DOI: 10.1002/masy.200950304

Simulation of Fibrillation of PC/LCP/Kevlar Blends and Its Characterizations

Madhumita Mukherjee,[1] *Tanya Das,*[1] *Saswata Bose,*[1] *Chapal Kumar Das,**[1] *Alexander P. Kharitonov,*[2] *Kaushik Banik,*[3] *Tham Nguyen Chung,*[3] *Gunter Mennig*[3]

Summary: Kevlar fiber was fluorinated and oxy-fluorinated directly in presence of undiluted fluorine and fluorine gas mixture and processed with Polycarbonate and LCP at 320 °C under 20 rpm in a twin-screw extruder. The composites were then injection molded into dumbbell shaped specimens under different conditions like various mold temperatures, injection temperatures, injection speeds and mold filling rates. Various physico-chemical characterizations have been performed under definite processing parameter. Orientation of fibers under different injection parameters was evaluated using mold flow simulation technique. Most injection molded or extruded structures however, exhibit non-uniform fiber orientation across the final parts, with a diverging variety of different local fiber orientation states. Distinct skin and core regions were observed in the injection molded parts and it has also been found out that fiber orientation is different in skin and core region for both unmodified and modified derivative, which affects the flow behavior. Processing parameters significantly affect the fiber orientation pattern in the skin and core region for all blended materials. It is worth mentioning that the maximum fiber orientation occurred during the extrusion process at the wall but different extent of fiber orientation is observed during the injection molding depending on the shape of the dumbbell specimen. This fibrillation has been corroborated by the SEM study in both the skin and core region.

Keywords: fiber orientation; fibers; mold flow simulation technique; processing parameters; thermal properties

Introduction

Short fiber reinforced composites are pertinently used in the applications that require moderate stiffness, moderate loads, and high volume production as they retain some advantages of continuous fiber reinforced composites and can be processed without difficulties. The properties of the short fiber reinforcements in thermoplastic matrices are mainly dependent on the microstructure which in turn can be defined by fiber aspect ratios, length, orientation, size distribution, fiber-matrix adhesion at the interface, as well as the presence of reactive functionalities.[1] Besides thermotrpic liquid crystalline polymers have been used very successfully as self reinforcement as well as the processing aid in various matrix systems as they possess rigid rod like molecular structures.[2–5] The properties of the short fiber composites change from isotropic to anisotropic as the fiber orientation become less random. Majority of these characteristics is determined by processing conditions, including molding temperature, cooling rate, injection flow rate, melt temperature, holding temperature/time, annealing conditions and geometrical shape of the mold such as gating, section thickness and inserts.[6–12] Some researchers have carried out investigations on the analysis and control of injection molding variables such as the polymer melt temperature,

---

[1] Materials Science Centre, Indian Institute of Technology, Kharagpur, India
E-mail: chapal12@yahoo.co.in
[2] Institute of Energy Problems of Chemical Physics, Chernogolovka, Russia
[3] TU-Chemnitz, Chemnitz, Germany

filling rate and packing pressure profiles.[13–16] The microstructure of a short fiber reinforced composite depends on the manufacturing conditions and on the characteristics of the constituent short fibers and the matrix. Banik[17] has reported the influence of the injection molding process on the creep behavior of semicrystalline PBT during aging below its glass transition temperature. Na and co-workers[18] have demonstrated the crystal and phase morphology of dynamic-packing-injection-molded high-density polyethylene/ethylene vinyl acetate blends. Another important factor that regulates the properties of the short fiber reinforced thermoplastics very significantly is the fiber orientation in the composites, which in turn depends on the processing parameters.[6] Hence it is very important to predict the fiber orientation under different processing parameters. Various numerical as well as analytical methods have been reported predicting the fiber orientation of the polymeric materials.[19,20] Lee[21] has characterized the fiber orientation in short fiber reinforced composites with an image processing technique. There are many reports available which dealt with the effect of processing (injection) parameters on the glass fiber reinforced polymer composites.[22,23] In this present discussion a comprehensive study regarding the fiber orientation using mold flow simulation technique of PC/LCP blends reinforced with unmodified and modified (fluorinated and oxy-fluorinated) Kevlar fiber will be done and other physico-chemical properties of the same under a definite processing parameter will be reported to understand the effect of fluorination and oxy-fluorination of the Kevlar fiber in to PC/LCP blends.

Experimental Part

Materials and Sample Preparation

Materials

Polycarbonate used in this study was procured by Macrolon, Bayer Material Science, West Germany. Polycarbonate is a particular group of thermoplastic polymer. It can be easily molded and thermoformed which facilitates its wide uses in the modern chemical industry. It possesses good temperature resistance, high impact resistance and excellent optical properties positioning it between commodity plastics and engineering plastics.

The Aramid fibers used in this study were supplied by 1100 Dtex, manufactured by Du Pont Co possessing glass transition temperature (T_g) and the melting temperature (T_m) $>$300 °C and 500 °C respectively. Kevlar is very high strength polymer owing remarkably high modulus, abrasion resistance, good stiffness and very light weight.

In this study the liquid crystalline polymer (LCP) was Vectra C which contains 80% Hydroxy benzoic acid and 20% hydroxyl napthanoic acid and was supplied by Ticona, USA. LCPs possess some excellent properties like high heat resistance, flame retardant, chemical Resistance, dimensional Stability, moldability, heat aging resistance, adhesion, low viscosity, low cost and over all they act as viscosity reducing agent.

Sample Preparation

Kevlar was fluorinated and oxy fluorinated using a mixture of F_2: He (5%: 95%) at 0.4 bar total pressure during $\sim$1 hour and F_2: air: He (5%:5%:90%) under 0.8 bar pressure and for 30 minutes respectively at 17 °C.

Preparation of Composites

0.5 weight% of original, fluorinated and oxy-fluorinated Kevlar fiber was mixed with a mixture containing 100 weight% of PC and 20.8 weight% of LCP blend using a twin-screw extruder at 320 °C having L/D ratio 17 under 20 rpm and the corresponding compounding formulations are depicted in (Table 1). Then the mixtures were molded using injection molding under different processing conditions in a BOY22D having L/D ratio 17.5 and the corresponding processing parameters are tabulated in (Table 2).

Table 1.
compounding formulations.

Sample code	PC (%)	LCP (%)	Kevlar (%)
PC	100	–	–
H	100	20.8	–
I	100	20.8	0.5 (original)
J	100	20.8	0.5 (fluorinated)
K	100	20.8	0.5 (oxy-fluorinated)

Here we will concentrate on the processing parameter 2 to understand the effect of fluorination and oxy-fluorination of Kevlar fiber on the properties of PC/LCP/Kevlar composites and the simulation of fiber orientation of all composites under different processing parameters using mold-flow simulation technique.

Results and Discussions

Differential Scanning Calorimatric study (DSC)

The DSC heating profile of PC/LCP and unmodified and modified (fluorinated and oxy-fluorinated) Kevlar composites along with the neat polymer (in the temperature range 80°–200 °C) is depicted in (Figure 1) and the magnitude of glass transition temperature of the concerned blends are tabulated in (Table 3). Figure shows only one transition in the range of 150 °C for pure PC, which correlates with the glass transition temperature of poly carbonate.[24] With addition of LCP the T_g shifted to the lower temperature side along with an additional peak near about 135 °C,[25] which is the glass transition temperature of LCP in the PC/LCP blend as evidenced from the (Figure 1). The double humped peak arises due to the partial miscibility of the PC with LCP phase *i.e.* the synergistic effect PC and LCP in the resulting blend. The shifting of the glass transition temperature of PC phase towards the lower temperature side may be ascribed as three contributing factors: the partial miscibility of LCP with the PC matrix *i.e.* amorphous part of the LCP is miscible with amorphous PC phase, the decrease in the T_g of PC may be caused by the plasticization effect of low molecular weight fraction of the LCP and lastly the decrease in the T_g of PC is attributed to the surface effect *i.e.* addition of LCP into PC increases the surface area (per unit volume) of the polycarbonate as polycarbonate molecules at the interface region have higher mobility than those in the bulk due to less constraint, in turn increased surface area should decrease the T_g of Polycarbonate.[24] With addition of unmodified Kevlar fiber the DSC profile again exhibits a single T_g indicating the miscibility of the PC/LCP in presence of Kevlar fiber, although the magnitude of the T_g of PC matrix shifted towards the lower temperature side may be due to the poor fiber/matrix adhesion at the interface. Fluorination and oxy-fluorination of Kevlar fiber further shift the T_g of the aforementioned composites to the higher temperature side due to the better fiber/matrix adhesion at the interface as a result of incorporation of reactive functional groups onto the Kevlar surface, which is the synergistic effect between the PC/LCP and modified Kevlar. The shifting of T_g towards the higher temperature side is much more prominent in case of oxy-fluorinated derivative.

Thermal Properties

In order to monitor the effect of modified and unmodified Kevlar fiber incorporation on the thermal stability of PC/LCP blends

Table 2.
Processing parameters for injection molding.

Sample Code	T_m (°C)	T_{mold} (°C)	Flow rate (cm^3/s)
Series I1/Series J1/Series K1	300	60	20
Series I2/Series J2/Series K2	320	40	48
Series I3/Series J3/Series K3	320	40	20
Series I4/Series J4/Series K4	320	60	20

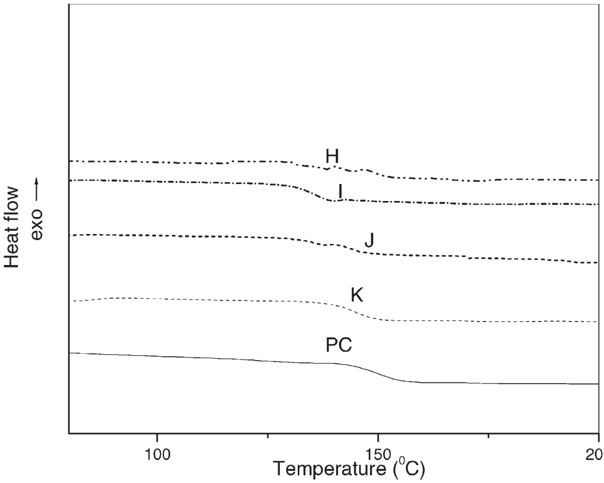

Figure 1.
DSC profile of (i) Pure PC (PC), (ii) PC/LCP (H), (iii) PC/LCP/unmodified Kevlar (I), (iv) PC/LCP/fluorinated Kevlar (J) and (v) PC/LCP/oxy- fluorinated Kevlar (K).

along with the LCP incorporation, the thermo gravimetric (TG) study was conducted. The TG curves of the composites obtained at a heating rate 10 °C/min in air and are shown in (Figure 2) and the respective parameters are tabulated in (Table 3). In order to avoid any ambiguity, the onset degradation temperature has been defined as the temperature at which polymer lost 1% of its weight. From the thermo gram it is observed that degradation starts at higher temperature for all Kevlar/PC/LCP blends than neat PC and PC/LCP. This enhancement in onset degradation temperature is more pronounced in case of modified Kevlar/PC/LCP composites.

This extent of enhancement of thermal stability on addition of LCP into PC matrix is attributed to the incorporation of the better thermally stable flexible chain polymers (LCP). Addition of Kevlar fiber further improves the thermal stability of the hybrid composites as the introduction of aromatic content of high thermal stability. Surface modification of Kevlar fiber further leads to the enhancement of the thermal stability of the PC/LCP/modified Kevlar composites (J, K) due to the incorporation of the functional groups on to the Kevlar surface resulting good compatibility between two polymeric species in case of fluorination and oxy-fluorination. Moreover, it is known that crystalline polymer is thermally more stable than its amorphous counter part due to energy input required overcoming both intermolecular and intermolecular forces. It is important to point out that the extent of

Table 3.
Thermal Properties of PC/LCP/Kevlar blends.

Sample code	Degradation temperature T_d (°C)	Mass Change (%)	Residue at 649 °C (%)	Glass transition temperature (T_g) (°C)	
				By DSC	By DMTA
PC	427.7	71.1	25.4	149.3	168.0
H	434.3	69.4	26.0	141.3	156.6
I	442.4	68.1	26.5	138.9	153.6
J	446.6	67.8	27.5	144.5	161.0
K	450.5	67.0	27.9	148.3	171.2

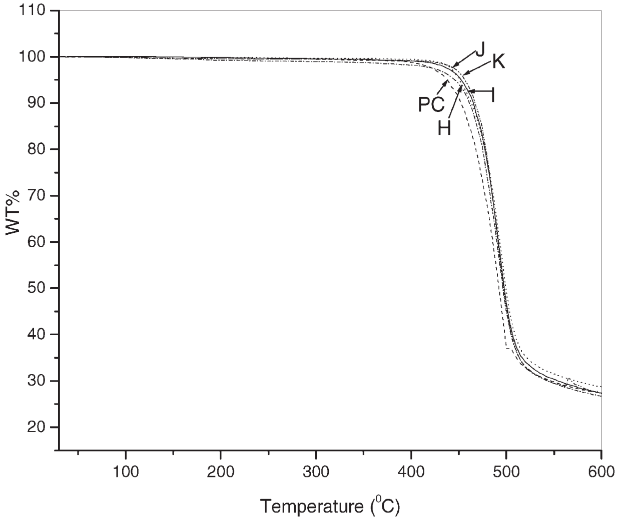

Figure 2.
TG plot of (i) Pure PC (PC), (ii) PC/LCP (H), (iii) PC/LCP/unmodified Kevlar (I), (iii) PC/LCP/fluorinated Kevlar (J) and (iv) PC/LCP/oxy-fluorinated Kevlar (K).

more interaction in case of oxy-fluorinated Kevlar/PC/LCP blends due to more functional groups of oxy-fluorinated Kevlar fiber can be responsible for a higher thermal stability of the oxy-fluorinated Kevlar fiber reinforced (composite R) composite as oxy-fluorination generates controlled amount of long-living RO_2^* radicals.[26]

X-ray Study

(Figure 3) shows the X-ray parameters of the blend system. PC shows a broad peak near about $2\theta = 16.5^\circ$ due to the amorphous nature of the matrix polymer. Addition of LCP generates a very minute change in the X-ray pattern near about $2\theta = 19.5^\circ$, may be due to the LCP ($2\theta \sim 20\,^\circ C$).

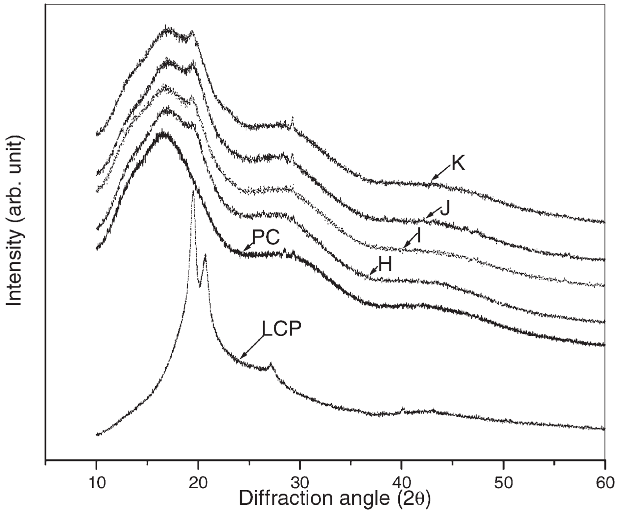

Figure 3.
X-ray diffraction pattern of (i) Pure PC (PC), (ii) PC/LCP blend (H), (iii) PC/LCP/unmodified Kevlar (I), (iv) PC/LCP/fluorinated Kevlar (J) and (v) PC/LCP/oxy-fluorinated Kevlar (K).

From this we can infer that LCP is partially miscible with the amorphous PC matrix. The intensity of that small peak increases with the introduction of Kevlar fiber into the PC/LCP matrix. Which can be ascribed as the nucleating effect of Kevlar into the PC/LCP matrix and LCP/Kevlar induces very little crystallinity into PC. Surface modification of Kevlar further increases the intensity and shifts the peak to somewhat higher 2θ value for this small peak ($2\theta = 19.75°$) revealing better fiber matrix adhesion at the interface. This effect is more pronounced in case of oxy-fluorinated derivative.

Dynamic Mechanical Analysis (DMA)

Dynamic mechanical analysis is a significant tool for studying the relaxation in polymeric materials. Analysis of the storage modulus and tan δ curves is very utile in determining the performance of a material under stress and temperature. DMA not only appraises the dynamic mechanical attributes of a material, but also detects changes in the solid structure of a polymer after compounding with other materials. (Figure 4 and 5) display the dynamic mechanical profile (storage modulus E' E' and tan δ) as a function of temperature for PC/LCP/Kevlar composites.

The storage modulus is closely related to the capacity of a material to absorb or return energy attributed to its elastic behavior.[27] From (Figure 4) it is very much evident that addition of LCP leads to the appreciable enhancement of the magnitude of storage modulus. This is ascribed to be due to the high intrinsic modulus of LCP phase consisting rigid rod like structure. Das et al.[28] have reported the same observation in the PTFE/LCP blends. Figure 4 shows a sharp drop in storage modulus of every composite along with neat polymer corresponding to the glass transition temperature (T_g). This modulus drop can be imputed to an energy dissipation phenomenon involving cooperative motions of the polymer chain. Figure 4 also shows that with addition of Kevlar fiber into the PC/LCP blend further increases the storage modulus of the concerned blend, which may be due to the reinforcing nature of the Kevlar fiber into the PC/LCP matrix. Surface modification leads to the further enhancement of the magnitude of storage modulus of the fluorinated and oxy-fluorinated Kevlar fiber reinforced PC/LCP blend due to the incorporation of the reactive functional groups onto the Kevlar surface leading to better fiber matrix adhesion resulting the improved stiffness of

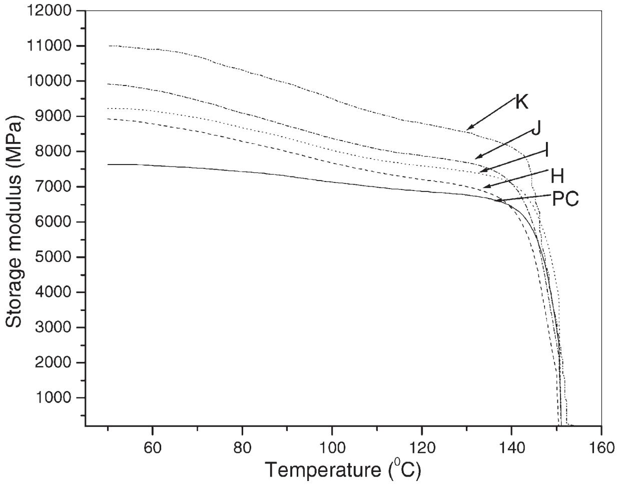

Figure 4.

Storage modulus *vs.* temperature curve of i) Pure PC (PC), ii) PC/LCP blend (H), ii) PC/LCP/unmodified Kevlar (I), iv) PC/LCP/fluorinated Kevlar (J) and v) PC/LCP/oxy-fluorinated Kevlar (K).

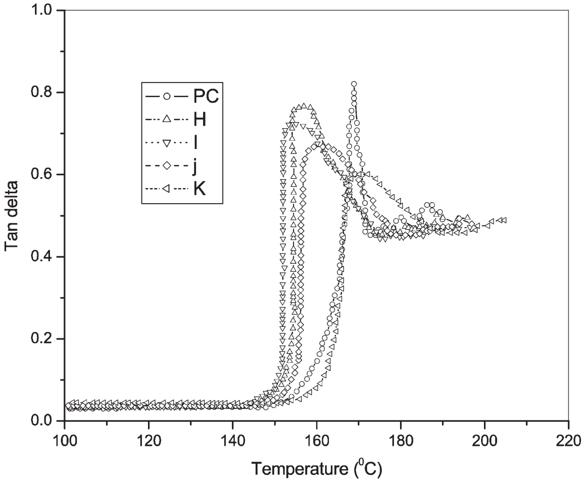

Figure 5.
Tan delta vs. temperature curve of i) Pure PC (PC), ii) PC/LCP blend (H), iii) PC/LCP/unmodified Kevlar (I), iv) PC/LCP/fluorinated Kevlar (J) and v) PC/LCP/oxy-fluorinated Kevlar (K).

the modified composites. This phenomenon is also supported by the results obtained from the XRD study where surface modification induces some crystallinity into the PC/LCP blend. Incase of oxy-fluorinated derivative this enhancement of storage modulus is more prominent.

The damping properties of the materials give the balance between the elastic phase and the viscous phase in a polymeric structure. The loss tangent (tan δ) of base polymer and their composites as a function of temperature is represented in (Figure 5) and the corresponding parameters are tabulated in (Table 3). The glass transition temperature (T_g) is selected as the peak position of the tan delta curve when plotted against temperature. From Figure 5 it is evident that all the composites along with the pure polymer show a single peak near about 160 °C, which is the glass transition temperature of the PC matrix polymer. In case of PC/LCP/Kevlar composites the loss peak broadens may be due to the overlapping peak of PC and LCP, which suggests the partial miscibility of the LCP with PC matrix phase as mentioned earlier. The broadening of loss peak in the presence of fiber can also be ascribed to matrix-fiber (filler) interaction.

The matrix polymer (PC/LCP) in the adjacent portion of the fiber can be considered to be in different state in comparison to the bulk matrix, which can disturb the relaxation of the matrix resulting in a broad tan δ peak T_g value shifted to the lower temperature side in case of PC/LCP (H) in comparison to the pure matrix (PC) may be due to the partial miscibility of PC with LCP. In case of PC/LCP/unmodified Kevlar (I), the magnitude of T_g further decreases may be due to the poor fiber/matrix adhesion at the interface. Fluorination and oxy-fluorination of Kevlar fiber enhances the glass transition temperature appreciably in case of the concerned composites (J, K). This can be ascribed as the better fiber/matrix adhesion at the interface due to the incorporation of reactive groups on the fiber surface. The relative decrease in the height of tan δ peak related the increase in the extent of crystalline properties imposed by the LCP and Kevlar fiber in the polymers since the transition behavior is associated with the local mobility of polymer chains in the amorphous region of the polymer, which is also reflected in the increase of storage modulus of the samples. More over, the T_g values obtained from the two techniques

(DSC and DMTA) are different because of the sensitivity difference between the two methods towards the glass transition temperature and also mentioned in literature[29] and also the frequency dependent.

Simulation of Fiber Orientation Using Mold Flow Simulation Study

Overtures in computer technologies have allowed immense studies to be carried out using simulation programs based on finite element analysis such as Mold flow, C-Mold and Cadmould. Mold flow Simulation software is extensively used in the design of injection molded parts, because of the stability of the Hele-Shaw flow approximation to describe the mould filling processes substantially.[30] This program enables the filling, post-filling and cooling phases of the injection molded product to be studied. Mold flow simulation study follows the Tucker-Folgar's model for fiber orientation modelling in concentrated suspensions. The model (Eq. 1) has been given in this form by Advani and Tucker[31]

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

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

ν_k is the velocity component

ω_{ij} and γ_{ij} are the vorticity and deformation tensors

λ is a constant that depends on the geometry of the particle

δ_{ij} is a unit tensor

C_I is the interaction coefficient

In this recent study we have used mold flow simulation technique to evaluate the fiber orientation in PC/LCP/unmodified, fluorinated and oxy-fluorinated Kevlar fiber under different processing parameters. The variations of orientation tensor with normalized thickness under different processing parameters have been displayed in (Figure 6(a–c)) and corresponding results are displayed in (Table 4).

From (Figure 6(a–c)) and (Table 4) it is very much evident that melt temperature (I1, Figure 6a, J1, Figure 6b, K1, Figure 6c, and I4, Figure 6a, J4, Figure 6b, and K4, Figure 6c) has pronounced effect on the fiber orientation of PC/LCP/Kevlar composites in both the skin and core region.

Although the fiber orientation exhibits similar trend in the core as well as in skin region at both higher and lower melt temperature. More fibers are oriented in the core region (higher magnitude of orientation tensor) than that of the skin. However, higher melt temperature possess some what less fiber orientation tensor than that of the lower variable. Figure 6(a–c) and Table 4 again exhibits the fiber orientation in the PC/LCP/Kevlar composites under varying flow rate.

From those Figures it is evident that flow rate has significant effect on the fiber orientation of the composites. At lower flow rate more fibers are orientated in the skin region in flow direction (evidenced from orientation tensor value) I3, (Figure 6a), J3, (Figure 6b), and K3, (Figure 6c) than that of higher counter part I2, (Figure 6a), J2, (Figure 6b), and K2, (Figure 6c). This can be ascribed as an increase in the mold wall – polymer contact time at lower flow rate leading to a thick solidified layer *i.e.* the skin structure. This solidified skin layer high shear flow field at the solid-melt interface. Such a shear flow orients the fibers in flow direction. Orientation in the flow direction increases with increasing shear rate. On the other hand, the long contact time provided by the low injection speed results in the thicker skin structure and in preservation of the fiber orientation patterns in the concerned zone *i.e.* skin region. An interesting trend of fiber orientation has been observed in case of varying mold temperature (I3, J3, K3 and I4, J4, K4), (Figure 6(a–c)) and (Table 4). At higher mold temperature more fibers are oriented in core region than that of the skin (higher orientation tensor value) and in case of lower mold

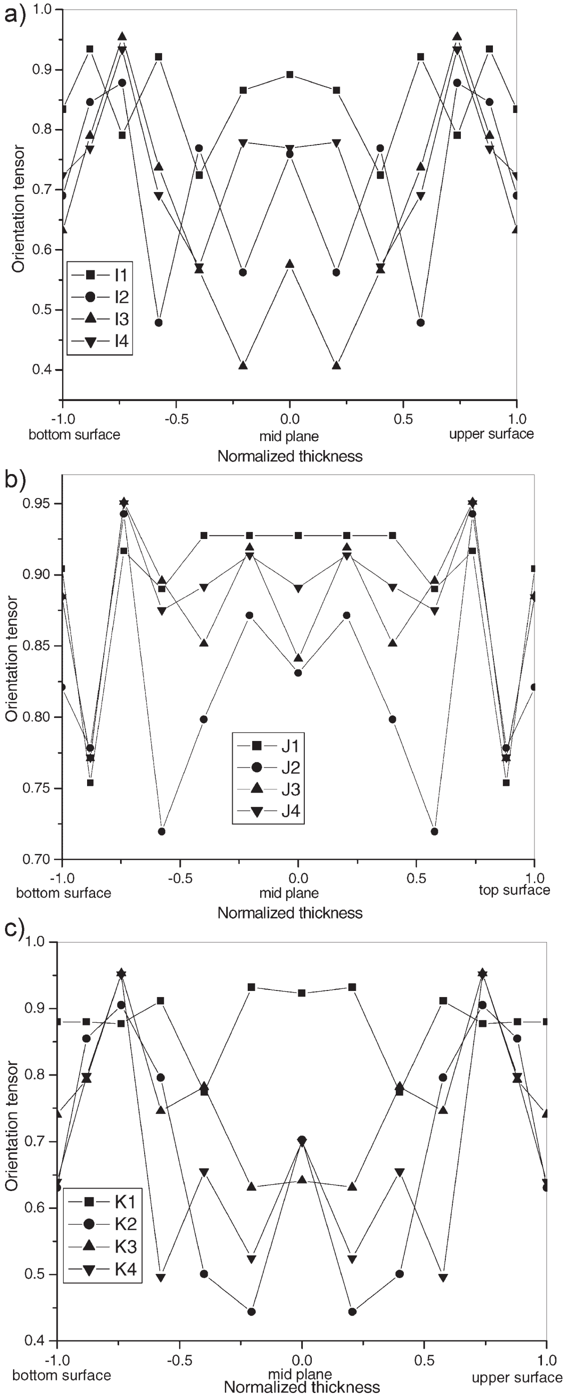

Figure 6.

a) Fiber orientation tensor *vs.* normalized thickness of PC/LCP/unmodified Kevlar (I) under different processing parameters (1, 2, 3, and 4). b) Fiber orientation tensor vs. normalized thickness of PC/LCP/fluorinated Kevlar (J) under different processing parameters (1, 2, 3, and 4). c) Fiber orientation tensor vs. normalized thickness of PC/LCP/oxy- fluorinated Kevlar (K) under different processing parameters (1, 2, 3 and 4).

Table 4.
Normalized thickness *vs.* Orientation tensor along the gap wise direction.

Sample Code	Normalized thickness	Orientation tensor
I1	−1	0.834123
	0	0.891039
	+1	0.834123
I2	−1	0.689984
	0	0.759418
	+1	0.689984
I3	−1	0.632284
	0	0.575498
	+1	0.632284
I4	−1	0.724652
	0	0.76954
	+1	0.724652
J1	−1	0.904304
	0	0.927326
	+1	0.904304
J2	−1	0.820934
	0	0.830934
	+1	0.820934
J3	−1	0.884709
	0	0.840919
	+1	0.884709
J4	−1	0.884479
	0	0.890948
	+1	0.884479
K1	−1	0.880099
	0	0.923133
	+1	0.880099
K2	−1	0.630386
	0	0.702878
	+1	0.630386
K3	−1	0.740444
	0	0.641091
	+1	0.740444
K4	−1	0.639416
	0	0.699416
	+1	0.639416

temperature the opposite trend has been observed. This can be assigned as at high mold temperature, the temperature difference between the molten fluid and mold temperature leads to the thinner solidified skin leading to the lower flow field at the solid-melt interface and lower shear rates in the solid-melt interface thus orienting lesser fiber in the flow direction in the skin region. However, MOLDFLOW does not consider fiber/matrix adhesion in their program. As mentioned earlier that it uses the Folgar-Tucker model, which is a modification of the Jeffery model by adding a diffusive term to consider the fiber-fiber interaction. In the Jeffery model, inertia and Brownian motion of the fibers are neglected. The fibers the Jeffery model considers are rigid particles moving in a Newtonian fluid, which - however - do not disturb the motion of the fluid. Although from Table 4 it is also clearly evident that the magnitude of fiber orientation is higher in case of modified composites under all processing parameters in comparison to the unmodified one both in the skin and core region. From this we can infer that due to the surface modification of fibers by means of fluorination and oxy-fluorination the better fiber/matrix adhesion taken place augmenting the orientation of fibers or LCP fibrils along the flow direction which can be corroborated from the SEM study discussed later.

SEM Study

To understand the morphology of the composites, SEM study of the cryofractured samples were carried out. Representative SEM images of the PC/LCP/unmodified and modified Kevlar composites under the same processing parameter (2) have displayed in (Figure 7(a–f)), where changes in LCP morphology with the addition of unmodified and modified Kevlar fiber can be clearly observed and also skin/core morphology has also been observed, which is very common in PC/LCP systems.[32,33] This is the product of the ‘‘fountain flow’’ at the flow front and shear flow near the walls of the die. (Figure 7a) shows the LCP fibrillation at skin region in bundle form in presence of unmodified Kevlar fiber (Series I2) but not in oriented fashion but in core region (Figure 7b), the fibrillation of LCP fibers are more prominent and appears in more oriented manner supporting the orientation tensor value obtained from mold flow simulation study although the Kevlar fibers are covered by the matrix. In case fluorinated Kevlar reinforced composites (Series J2, Figure 7c) in the core area the LCP fibrils are more prominent and distributed through out the matrix phase but appeared as bundle form but in more oriented manner in comparison to the unmodified derivative. In the core

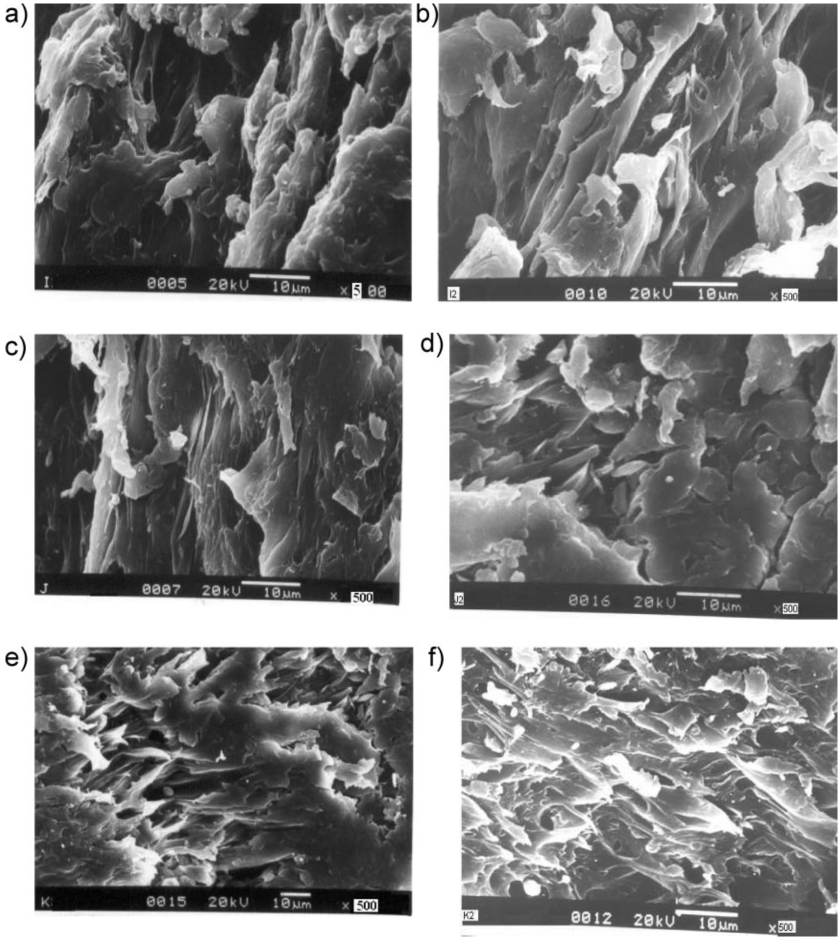

Figure 7.
a) SEM picture of PC/LCP/unmodified Kevlar (I2) in skin region, b) SEM picture of PC/LCP/unmodified Kevlar (I2) in core region, c) SEM picture of PC/LCP/fluorinated Kevlar (J2) in skin region, d) SEM picture of PC/LCP/fluorinated Kevlar (J2) in core region, e) SEM picture of PC/LCP/oxy-fluorinated Kevlar (K2) in skin region, and f) SEM picture of PC/LCP/oxy-fluorinated Kevlar (K2) in core region.

region Figure 7d exhibits the more orientated LCP fibrils in the flow direction which suggests the greater orientation tensor as evidenced from Table 4 by mold flow simulation study. On the other hand oxy-fluorinated derivative (K2, Figure 7e and f) exhibit fine micro fibrils are homogeneously dispersed all over the PC matrix phase in the skin as well as in the core region. But in the core region the micro fibrils are far more oriented in comparison to that of the skin region again corroborating the results obtained from the mold flow simulation study (Table 4). The SEM images also support the better thermal, dynamic mechanical properties of the composites.

Conclusions

Properties and simulation of fiber orientation of injection molded PC/LCP/unmodified and fluorinated and oxy-fluorinated Kevlar composites have been extensively studied. Fluorinated and oxy-fluorinated Kevlar reinforced composites exhibit better thermal, dynamic mechanical and crystalline properties in comparison to the unmodified one. The aforementioned studies were carried out under one specific injection parameter. However, simulation of fiber orientation of PC/LCP/unmodified and modified Kevlar composites was investigated under different processing parameters using mold flow simulation study. Distinct skin-core pattern has been observed and the fiber orientation pattern in these regions is different from each other. The orientation of LCP fibrils is also different under different processing parameters in both skin and core region. The orientation of LCP fibrils is not uniform throughout the matrix phase. The SEM images also corroborate the results obtained from mold flow simulation technique.

[1] J. K. Kim, W. Y. Mai, "Structure and Properties in Composites", VCH Publishers, Germany **1993**, p. 239.

[2] P. Olszynski, M. Kozlowski, A. Kozlowska, *Mat. Res. Innovat* **2002**, *6*, 1.

[3] Q. W. Xu, H. C. Man, W. S. Lau, *J. Mater. Process. Techn.* **1997**, *63*, 519.

[4] Y. Son, R. A. Weiss, *J. of Appl. Polym. Sci.* **2003**, *87*, 564.

[5] Y. C. Lam, C. Y. Yue, Y. X. Yang, K. C. Tam, X. Hu, *J. of Appl. Polym. Sci.* **2003**, *87*, 258.

[6] M. Akay, D. Barkley, *J. Mater. Sci.* **1991**, *26*, 2731.

[7] S. Y. Fu, B. Lauke, E. Mäder, C. Y. Yue, X. Hu, *J. Mater. Proc. Technol.* **1999**, *89*, 501.

[8] S. E. Barbosa, J. M. Kenny, *J. Reinforced Plast. Compos.* **1999**, *18*, 413.

[9] P. Singh, M. R. Kamal, *Polym. Compos 989*(10), 344.

[10] A. Larsen, *Polym. Compos.* **2000**, *21*, 51.

[11] J. C. Malzahn, J. M. Schultz, *Compos. Sci. Technol.* **1986**, *25*, 187.

[12] M. Gupta, K. K. Wang, *Polym. Compos.* **1993**, *14*, 367.

[13] S. N. Huang, K. K. Tan, T. H. Lee, *ISA Trans.* **1999**, *38*, 361.

[14] Y. Yang, F. Gao, *Contr. Eng. Pratice* **2000**, *8*, 1285.

[15] K.-H. Han, Y.-T. Im, *Composite Struct.* **1997**, *38*, 179.

[16] D.-S. Choi, Y.-T. Im, *Composites Struct.* **1999**, *47*, 655.

[17] K. Banik, G. Mennig, *Mechanics of Time-Dependent Materials* **2006**, *9*, 247.

[18] Na Bing, Y. Wang, R. Du, Q. Fu, Y. Men, *J. of Polym. Sci., Part B: Polym. Phys.* **2004**, *42*, 1831.

[19] D. H. Chung, T. H. Kwon, *J. Non-Newtonian Fluid. Mech* **2002**, *107*, 67.

[20] D. H. Chung, T. H. Kwon, *Korea-Australia Rheology Journal* **2002**, *14*, 175.

[21] Y. H. Lee, S. W. Lee, J. R. Youn, K. Chung, T. J. Kang, *Mat Res Innovat* **2002**, *6*, 65.

[22] S. Patcharaphun, G. Mennig, *Polym. Compos.* **2005**, *26*, 823.

[23] W. Akkaoui, G. Bayram, *J. Reinf. Plast. and Compos* **2004**, *23*, 881.

[24] Q. Lin, A. F. Yee, *J. Mater. Sci.* **1997**, *32*, 3961.

[25] E. Shivakumar, S. B. Yadaw, K. N. Pandey, C. K. Das, *J. Appl. Polym. Sci.* **2006**, *100*, 3904.

[26] M. Mukherjee, C. K. Das, A. P. Kharitonov, K. Banik, G. Mennig, T. N. Chung, *Materials Science and Engineering A* **2006**, *441*, 206.

[27] A. K. Saha, S. Das, D. Bhatta, B. C. Mitra, *J. Appl. Polym. Sci.* **1999**, *71*, 1505.

[28] T. Das, S. Alam, A. K. Banthia, B. Adhikari, *Binary, PolymerPolym-Plast. Tech. Enging* **2006**, *45*, 1047.

[29] K. P. Menard, *Dynamic Mechanical Analysis: A practical Introduction*, CRC press, New York **1999**, 100.

[30] J. Vlachopoulos, D. Strutt, *Material Science Technology* **2003**, *19*, 1153.

[31] S. G. Advani, C. L. Tucker, III, **1990**, *34*, 367.

[32] D. Beery, S. Kenig, A. Siegmann, M. Narkis, *Polym. Eng. Sci.* **1993**, *33*, 1548.

[33] X. Hu, Q. Lin, A. F. Yee, D., *J. Microsc-Oxf* **1997**, *185*, 109.