SCREW ELEMENT CHARACTERIZATION IN AN IN-LINE LFT-D PROCESS

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Abstract

Studies have been done on three different elements (mixing element and kneading blocks) to determine their influence on fibre length and wetting properties during an in-line direct compounding process using glass fibre with PP at a nearly constant specific output. Effects of individual elements could be ascertained by using only 6D length of the barrel. At 30wt% loading, the screw element geometry plays a dominant role in fibre length distribution. At 50wt% loading, fibre length is influenced mainly by the screw speed. SEM analysis results of the samples are provided. Characterization of the individual type of elements can be used as guidelines in future application.

Introduction

The mechanical properties of fibre reinforced polymers are mainly influenced by the length of the reinforcing fibre. This is the reason Long Fibre reinforced Thermoplastics (LFT's) are recently in the focus of the automobile industry. Enhanced mechanical properties together with a high light-weight potential (low specific density) allow the replacement of metal parts in semistructural applications [1]. Market analyses confirm this trend to LFT applications. Up to 18% global growth is expected between 2004 and 2009. Polypropylene (PP) based applications dominating the LFT market with around 65% share. This dominance is driven by improved production economics and decreasing compound prices [1]. But there is still a potential to improve this technique especially regarding special tailored product specification for a particular application.

Common LFT processes contain two steps. First the manufacturing of a long fibre reinforced semi-finished product (LFT pellets, GMT). Second the final processing of these semi-finished products either by injection molding (LFT pellets) or compression molding (LFT pellets and GMT). This two-stage process has the disadvantages of a dependence on material suppliers, which leads to higher costs, and a degradation of the mechanical properties because of two heating periods [2]. To eliminate this second step, different processes were developed. C.P.I. (Composites Products, Inc.) introduced a process with two extruders (melting and mixing) using continuous fibre rovings were impregnated and broken up to discrete lengths in a side feeder and then introduced
into a compounding extruder. The direct in-line LFT (LFT-D-ILC) process was developed by Fraunhofer Institut für Chemische Technologie and Dieffenbacher GmbH. Continuous fibre rovings are directly introduced into the molten polymer matrix. In all these processes, the extrudate is immediately further processed. This single step process saves cost and offers a wide customized material spectrum [2] [3].

Adding fibre with higher initial lengths to a compounding process is a prerequisite in the case of LFT process. However, it does not inevitably lead to enhancement in mechanical properties. The processing condition plays an important role for the resulting fibre lengths in the final part. During the compounding process different fibre attrition mechanisms occur and lead to a specific fibre length distribution [4]. Also the fibre separation and wetting are important factors to achieve better mechanical properties. In this paper the influence of screw elements is analyzed for various process conditions. The goal is to understand the operating breaking mechanisms to predict the resulting fibrous structure. Afterward processors should be able to adjust the LFT-D process so that the final product shows the required specifications.

Experimental

Materials

Polypropylene matrix (REPOL H110MA) and 2% of a coupling agent (OPTIM P-403) was dry blended and introduced to the compounding process in the usual way by the main feeder. The reinforcing fibre was a continuous E-glass rovings (Vetrotex RO99 P319) specially designed for LFT processes with polypropylene matrix. They were preheated and introduced into the molten phase of the matrix polymer.

Process setup

The compounding of the LFT composite was done with a high-flight depth STEER OMega40 co rotating twin-screw extruder. The matrix polypropylene was melted in the normal manner (220 ˚C melt temperature) and then continuous glass fibre rovings were introduced into the devolatising vent at 6D from the die end. This short compounding distance enables to ascertain the effects of individual elements. For the trials the last 6D of the screw configuration varies only in one element: one mixing element (SME), one bi-lobed kneading block (RKB) and one tri-lobed eccentric kneading block (3KB). *(Figure 1)*. For each of the three different screw configurations, the screw speed (100 RPM, 200 RPM and 500 RPM) and the fibre content (30 wt% and 50 wt%) were varied.

A rectangular shaped composite extrudate was immediately further processed by compression molding using a positive mould and a hydraulic 25t press. Specimens of 150x100x4 mm were produced for the further analysis.

Analysis

The SEM analysis of the fibrous structure was done to determine the fibre length distribution for each process condition. Also SEM images of the specimen surfaces were investigated.

The analysis of the fibre length requires the separation of the fibres from the matrix and the preparation of the 3-D structure to a one-dimensional layer for an easy counting procedure. The matrix-fibre separation was done by burning away the Polymer (as per DIN EN ISO 1172). Long fibre materials show a wide range of length. This leads to an insufficient analysis because of the fact that short fibres are detected with low accuracy in macroscopic image ranges whereas long fibres exceed the borders of microscopic image ranges. Therefore it is necessary to split this length spectrum into smaller ranges. This was done by sieving a representative sample of the fibrous structure into four length fractions. This was done dry with a common laboratory sieves and an ultrasonic device. Additional fibre breakage during the sieving process was not noticed. The percentage of weight *j g* of each fraction was measured.

The length of 120 fibres of each fraction was measured and converted to relative frequencies *i h* . The number weighted *Ni h* and the volume weighted *Vi h* frequencies were determined:

$$h_{N_i} = \sum_j g_j \cdot \frac{N_{ij}}{\sum_i N_{ij}} \qquad (1)$$

$$h_{V_i} = \frac{L_i \cdot h_{N_i}}{\sum_i L_i \cdot h_{N_i}} \qquad (2)$$

These distributions have a qualitative character. For a quantitative analysis the average fibre lengths *N L* (number weighted) and *V L* (volume weighted) can be calculated:

$$\overline{L}_N = \sum_i h_{N_i} \cdot L_i \qquad (3)$$

$$\overline{L}_V = \frac{\sum_i L_i \cdot h_{V_i}}{\sum_i h_{V_i}} \qquad (4)$$

Irregularities in the fibrous structure, e.g. fibre bundles, were detected by using x-ray and transmitting light images of the specimens. These irregularities were analyzed by cross sectional SEM image analysis to determine whether the fibres are completely wetted or not.

Results

The fibrous structure was analyzed to characterize and compare the effects of different screw elements during a LFT-D compounding process. It was found that at the two fibre loadings tested the comparison between the elements shows a different characteristic. For 30 wt% fibre loading, the highest average fibre length is obtained with SME and the shortest with RKB. This was found for all processed screw speeds (*Figure 2*). Such a clear trend was not found for 50 wt% fibre loading. For 100 RPM the SME element shows the highest fibre length while RKB and 3KB are at the same level. For 200 and 500 RPM RKB shows the highest length and SME and 3KB are at the same level (*Figure 3*). Apart from the influence of the element type another effect was noticed. The screw speed plays an important role in the case of 50 wt% but not with 30 wt%. With 50 wt% the average fibre length increases with increasing the screw speed.

To understand these variations of the average fibre length the fibre length distribution was analyzed. Different fibre breakage mechanisms cause specific breaking lengths [4]. In the case of LFT-D only a two-phase state exists. The preheating of the fibre rovings prevents the solidification of the polymer (that would represent a third phase) through a decreased temperature. In this case mainly two fibre breakage mechanisms occur. The leakage flow between the screw flight and the barrel generate very high shear rates and leads mainly to short fibres (*Figure 4 M3*). The parameters for this mechanism are the geometry of the gap and the value of the leakage flow. The other mechanism is the breakage through bending while circulating in the melt pool (*Figure 4* M6). This leads to middle length fibres. The influencing parameters are shear stress and residence time [4]. The short fibre (*L mm i* £ 1) and the middle length fibre range (*mm L mm i* 1 < < 7) of the length spectrum were examined by determining the respective frequencies *V* 1-5 *h* (short) and *V* 6-34 *h* (middle).

In the case of 30 wt% the SME element shows significant less short fibre in comparison to the kneading blocks. The comparison of the kneading blocks shows more short fibre for the RKB element (*Figure 5*). The same was found for the middle length fibre fraction. The increased volume of short fibre when using kneading blocks is due to the effect of forcing the material through the narrow gaps between the kneading discs and the barrel wall. The tri-lobed kneading block has smaller tip angles than the bi-lobed. This leads to decreased shear rates that can prevent the fibre attrition. A reason for lower fibre attrition with the SME element could be the provision of additional channels that provides a convolute flow path without much circulation.

With 50 wt% fibre loading no consistent trend for the influence of the elements was found for the short fibre range (*Figure 6*). The middle fibre range shows for 100 RPM, less volume of fibre with the SME element. For 200 and 500 RPM, the RKB element generates less volume of fibre in comparison to the other elements (*Figure 7*). It seams that for 50 wt% the fibre-fibre-interactions are dominating over the mechanisms induced through the screw elements. The short fibre fraction shows for 100 RPM significant more fibre compared to the other screw speeds and with 500 RPM there are little less short fibre than with 200 RPM (*Figure 6*). The residence time, an important factor for the degree of attrition through fibrefibre- interactions, seems to have a greater influence than the shear rates and stresses induced by the element geometry. In this experimental setup, the screw speed is an indicator for the residence time of the extrudate since the same number of glass rovings were used and the matrix input was adjusted as required leading to nearly constant specific output (output/speed). The degree of fill in the channel was 100% for all elements.

The examination of the cross sectional specimens surfaces show for 30 wt% fibre loading a good separation and wetting of the fibre (*Figure 8*). The wetting of fibre bundles depends on the size of the bundle. Great bundles are very badly wetted (*Figure 9*) and smaller fibre bundles are partially wetted (*Figure 10*). The SME element shows more relatively great fibre bundles compared with the kneading blocks. This could be an effect of the additional channels provided by the SME element that allows the bundles to flow in convolute path without shear peaks. The 50 wt% fibre loading specimens show no fibre bundles. The massive fibre-fibre-interactions break up all agglomerations. But different wetted areas can be found (*Figure 11, Figure 12*). With decreasing screw speed areas with compact fibre arrangements increase.

Discussion

The ideal fibrous structure of a fibre filled extrudate is characterized by high fibre lengths and a uniform distribution of the fibre (completely wetted). The complete separation of the fibre bundles is absolute necessary in the case of further processing without much material flow, e.g. compression molding. The results show a sufficient fibre length for all elements and process conditions, i.e. the average fibre length easily exceed the critical fibre length in the case of proper wetting. Screw mixing elements (SME) avoid much short fibre. But also improved geometries of kneading blocks (decreased tip angle) leads to less fibre breakage. To determine the influence of the elements for higher fibre loadings it is necessary to exclude the residence time factor by provide a constant output.

The effect of the fibre bundles found with 30 wt% fibre loading has to be investigated. Even the existence of just a few fibre bundles that are not wetted can lead to considerable reduction in mechanical properties. With 50 wt% loading the fibre rovings are completely broken up. But the structure of areas with different degrees of fibre wetting can lead to non-uniform mechanical properties. Therefore it is necessary to improve the distributive mixing action of the extruder.

Conclusions

Effects of different screw elements could be found especially in the case of 30 wt% fibre loading. With 50 wt% loading no characterization was possible because of heavy fibre-fibre interaction that was strongly influenced by the screw speed (residence time). The SME element shows the longest fibre length due to avoidance of high shear peaks. The Tri-lobed kneading block with smaller tip angles (less shear) shows larger volume of long fibre than the bi-lobed kneading block. The wetting of the 30 wt% samples is sufficient but fibre bundles were found. The SME element shows more bundles compared with the kneading blocks. In the case of 50 wt% samples, the fibre-fibre interaction completely break up the fibre roving but wetting is insufficient.

References

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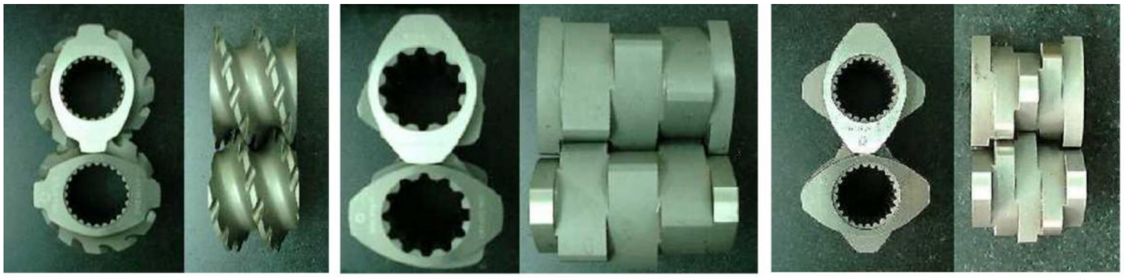

Screw Mixing Element (SME) **Eccentric Tri-lobed Kneading (3KB)** **Right handed Kneading (RKB)**

Figure 1. Pictures of SME, 3KB and RKB Elements

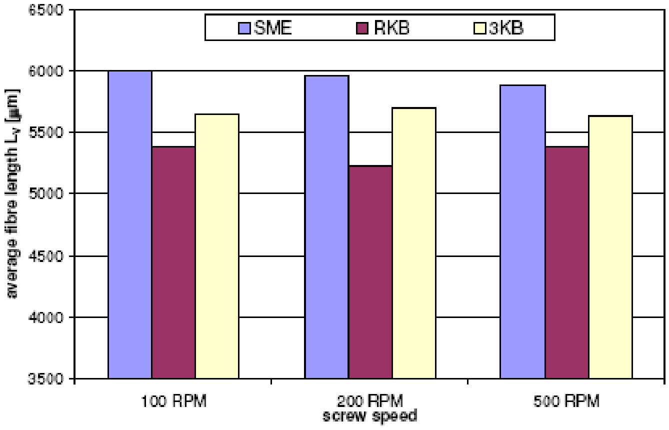

Figure 2. Comparison of average fibre lengths of 30 wt% specimens

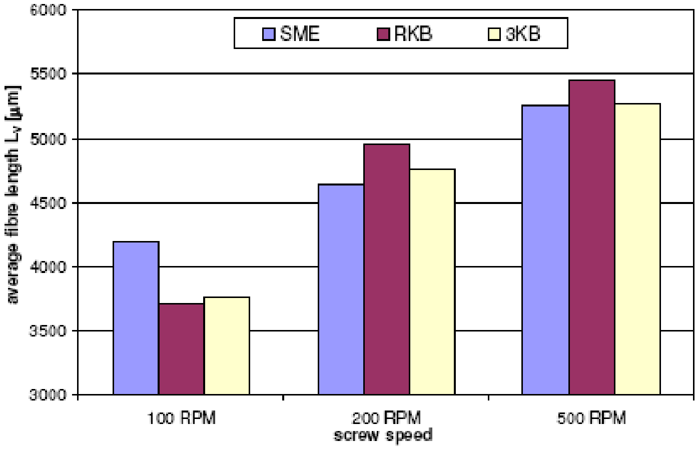

Figure 3. Comparison of average fibre lengths of 50 wt% specimens

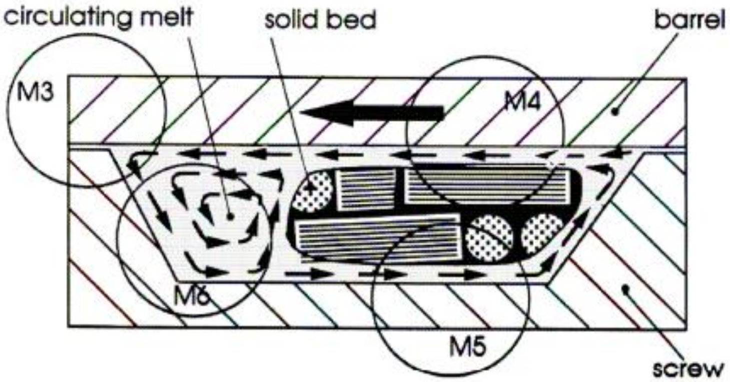

Figure 4. Fibre breakage mechanisms in a screw channel [4]

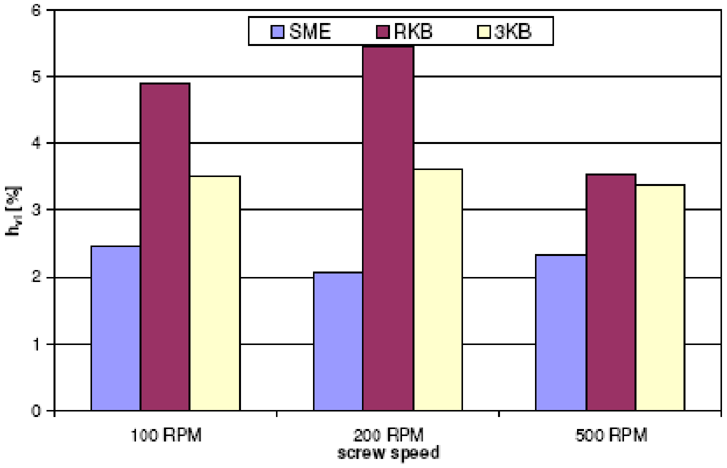

Figure 5. Frequencies of short fibre for 30 wt% specimens

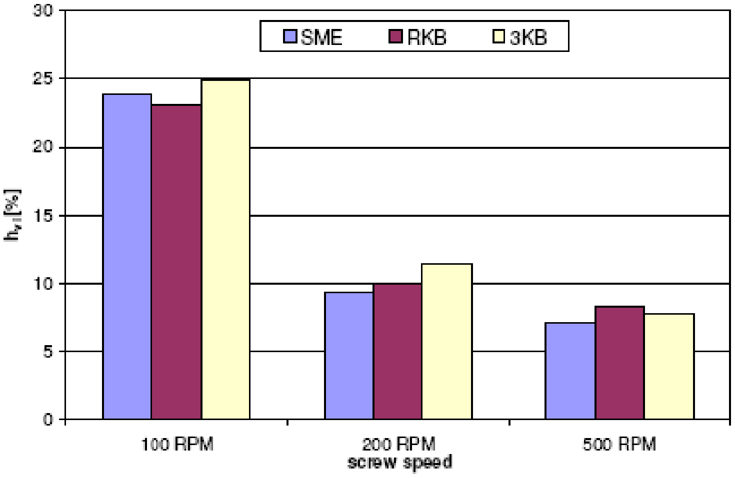

Figure 6. Frequencies of short fibre for 50 wt% specimens

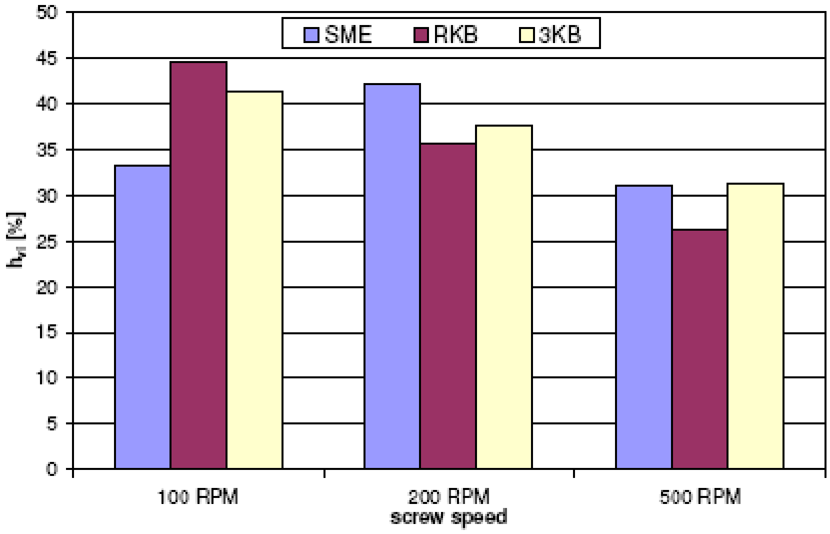

Figure 7. Frequencies of middle length fibre for 50 wt% specimens

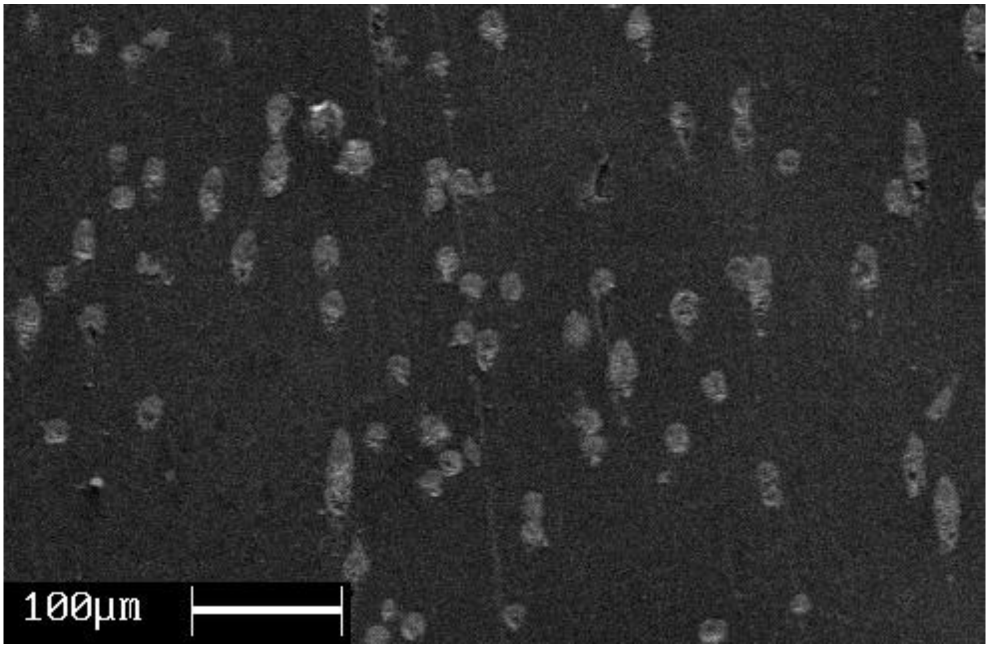

Figure 8. Cross-sectional SEM image of 30 wt% specimen

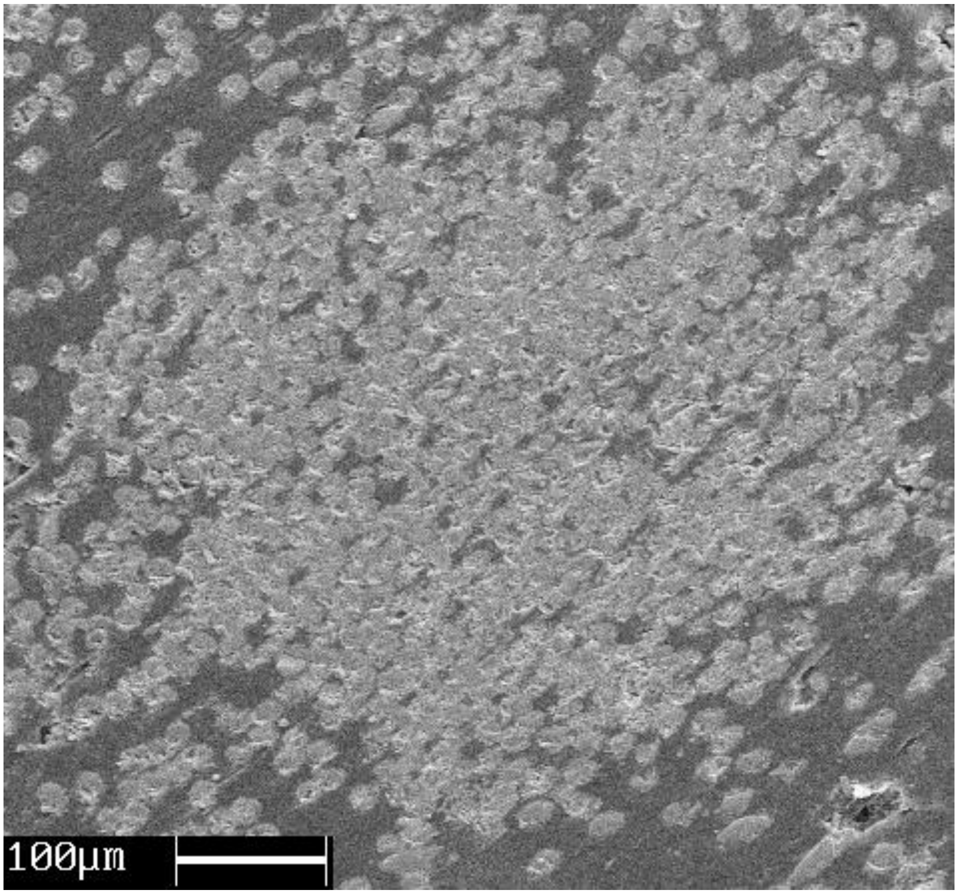

Figure 9. Cross-sectional SEM image of a great fibre bundle of a 30 wt% specimen

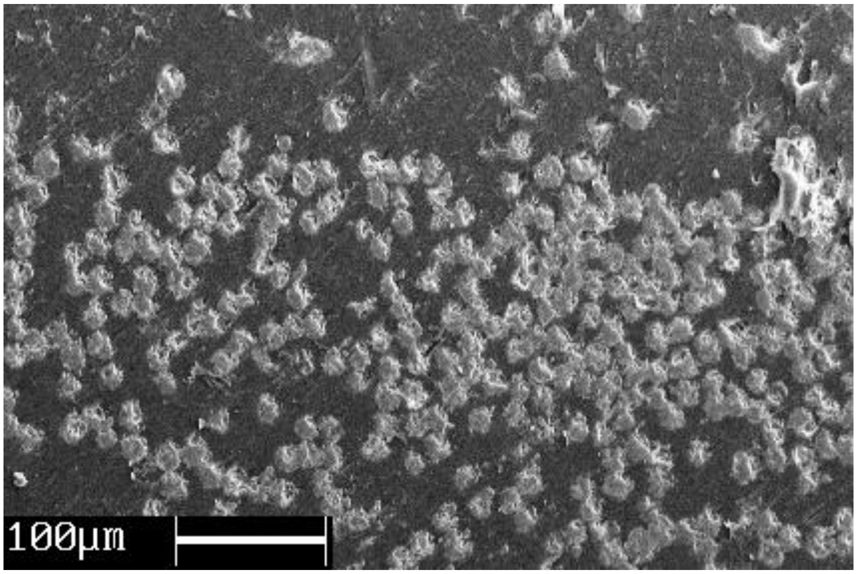

Figure 10. Cross-sectional SEM image of a small fibre bundle of a 30 wt% specimen

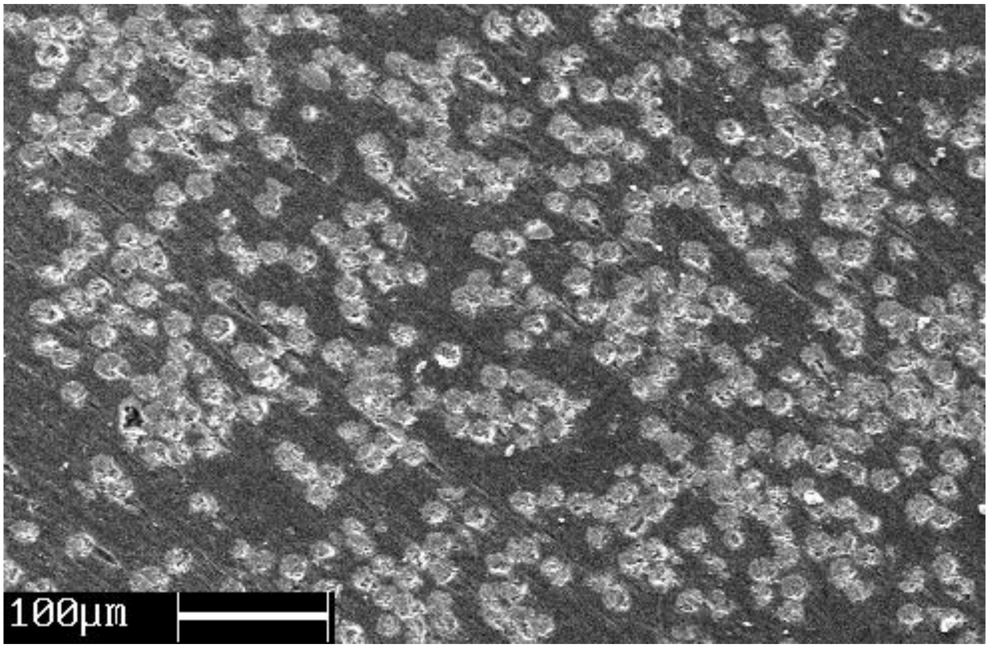

Figure 11. Cross-sectional SEM image of a compact fibre arrangement of a 50 wt% specimen

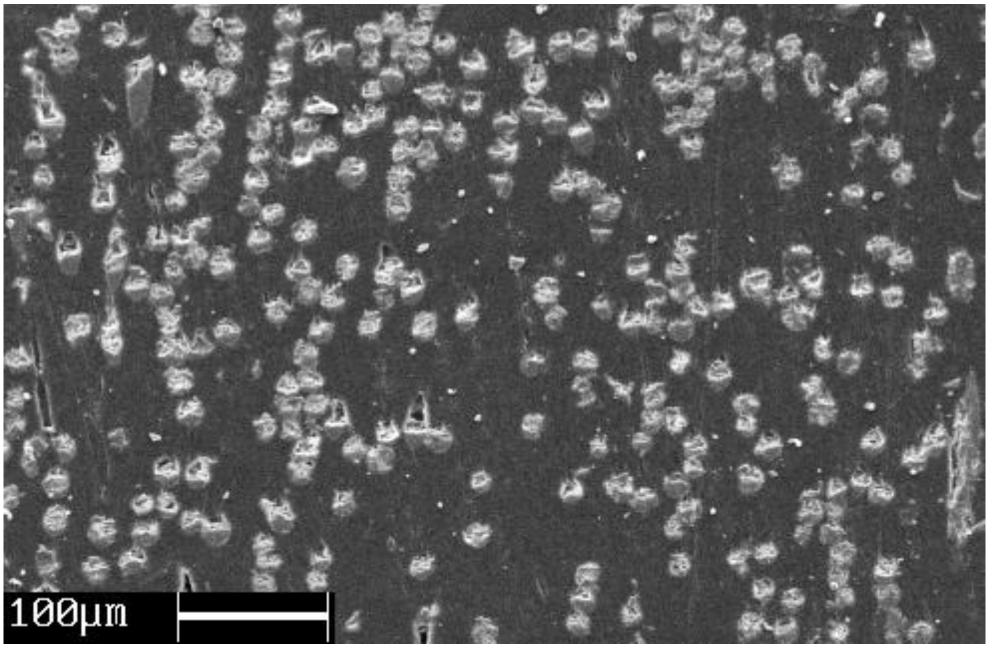

Figure 12. Cross-sectional SEM image of a less compact fibre arrangement of a 50 wt% specimen

Key Words: LFT-D, Long Fibre technology, Element Characterization, Compounding.