE FRACTURE PERFORMANCE OF LONG GLASS FIBER REINFORCED POLYPROPYLENE

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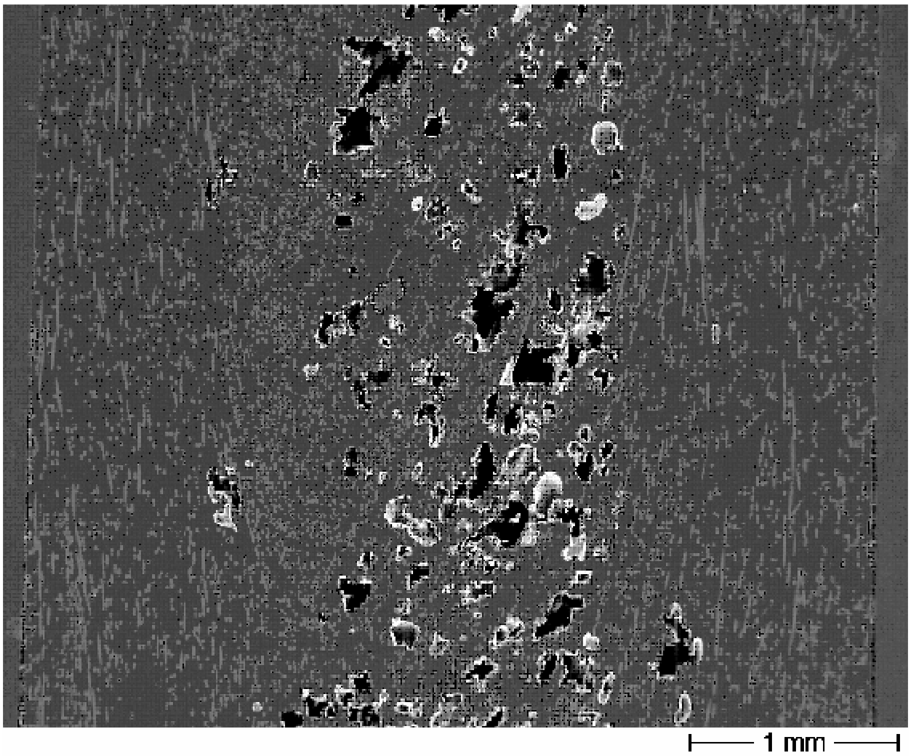
ABSTRACT

This report describes the void-content-related static fracture behavior of discontinuous long glass fiber reinforced injection molded polypropylene. The composite material investigated was supplied in the form of injection molded simple plate-tools with a size of 80mmx80mmx4mm. Compact tension specimens with notches either parallel (longitudinal, L-notch) or perpendicular (transverse, T-notch) to the mold fill direction were machined from the plate-tools. In order to avoid edge effects as far as possible, the samples were taken from the central part of plate-tools. In this study, compact tension specimens were loaded in a static testing machine in a laboratory environment. From the resulting load-displacement curves the fracture toughness was determined on the basis of the linear elastic fracture mechanical concepts. It should be mentioned that compact specimens with different void content were tested. Fracture toughness was studied as a function of volume fraction of voids. Fractographic studies with a scanning electron microscope were carried out to define the dominant mechanisms of energy absorption during breakdown of the composites and to compare the observed mechanisms of crack growth with details on the fracture surfaces. Scanning electron microscope studies revealed that the composite material was significantly voided. The composite density was determined both theoretically (from weight fractions) and experimentally. The difference in densities indicated the void content. It was found that the void content of the composite system investigated significantly affected its fracture mechanical behavior. Higher void content causes a decrease in the fracture resistance. Therefore the knowledge of the void content is desirable for estimation of the composite quality. The basic conclusion from this study is that a good quality composite should have less than one percent voids.

1. INTRODUCTION

Structural elements made by fiber reinforced composite materials are now used in a variety of components for automotive, marine, aerospace and building structures. Channel sections, I-beams and other structural elements used in buildings can be made of fiber reinforced plastics. Corrosion resistance and electrical and thermal insulation are important advantages of composites compared with steel in such applications. Composite structural components have the advantages of better vibration-damping characteristics than metallic parts. High stiffness-to-weight ratio of glass fiber reinforced composite materials is also very important in structural applications. Therefore, the use of composite structural components continues to grow. Polypropylene is one of the most interesting thermoplastics with wide application in various branches of the engineering. Polypropylene is characterized by many useful properties such as very good processability, low density, relatively high resistance to degradation. By incorporating proper reinforcement into polypropylene, its strength, stiffness, fracture toughness and fatigue crack propagation resistance can be enhanced significantly to fulfill the requirements for load-bearing industrial applications. A new trend in the reinforcement of injection-moldable thermoplastics has been observed in the last few years. Instead of the use of short reinforcing fibers (with average aspect ratios in the range 20 – 30), much longer fiber lengths are now being maintained in the injection molding technique (with fiber aspect ratios of about $10^2 - 10^3$). The longer fiber lengths result in improved strength, stiffness, fracture toughness and fatigue crack growth resistance of this group of discontinuous fiber reinforced composite materials. Since these composites are considered to replace traditional short fiber reinforced composite materials in structural parts, it is particularly important to know more about their fracture mechanical performance. The fracture toughness is a material parameter which implies stiffness, strength and strain to failure. This parameter is of major importance for application areas in which impact can occur and high safety requirements have to be fulfilled by the designer. There is a wide variety of microstructure-related factors (fiber aspect ratio, fiber volume fraction, matrix ductility, fiber layer structure, etc.) which may influence the composite's fracture performance in different ways. Therefore, the adequate description of fracture toughness remains a challenging task for researchers dealing with fiber reinforced composites. It should be noted that the properties of injection molded long fiber reinforced polypropylenes have been summarized in a number of studies [1, 2, 3, 4, 5]. However, in these investigations it has been assumed that voids are not presented in the matrix of the composite. In the reality, however, it happens sometimes to deal with polymeric composite materials whose matrixes are voided (Fig. 1). Therefore, from scientific point of view, it is interesting to perform an investigation about the effect of void content on the fracture performance of long glass fiber reinforced polypropylene.



"**Fig. 1.** Scanning electron microscope micrograph of a voided area in a cross section of long glass fiber reinforced polypropylene."

It is the objective of the present work to compare the fracture performance of long glass fiber reinforced polypropylene with different void contents. The fracture toughness will be determined by using compact tension test. The analysis of the experimental data will be carried out on the basis of the linear elastic fracture mechanics. Fracture mechanical study will be combined with a characterization of the failure mechanisms by using electron microscopy in order to gain more understanding for the effects of void content.

2. MATERIALS

The material used was long glass fiber reinforced polypropylene with 50 weight percent glass fibers. The average fiber aspect ratio was of about 160. The composite material was supplied as injection molded plaques with a size of 80mmx80mmx4mm. The inlet was a film gate with 1 mm thickness. The injection molding was carried out with a volumetric flow rate of 150 cm^3/s at a melt temperature of 270^0C and mould temperature of 40^0C. The weight fractions can be transferred into fiber volume fraction, V_f, by the following relationship

$$V_f = \frac{W_f / \rho_f}{W_f / \rho_f + W_m / \rho_m}, \qquad (1)$$

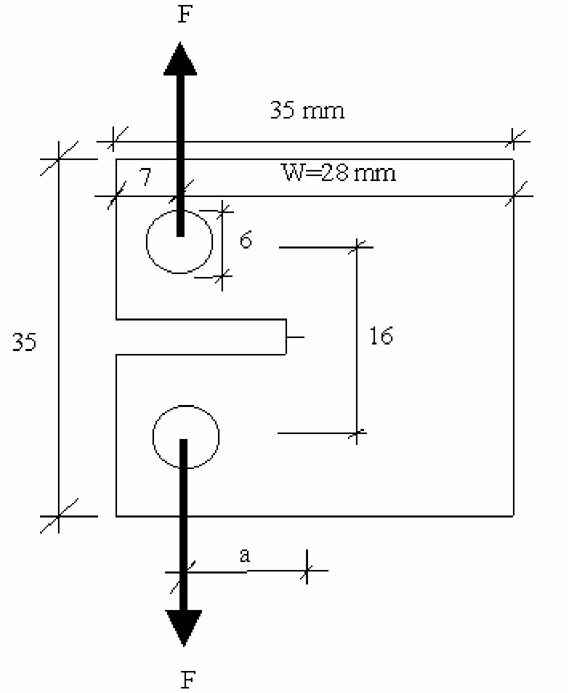
where W_f and W_m are the weight fractions of fibers and matrix, respectively. The densities of the glass fibers and the polypropylene matrix are denoted by ρ_f and ρ_m, respectively. By using equation (1) the following fiber volume fraction was calculated: 26.20 vol. %.

The density of the composite material, ρ_c, in terms of weight fractions can be written as

$$\rho_c = \frac{1}{W_f / \rho_f + W_m / \rho_m}. \qquad (2)$$

Assuming that $\rho_f = 2.54$ g/cm^3 and $\rho_m = 0.90$ g/cm^3, the following value of density of the composite material was obtained: $\rho_c = 1.33$ g/cm^3. The density of the matrix in these calculations is assumed to be the same as it is in an unreinforced bulk state. This leads to a slight error, because it is thought that the matrix density is higher than the bulk one. However, the error is small because the fibers are much denser than the matrix.

The density of composite material was determined also experimentally. The following values of the density of the composite material were measured: 1.3171 g/cm^3, 1.3144 g/cm^3, 1.2740 g/cm^3, 1.239 g/cm^3. It should be noted that for each material five measurements were performed and average values of the density were obtained.



"**Fig. 2.** Geometry of compact tension test specimen."

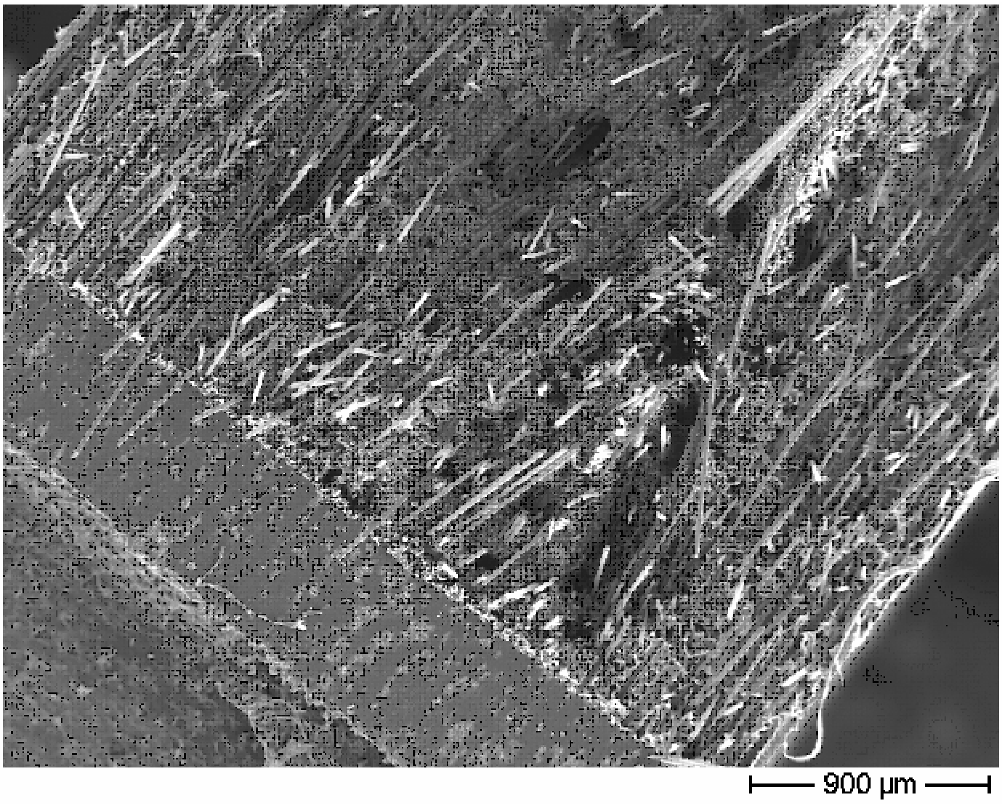
It is clear that the composite density calculated theoretically by using relation (2) is not in agreement with the experimentally determined density. This fact shows that voids are presented in the composite material investigated. The volume fraction of voids, V_V, is given by the following expression:

$$V_V = \frac{\rho_{ct} - \rho_{ce}}{\rho_{ct}}, \qquad (3)$$

where the theoretical composite density is denoted by ρ_{ct} and the experimentally determined density by ρ_{ce}. By using formula (3) the following volume fractions of voids were obtained: 0.97 vol. %, 1.17 vol. %, 4.20 vol. % and 6.82 vol. %.

3. CRACK MECHANICS TEST

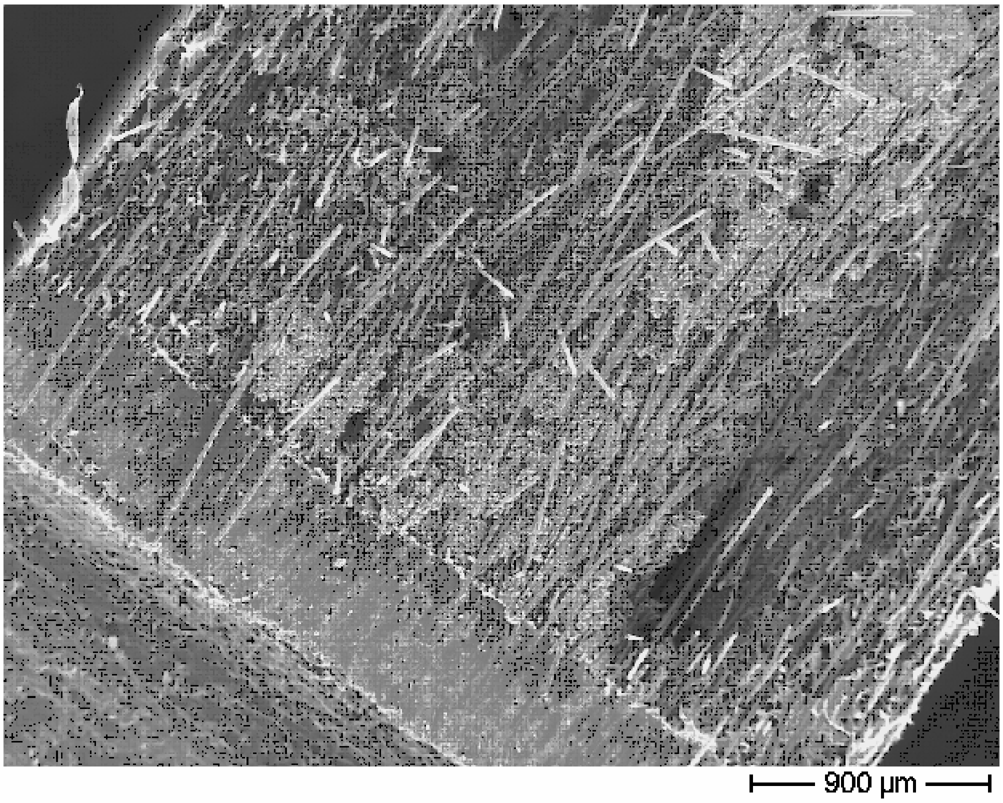
Fracture toughness tests on compact tension specimens (Fig. 2) were performed at a cross-head speed of 5 mm/min. The tests were carried out at room temperature (23^0C). The compact tension specimens were machined from the injection molded plates so that the initial crack tip position coincided with the central point of the plate.



“**Fig. 3.** Scanning electron micrograph of a fracture surface of a longitudinal crack in a compact tension specimen showing voids (as dark spots) in the matrix.”

Because the fiber alignment in injection molding yields highly anisotropic mechanical properties of these materials, the compact tension specimens had two different orientations. Samples with cracks perpendicular to the mould-filling direction are refereed to as transverse direction samples and samples whose cracks were parallel to the mould-filling direction are refereed to as longitudinal direction samples.

The compact tension specimens had sharp cracks introduced by pressing a fresh razor-blade into the notch tip, to a dept of about 0.8 mm. Fig. 2 shows the exact geometry of the specimen. Fig. 3 shows the fracture surface of a L-cracked compact tension sample. Fracture has developed from the initial razor notch. The fracture surface is dominated by numerous fibers which were pulled-out from the counter-surface. The voids in the matrix between fibers are clearly visible as dark spots. An analogous situation has been found in a T-cracked specimen (Fig. 4).



“**Fig. 4.** Fracture surface a transverse crack in a long glass fiber reinforced polypropylene compact tension specimen showing voids (as dark spots) in the matrix.”

Fracture toughness values were calculated from the load-displacement diagrams (Fig. 5) by using the standard formula:

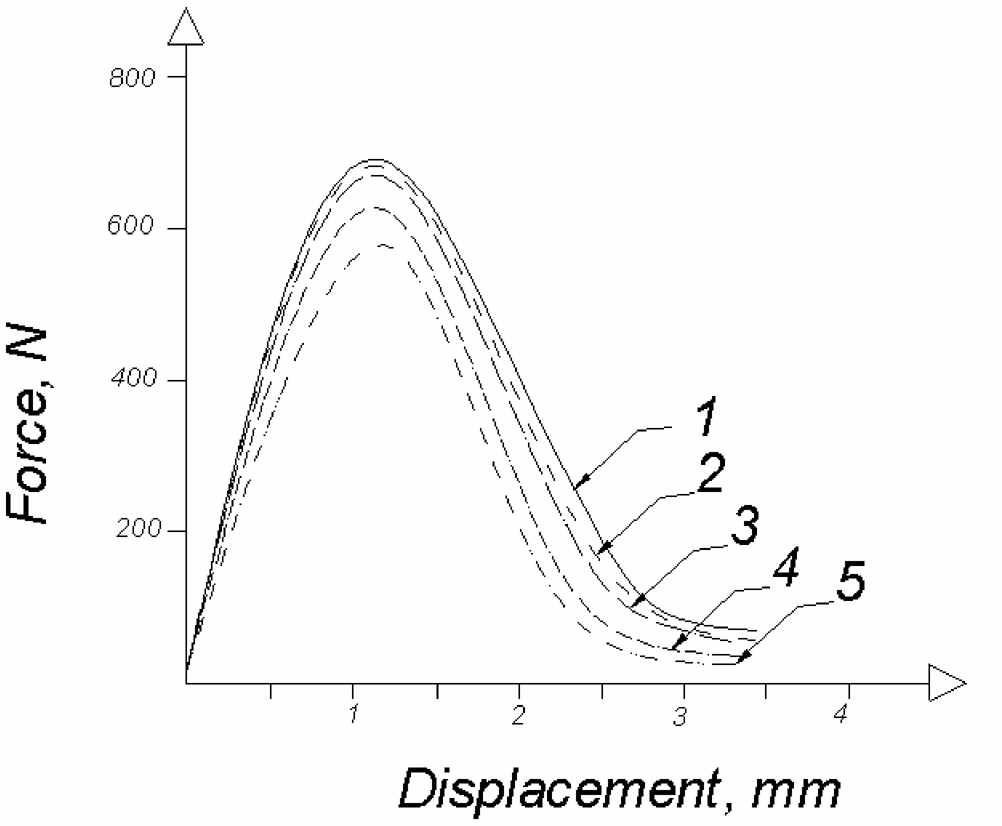
$$K_Q = \frac{F_Q}{BW} Y\left(\frac{a}{W}\right), \tag{4}$$

where F_Q is the load of intercept between 95 % linear slope line and compact tension test load-displacement diagram, B is the specimen thickness (4 mm), W is the specimen width (28 mm), a is the crack length, and $Y\left(\frac{a}{W}\right)$ is the polynomial correction factor according to European Structural Integrity Task Group on Polymers and Composites (ESIS) for compact tension specimens [6].

During the test the crack length was monitored by a video camera and an image analyzer system. It was observed that in specimens, manufactured from composites with voided matrix, the crack path had a zigzag shape, while in specimens with non-voided matrix the crack path was almost a straight line.

It should be mentioned that compact tension specimens prepared from composites with and without voids in the matrix between the fibers were machined and tested. The fracture toughness data generated with compact tension specimens are summarized in Table 1. It should be noted that a higher void content causes an increase in the scatter of the measured fracture resistance values. For instance, for composites with non-voided matrix the scatter was small (maximum deviation μ4 %), while for composites with volume fraction of voids 6.82 %

the maximum deviation was μ15 %. The fracture toughness values are higher for the specimens with the crack direction transverse to the fiber orientation in the surface layers (T-cracked direction).



"**Fig. 5.** Load-displacement diagrams for L-cracked compact tension specimens: 1 – non-voided material (i. e., $V_V = 0$ vol. %); 2 – $V_V = 0.97$ vol. %; 3 – $V_V = 1.17$ vol. %; 4 – $V_V = 4.20$ vol. %; 5 – $V_V = 6.82$ vol. %."

Further it can be noted that the fracture toughness values of composites containing voids are lower than these of composites without voids. The voids enable cracks to grow more easily, resulting in lower fracture toughness compared to the composites with non-voided matrix. The difference between composites with voided and non-voided matrix is higher for specimens with notches parallel (L-cracked direction) to the mold fill direction. One explanation for this is that the voids are mainly concentrated in the core region of the crossection of the plaque. The fibers in the core region (which are predominantly transversely aligned to the crack propagation direction) play major role in hindering the crack growth in L-cracked specimens. Therefore, the decreasing effect of voids on crack propagation resistance in L-cracked direction is higher compared to T-cracked specimens.

It can be observed also from Table 1 that the decreasing effect of voids on fracture toughness of composite with volume fraction of voids less than 1 % (i. e., $V_V<1$ vol. %) is less than 3 % which is lower compared to the analogous effect for $V_V>1$ vol. %.

4. CONCLUSIONS

The fracture performance of long glass fiber reinforced injection molded polypropylene was studied with respect to the void content. The fracture toughness was determined by using compact tension tests. Compact tension specimens were machined from injection molded plaques either perpendicular (T-notch) or parallel (L-notch) to the mould fill direction. Injection molded composites with different volume fractions of voids were examined.

"**Table 1.** Fracture toughness data obtained from compact tension test. Decreasing is given with respect to the reference case $V_V=0$."

Volume fraction of voids V_V, %	Fracture toughness K_Q, MPa $m^{0.5}$			
	L-notch	Decreasing, %	T-notch	Decreasing, %
0.00	5.12	0.0	5.99	0.0
0.97	5.00	2.4	5.86	2.1
1.17	4.82	5.8	5.67	5.4
4.20	4.54	11.3	5.36	10.5
6.82	4.39	14.2	5.205	13.1

Scanning electron microscopy studies on microstructural details of the different sets of materials were performed. It was found that the cross-section of injection molded composites has a three-play laminate structure with two surface layers and one central layer, each with a different fiber orientation. In the surface layers the fibers were oriented predominantly parallel to the mould fill direction. In the core region the opposite fiber orientation pattern was established, i. e. the fibers were oriented transverse to the mould fill direction. Static crack propagation measurements were carried out in a laboratory environment. The topology of the fracture surfaces was studied by scanning electron microscopy. From the resulting load-displacement curves the fracture toughness was calculated by using the linear-elastic fracture mechanics. The calculations show that the fracture toughness is strongly dependent on the volume fraction of voids. The resistance to crack propagation decrease as the void content increases. It should be mentioned that the fracture toughness is strongly affected by the fiber layering pattern discussed above. It was found that the thickness of the two surface layers is higher than the thickness of the core layer. Thus T-notched specimens have more fibers which are oriented perpendicular to the crack propagation direction. This fiber arrangement hinders the crack growth more effectively than that of L-notched specimens (Table1).

For composites with volume fraction of voids less than 1 vol. % the effect of voids on the fracture toughness is rather small (the decreasing of the fracture toughness values compared to the reference case $V_V=0$ is less than 3% (Table 1)). The most important conclusion from the present study is that long glass fiber reinforced composites of good quality must have void content less than 1 vol. %.

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