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A review of Long fibre-reinforced thermoplastic or long fibre thermoplastic (LFT) composites

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ABSTRACT

Long fibre-reinforced thermoplastic or long fibre thermoplastic (LFT) composites possess superior specific modulus and strength, excellent impact resistance, and other advantages such as ease of processability, recyclability, and excellent corrosion resistance. These advantages make LFT composites one of the most advanced lightweight engineering materials and enable their increasing use in various applications. This review paper summarises the research and development work that has been conducted on LFT composites since their initial development. Different aspects of LFTs, such as process development, fibre orientation distribution (FOD), fibre length distribution (FLD), and their effects on the mechanical properties of LFT composites are described. The characterisation of the FOD and FLD in the LFT composites using advanced imaging technology such as high-resolution 3D micro-CT scanning technique is summarised. Research and development of LFT hybridisation and LFT additives are also discussed. Finally, conclusions are made and the future outlook of LFT composites is given.

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KEYWORDS

Long fibre thermoplastics; composites; properties; fibre orientation distribution; fibre length distribution

Introduction

Long fibre-reinforced thermoplastics (LFT) are composite materials comprised of the thermoplastic polymer matrix and discontinuous reinforcement fibres with a length to a diameter aspect ratio greater than the critical aspect ratio. These composites have been widely used in various applications as a result of their superior mechanical properties, excellent processability, low density, recyclability, low cost, excellent corrosion resistance, good vibration damping, and infinite shelf life. Compared to short fibre-reinforced thermoplastic or short fibre thermoplastic (SFT) composites, LFTs offer better mechanical properties [1–16], which, in conjunction with their ease of processability, have enabled their use as advanced lightweight engineering materials, particularly within the automotive sector. As a result, LFT production has experienced rapid growth since year 2000. The global market grew from 108 to 245 million kg from 2004 to 2009 with an annual growth rate of 18% [17]. A market survey published in Jan 2017 estimated that the LFT global market will grow from USD 3.28 billion to USD 5.55 billion by 2022 at an annual growth rate of 9.29% [18]. The increasing use of LFTs in the automotive and electrical and electronics industries is expected to drive the growth of the LFT market [18].

Various thermoplastic polymers have been used as LFT matrices, ranging from commodity polymers to

high-performance engineering polymers. The thermoplastic polymers used in LFT include polypropylene (PP) [19–24], high-density polyethylene (HDPE) [25,26], nylon 6 or polyamide 6 (PA6) [27–29], nylon 66 or polyamide 66 (PA66) [5,6,30], polylactic acid (PLA) [31], polymethylmethacrylate (PMMA) [32], poly butylene terephthalate (PBT) [33], polyethylene terephthalate (PET) [34], thermoplastic polyurethane (TPU) [35], polyoxymethylene (POM) [36,37], polyphynelenesulfide (PPS) [38–41], polyaryletherketone (PAEK) [42], and polyetherketoneetherketoneketone (PEEKEK) [43]. It is estimated that 65% of the LFT market is polypropylene-based. Polyamide-based LFTs have about 20% of the market share and LFTs with other polymer systems comprise the remaining 15% [17]. Though single polymer systems are most commonly used as the matrix in LFTs, multiple polymer systems have also been studied such as TPU + POM [44], PP + polystyrene (PS) [45], TPU + acrylonitrile butadiene styrene (ABS) [46], PBT + PET [47,48], polycarbonate + PBT [49], TPU + styrene acrylonitrile (SAN) [50], PA66 + PP [51,52], PP + PBT [53], and polyvinyl chloride (PVC)+PP [54]. LFTs with multi-matrix systems can gain the benefit of both the matrix polymers. For example, LFTs with a PP + PA66 matrix can benefit from the low water absorption and excellent

processing properties of PP and the high mechanical strength and temperature resistance of PA66 [51].

Glass fibre is predominantly used as the reinforcement material in LFT composites due to its low cost and superior mechanical properties. The most studied LFT is glass fibre-reinforced polypropylene (glass/PP) [14,20,22,54–63], driven by its popularity in the automotive industry. Other fibres such as carbon fibre [27,29,35,39,64], basalt fibre [37,65,66], aramid fibre [67,68], PP fibre [69], polyimide fibre [33], and PET fibre [70] are also used as reinforcement. Although natural fibre-reinforced polymer matrix composites have not been traditionally considered to be LFTs, an increasing number of composites reinforced with long natural fibres have been developed and studied [71]. Long natural fibre composites include chicken feather fibre/PLA [72], keratin feather fibre/polyethylene [73], flax fibre/PP [74,75], viscose fibre/PP [76], sisal fibre/PP [77], pita fibre/polyhydroxybutyrate [78], rayon fibre/PP [79], hemp fibre/PP [80], and jute fibre/PLA [31,81]. In addition, more than one type of fibre reinforcement may be used within a single LFT. For example, Lee [82] used both glass and carbon fibres in a PP matrix LFT composite to study the electrical percolation and the hybrid effect of multiple fibre types. It was found that the percolation threshold point is between the loading of 6 and 10 vol.-% carbon fibre. As the loading of carbon fibres increases, the modulus increases while the strength reduces [82]. Wood pulp fibres have been added to jute/PP LFT as an impact modifier to achieve higher impact performance [83–85]. Synthetic fibres are also used with natural fibres together in LFTs [86,87]. The synthetic fibres offer superior mechanical properties, while the natural fibres can provide recyclability and sustainability. The incorporation of 10% glass fibres into a jute fibre LFT was found to improve the flexural and tensile strength of jute fibre-reinforced PP composites by about 60–74% and impact strength by almost one magnitude [87].

Although the fibres used as reinforcement in LFTs are discontinuous, these composites possess excellent mechanical properties owing to high fibre length to diameter ratio or fibre aspect ratio which are higher than the critical fibre aspect ratio. The critical fibre aspect ratio, $(l/d)_c$, is defined as Equation (1) [1].

$$\left(\frac{l}{d}\right)_c = \frac{\sigma_{fu}}{2\tau} \quad (1)$$

where l is the fibre length, d is fibre diameter, σ_{fu} is the ultimate tensile strength of the fibre, and τ is the interfacial bonding strength between the fibre and the matrix [1]. Figure 1 shows the effect of fibre aspect ratio on the stress state of a single fibre [1]. It should be noted that if the fibre aspect ratio is greater than $(l/d)_c$, the maximum fibre stress may reach its ultimate

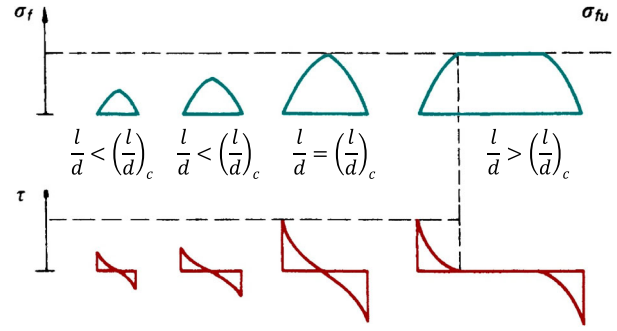


Figure 1. The change of the fibre tensile stress, σ and interfacial shear stress, τ with fibre aspect ratio, (l/d) . The fibres in LFT composites have the aspect ratio equal to or greater than $(l/d)_c$, critical aspect ratio [1].

tensile strength. LFTs generally have a fibre aspect ratio equal to or greater than $(l/d)_c$, and therefore, the fibres are used to their maximum capacity. When the fibre aspect ratio is below $(l/d)_c$, as in SFTs, the maximum stress on the fibre is below the fibre tensile strength and fibre pullout is expected to occur, indicating that the fibres are not used to their maximum capacity. Consequently, SFTs generally exhibit lower mechanical properties than LFTs.

If the values for the fibre diameter, interfacial bonding strength, and fibre tensile strength are known, the critical fibre length may be determined and the critical fibre aspect ratio can be calculated. For instance, the critical fibre length for kenaf fibres in a PP matrix was calculated to be 2.4 mm for a fibre tensile strength of 374.5 MPa, fibre-matrix interfacial shear strength of 4.9 MPa, and an average diameter of the kenaf elementary fibres of 62.2 μm [88]. The critical fibre aspect ratio is approximately 39. The critical fibre length and critical fibre aspect ratio can be different if the same fibre is used in a different polymer matrix due to changes in the interfacial bond strength. For example, the critical fibre length in glass/PP LFTs is between 3.2 and 4.4 mm [89,90], whereas the critical fibre length for glass/PA66 is about 1.24 mm [91], which results in a critical fibre aspect ratio of approximately 213–293 for the glass/PP LFT and 83 for the glass/PA66 LFT, respectively. Surface treatment on the fibres or the addition of coupling agents in the matrix may result in different critical fibre lengths and critical fibre aspect ratios because of their influence on the fibre/matrix interfacial bond strength [92]. For a given matrix and fibre (i.e. fixed diameter), we can use just critical fibre length.

Fibre length is one of the main parameters that determines the properties and processability of LFT composites. With increasing fibre length, mechanical properties, such as strength, modulus, impact resistance [16,40,47,93], and wear resistance [94] increase. However, processing of the composites becomes increasingly difficult as shown in Figure 2 [1,14,95]. The shaded area in Figure 2 approximately shows the

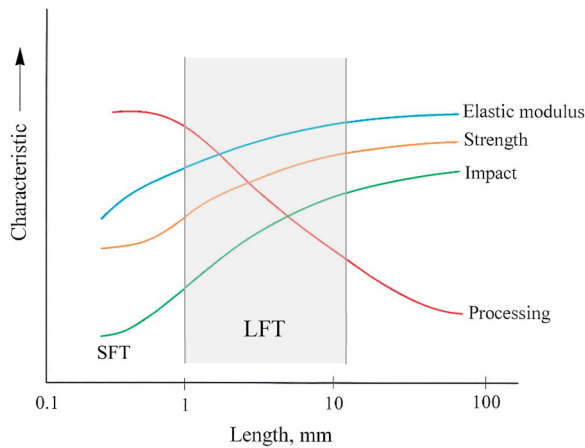


Figure 2. The effect of fibre length on the mechanical properties and processability [1,14,95]. The shaded area approximately shows the typical range of fibre length in carbon fibre and glass fibre LFT (long fibre thermoplastic) composites, which possess both great processability and superior mechanical properties. SFT (short fibre thermoplastic) composites have a fibre length less than LFT.

typical range of fibre length in carbon fibre or glass fibre LFT composites. It should be noticed that the composites with this range of fibre length possess both great processability and superior mechanical properties.

Increasingly rigorous requirements and governmental regulations on gas mileage, such as the Corporate Average Fuel Economy (CAFÉ) standard, have continuously pushed the use of lightweight materials such as LFT composites in automobiles. Since the first papers related to LFTs were published in the 1970s and late 1980s [5,6,53,96–101], they have been quickly adopted by the automotive industry. It was estimated that 80% of the volume of LFTs are used in automotive applications in America and Europe [102]. In 2010, composites accounted for approximately 7% of a vehicle's weight, a number that is predicted to reach 20% by 2035 [103]. As an important member of the composite family that offers both processability

and superior properties, LFTs are expected to see continuously increasing use in automobiles and the automotive industry will remain the prime consumer of LFTs over the next 20 years. LFTs have been used mainly secondary structural automotive components such as front end modules [17,102,104–110], underbody panels [105,107,110,111], trunk lids [105], hatchbacks [102,107], seat components [17,102,105,107,110,112,113], door components [17,102,105,107,110,114,115], instrument panel carriers [17,102,104,105,107], spare-wheel pans [102,105,107], bumper beams [102,105,107,110,116,117], roof modules [107], leaf springs [118,119], brake pads [120], engine hoods [121], battery trays [121], wheels [122], and sound absorbing shells [105,107]. Figure 3 shows some of the typical automotive components made using LFTs [102].

LFTs have also found use in other fields such as transportation [123–126], medical devices [43,127–129], military [39,130–132], sports equipment such as surf boards [99] and sail boats [133], laptop computer housings [134], safety equipment such as fire extinguishers [135], dumpster covers [134], gears [136], and oil and gas drilling components such as bushings [134], buoyancy collars and hardware [137–139]. Some of those unconventional applications require the LFT material endure extremely high pressure [131,135,137–139], highly corrosive media [99,133,134,137–139], and even exceptionally elevated temperature despite for a short period of time [131]. LFT composites have demonstrated their success in meeting these significant criterions. Those successful application cases indicate that LFT composites have great potential for more unconventional applications with extreme conditions.

Since the 1990s, a large amount of research has been conducted to study the relationships among processing, structure and final properties of LFT composites. Fibre orientation distribution (FOD) and fibre length distribution (FLD) have been studied under different processing conditions and LFT processing has been tremendously improved. Over time, significant

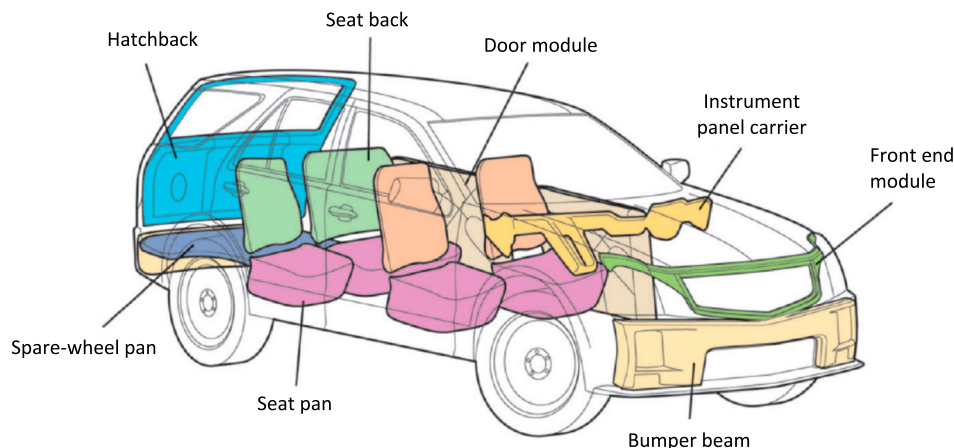


Figure 3. Typical automotive components made of LFT composites [102].

characterisation of a wide range of material properties, including quasi-static mechanical behaviour (tensile, flexural, and compressive loading), dynamic performance (fatigue, impact toughness, and vibration damping), and other properties such as fire resistance, wear resistance, and UV resistance have been investigated. Models have been developed and validated to predict the fibre orientation and length distribution in moulding processes and the resultant bulk properties. The paper summarises the progress of the research and development work of LFT composites and offers the future outlook of the LFT composite.

Process development

It is well known that thermoplastic polymers, even when melted, have a much higher viscosity than thermoset polymers. Their high viscosity makes it challenging to impregnate fibres and mould the final product in a one-step process. Instead, an intermediate form, generally pre-impregnated pellets, is produced before the final product is manufactured using compression moulding or injection moulding. The production of LFT pellets is normally done via a process called hot melt impregnation; it starts by pulling continuous fibre tows through an impregnation die supplied with the molten thermoplastic polymer. Once the fibre tows are impregnated into the molten polymer, the material is drawn into a rod, cooled, and cut into pellets of a specific length. Figure 4 shows a schematic of the hot melt impregnation process for producing LFT pellets.

Hartness et al. [140] reported the details of LFT pellet production using the hot melt impregnation process through pultrusion or Direct Reinforcement Fabrication Technology (DRIFT). In this case, the impregnation line is comprised of a fibre creel with a tension control, a fibre heating oven, an impregnation

die which is fed polymer by a standard extrusion machine, a chiller to cool the prepreg, a puller that controls the line speed, and a chopper that chops the continuous rod into pellets with desired lengths, typically 6–25 mm (0.25–1"). Glass contents in the pellets from 10 to 70% (by weight) have been demonstrated with a control of $\pm 2\%$ [140]. It was found that the fibres have good wetout with PP matrix using this method. This process is a typical impregnation process that has been used to produce LFT pellets by many research groups [49,104,105,141–147]. Other pellet production processes include commingling [70], powder impregnation techniques [107,148], solid-state polymerisation [149], wire coating [136], and cross-head extrusion [107].

Other similar manufacturing processes, such as direct strand deposition [150], have been developed to produce LFT charges using a single-screw extruder directly from dry fibres and thermoplastic polymer. The direct strand deposition process skips the pre-impregnation step and directly blends melted thermoplastic polymer with chopped dry fibre strands using a single-screw extruder, normally resulting in longer fibres than a twin screw extruder [45]. The process completely relies on the single-screw plastication for both fibre impregnation and dispersion. It was suggested that chopped strands in bundles of 100–300 individual filaments and PP powder should be used to obtain the best impregnation and wetout [150]. Ren et al. [151] encountered the same challenge when directly compounding dry fibres with PP in a single-screw extruder. Poor impregnation was observed and it was recommended to reduce the volume fraction of fibres and use PP with a high melt flow index to improve impregnation and dispersion.

The two primary processing routes for converting LFT pellets into moulded components are injection moulding and compression moulding. In injection

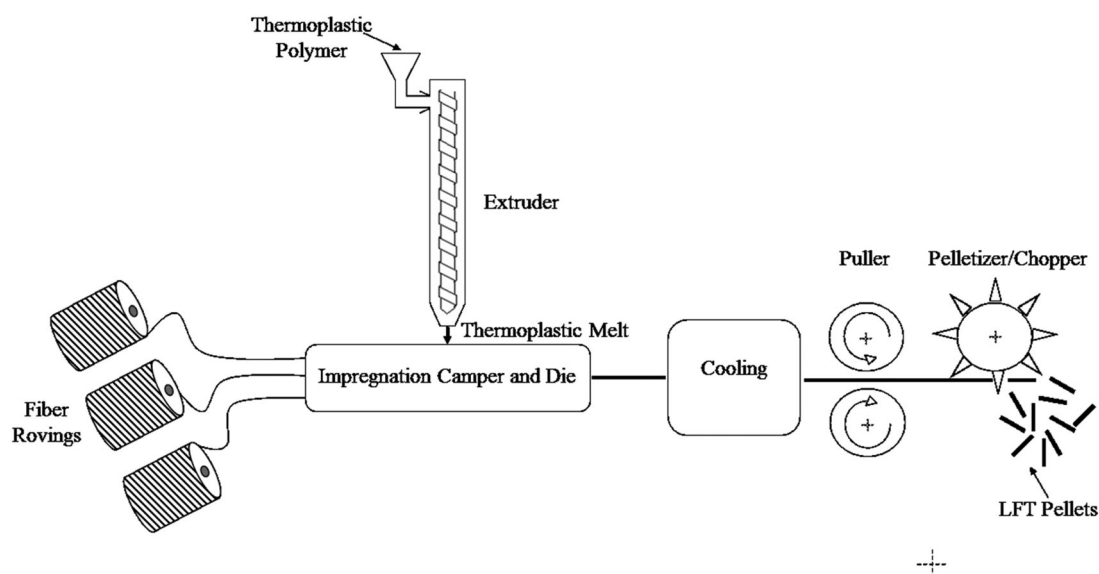


Figure 4. Schematic of the hot melt impregnation process for producing LFT pellets.

moulding, the LFT pellets are fed into an extruder for melting and plastication and the molten material is then injected into a closed mould. Extremely high pressures are normally used. This process is able to produce components with highly oriented fibres in the flow direction which results in improved mechanical properties in that direction [12,152]. However, a high degree of fibre attrition occurs in injection moulding due to the large shear forces imposed during melting and plastication, resulting in a reduction in fibre length from 70 up to 90% [25,153–155]. For example, the average fibre length was decreased from 10 to approximately 1 mm for glass/PP LFT composites [154]. Bijsterbosch and Gaymans characterised the glass fibre shape from an injection-moulded glass/PA6 LFT composite and found that the fragmented glass fibres formed a triangular shape as shown in Figure 5 [152]. They also reported that the fibre orientation along the flow direction was approximately 70%. With increasing fibre concentration, the fibre orientation remained constant but the fibre length decreased considerably [152].

The reduction of fibre length during injection moulding has a negative influence on the resulting mechanical properties. However, fibre length is not the only parameter that affects component performance. Highly oriented fibres caused by the flow can partially compensate for the mechanical property loss, but only in the fibre direction. Although a reduction in fibre length associated with injection moulding was observed, it did not necessarily affect the tensile properties significantly [74]. In fact, the reduction in fibre length was partially counterbalanced by improvements in fibre orientation along the direction of polymer flow. A flow restriction added to the injection moulding glass fibre PA66 caused a reduction in fibre length but increased fibre orientation in the direction of flow. As a result, the effect of orientation was found to be more significant and provided an improvement in the tensile strength of the composite [30].

Several approaches have been implemented to reduce the shear force and the consequent fibre attrition in injection moulding. Decreasing shear stresses in the melt during the plastication, filling and post-filling steps were identified to be the main influence in retaining fibre length [91,156,157]. The effect of the fill time/injection speed on the fibre length during injection moulding was studied and it was found that average fibre length increased with fill time [158,159]. The average fibre length was 0.73 mm for a 4-second fill time, 0.85 mm for a 1-second fill time, and 0.9 mm for a 2-second fill time [158]. Reduction of fibre degradation could also be realised with a modified screw geometry [160], a lower compression ratio in the screw, a longer melting zone, and larger melt channels for the nonreturn valve and nozzle [60,91,156]. Fibre length degradation for injection-moulded glass/PP was reduced by 40% through increasing the nozzle diameter and the ring spacer gap. A final average fibre length of 3.3 mm could be achieved from initial 12 mm fibre length [60].

Increasing processing temperature results in improvement in the mechanical properties of injection-moulded LFT composites. Increasing temperature from 210, 250 to 290°C led to more evenly distributed glass fibres and increased the tensile strength, flexural modulus, impact strength, and the degree of crystallinity [63]. A similar finding was reported by Teixeira et al. [161] and it showed that the barrel temperature is among the top two factors affecting the flexural strength of a glass/PA66 LFT composites. The effects of glass fibre sizing on the fibre distribution, melt flowability and mechanical properties were studied in injection-moulded carbon/PA6 LFT composites [146]. A higher concentration of sizing up to 20% was found to enhance the fibre–matrix adhesion and therefore resulted in higher tensile and flexural strengths [146]. However, increasing initial fibre length does not necessarily result in any improvement in fibre length retention [162] or property enhancement [156].

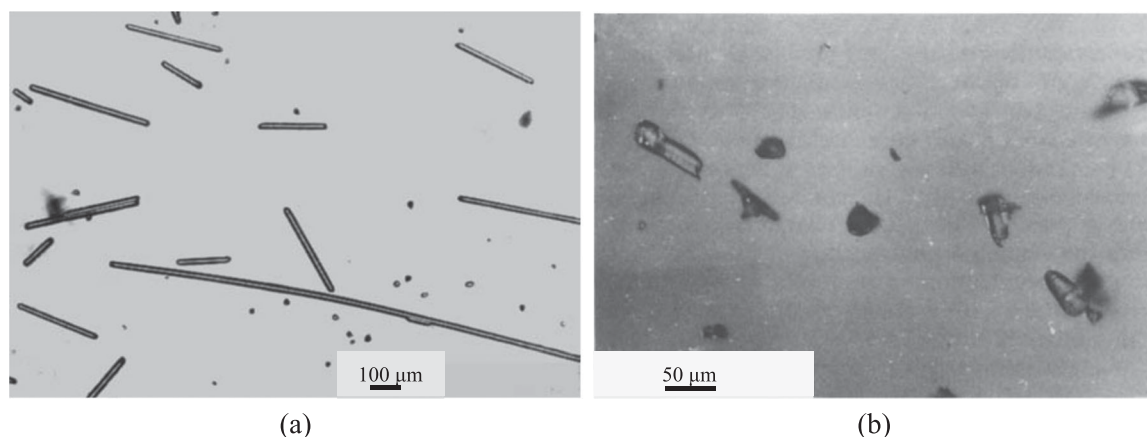


Figure 5. Micrographs showing (a) small glass fibre particles in an injection moulded glass/PA6 LFT composite [152]; and (b) the geometries of the glass fibre particles.

The flexural properties of glass/PA66 LFT composites did not show any improvement as the fibre length was increased from 10 to 25 mm. Instead, the increase in fibre length amplified structural heterogeneities such as fibre clusters, local porosity, and the anisotropy of the moulded parts [156].

Compression moulding is the other main process used to produce LFT products. Here, a low shear extruder produces an LFT charge that is placed into a mould and compressed into the final product geometry. The majority of compression moulding has been done in conjunction with extrusion [125,163,164], although extrusion was skipped in some cases [148]. The retention of fibre length is the main attraction of extrusion compression moulding (ECM) because of the low shear force involved compared to injection moulding. Therefore, it has gained a great deal of attention from the automotive industry and other unconventional applications. The low shear involved in the extrusion and compression process results in low fibre length attrition [125,163]. In one case, the average fibre length of an ECM LFT glass/PP component for a mass transit application was reduced from an initial length of 25 to only 9.5 mm [125]. Figure 6 shows the glass fibres after burning off the PP matrix and the FLD of 600 fibres. Approximately 75% of the fibres have a length of more than 5 mm.

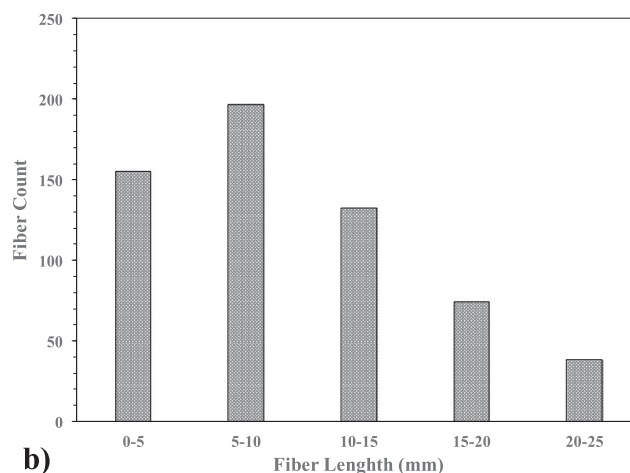
The flow of the LFT melt during compression moulding also leads to preferable fibre orientations, which is, however, not as high as that experienced in injection moulding. A preferable fibre orientation can still induce a difference in mechanical properties between the flow and transverse directions [27,165–167]. For a 40 wt-% glass/PP LFT, the tensile strength in the longitudinal direction was 114 MPa, but only 68 MPa in the transverse direction [166]. Microstructural analysis performed on observing the fibre orientation in the glass/PP LFT has verified the preferable fibre orientation in the flow direction [166].

The semi-finished LFT pellets were commonly manufactured and injection and compression moulding were consequently used until the LFT technology was improved further with a more efficient and cost-effective process being developed. The drive for reducing processing steps and saving shipping and handling costs for LFT pellets resulted in the adoption of Direct LFT In-Line Compounding (D-LFT-ILC or D-LFT), in the 1990s. The D-LFT process combines the moulding station (either injection moulding [168] or compression moulding [27,28,169–171]) with the in-line compounding of fibres with the matrix polymer. The charge produced from in-line compounding is used for subsequent injection or compression moulding, as shown schematically in Figure 7. D-LFT eliminates the steps required for packing, handling, and shipping the LFT pellets [168,172] and enables the processing of the materials at low temperature [173]. The polymer matrix undergoes only a single melt history, which minimises degradation and improves the physical properties [168]. D-LFT has gained tremendous attraction from the automotive sector and it was estimated that more than 90% D-LFT process was used for automotive parts [134]. The elimination of the intermediate processing step resulted in as much as a 50% reduction in raw material costs versus purchased pellets for injection moulding [110,168]. Although this approach also incurs added equipment costs these can be amortised at modest annual production volumes of 30,000 to 50,000 units [110].

Though injection moulding and compression moulding are the most common processing methods for LFTs, other processing methods have been developed such as injection compression moulding [20], extrusion blow moulding [25,174], Direct Incorporation of Continuous Fibres (DIF) [175,176], and the LFT foam process [177–179].



a)



b)

Figure 6. (a) Micrograph for dispersed glass fibres extracted from a moulded glass/PP LFT automobile door component; (b) Fibre length distribution from measuring the length of 600 fibres showing that 75% of the fibres have a length more than 5 mm [125].

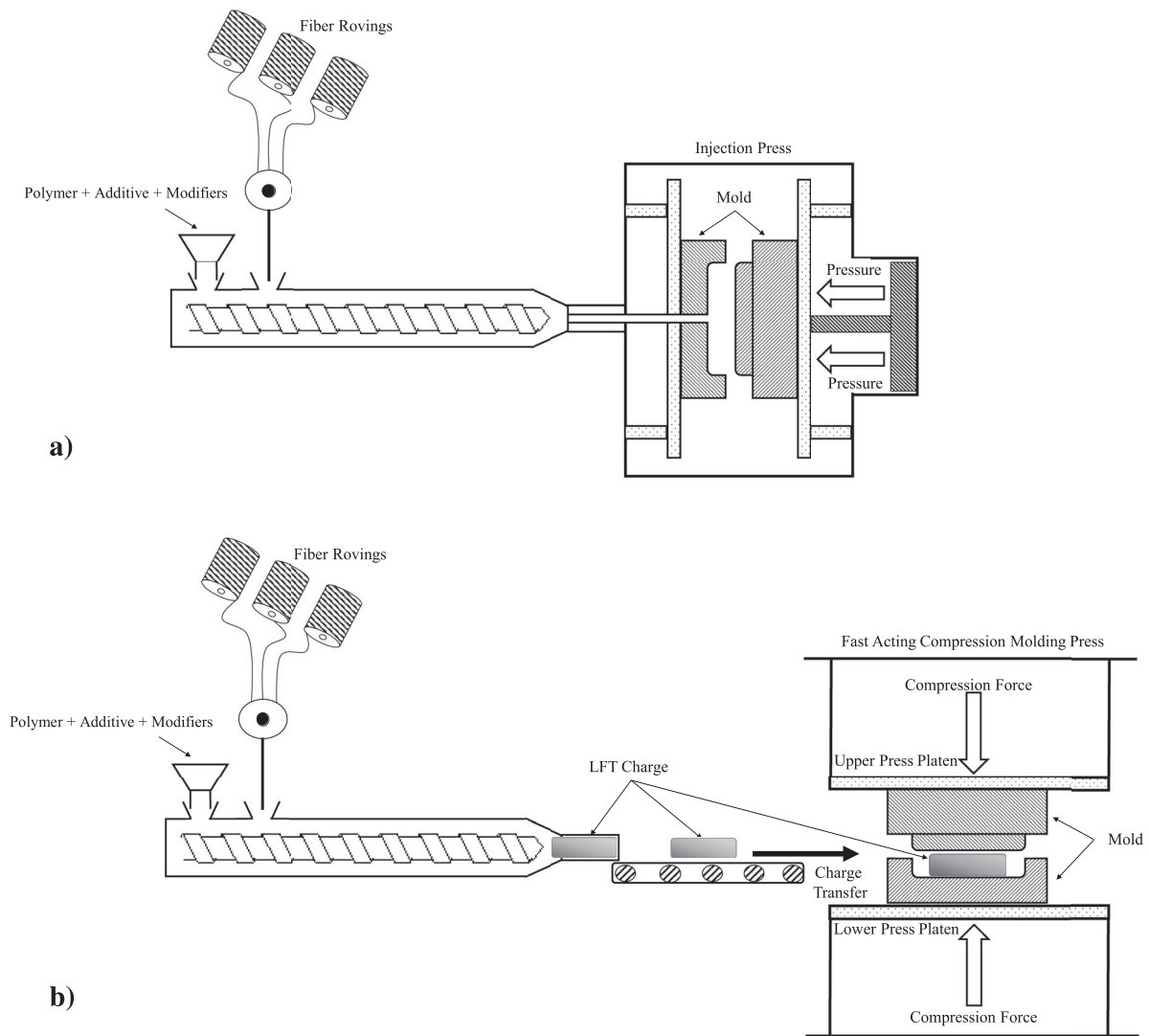


Figure 7. Schematic of inline compounding D-LFT; (a) with compression moulding and (b) with extrusion compression moulding (ECM) process.

Fibre content, FOD, and FLD

Fibre content has a direct effect on the mechanical properties of LFTs. Increasing fibre content to certain percentage (50% by weight (wt-%)) has improved the mechanical properties [14,149,156,169,180,181]. Thomason [61,62] studied injection-moulded long glass fibre PP with a large range of fibre contents from 0 to 73 wt-% (0–50 vol.-%). It was concluded that the composite modulus increased linearly with fibre volume fraction over the whole range. However, both strength and impact performance peaked in the 40–50 wt-% (20–28 vol.-%) fibre range and then decrease at higher fibre content as shown in Figure 8 [61,62]. The properties dropped to the unreinforced PP performance at the highest fibre content of 73 wt-% [61]. Fibre bundles caused by inadequate dispersion were the proposed reason for the property decrease at high fibre contents [61]. Similar trends have been found for the tensile modulus and flexural modulus of PP fibre-reinforced propylene-ethylene copolymer LFT [69] and the impact strength for LFT glass/PA6

[149]. The properties peak at approximately 50 wt-% fibre content [69,149].

Many studies have been conducted on the FOD and FLD in LFT composites, as both factors also significantly affect the mechanical properties. Several methods have been developed for measuring the FOD and FLD. Microscopy is often used to measure

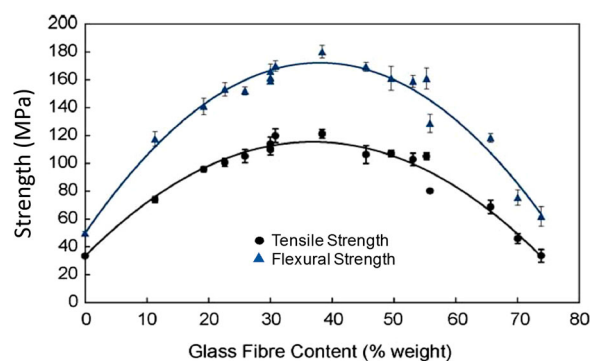


Figure 8. The effect of fibre content on the tensile and flexural strength of glass/PP LFT [61,62].

FLD after burning off the polymer matrix [125,182–186]. This method was used to study the fibre length attrition in glass fibre LFT composites and valuable findings were obtained [185]. It has been found that the average residual fibre length of glass/PA LFT exhibited a strong inverse dependence on fibre content and it is significantly less than the average residue fibre length in glass/PP LFT [185,186]. It should be mentioned that in the process of FLD measurement, a given sample only represents the FLD at a single point in the moulded part. The standard burn-off / sample separation technique to FLD measurements in LFT samples often results in skewed distributions [183] because this technique was designed for short fibre composite. LFTs have much broader FLDs and the fibres in LFTs have a tendency to bend and curl. Other methods include selecting a small quantity of fibres with tweezers after matrix burn-off, but these results in fibre breakage which leads to more dropping of short fibres, tending to skew FLD measurements. As a consequence of these challenges, another procedure for sample preparation for FLD measurement in LFT samples was developed, which can be summarised as: (a) composite coupon isolation, (b) constrained removal of matrix material, (c) fibre sample isolation, (d) filament dispersion, and (e) imaging and individual filament length measurement [183].

It is much more challenging to characterise the FOD in LFT composites. 2D image analysis [187–192] has initially been used to map the fibre orientation in LFTs. This technique is sometimes coupled with relief etching that is used to etch away the polymer matrix of several microns thickness on a polished surface and therefore show fibre orientation [193–196]. In this method, information from a 2-D section is used for the characterisation of a 3-D material. The sectioned

fibres appear as ellipses in the cross-section, for which geometric parameters such as minor axis, major axis, and in plane angle may be measured (Figure 9) [195,196]. Single-fibre orientation angles and components can, therefore, be determined experimentally and then converted to components of a second-order orientation tensor (a_{ij}) that is shown in Figure 9 [195,196]. This method enables the construction of 3D fibre orientation based on the 2D fibre cross-sections. With the advancement of X-ray scanning technology and the development of powerful image processing and computing capabilities, 3D micro-computerised tomography (Micro-CT) has recently become a common technique for characterising the FOD and FLD in LFTs [197–206]. It is able to scan an LFT sample and generate 2D images, from which a 3D image is constructed. Since the fibres normally have small diameters, high resolution of the Micro-CT scanner is indispensable to capture the details of the FOD. A resolution of approximately 4 μm or lower has been suggested to ensure that individual fibres with diameters of 15 μm can be observed [200]. This technique essentially provides a direct visualisation of the 3D fibre orientation in LFTs and quantitative analysis of FOD can also be realised. Sun et al. [203] measured and quantitatively analysed the FOD in injection-moulded LFTs using the Micro-CT scanning method. The Micro-CT image showed a symmetric distribution of fibres through the thickness direction, which consisted of an outer skin, transition zone and the core. It was also found that the skin layer was thin and it had only one layer of highly oriented fibres. The core layer also had highly oriented fibres but the orientation of fibres was different from that of the skin layer [203]. The high resolution of the Micro-CT normally results in a large number of data

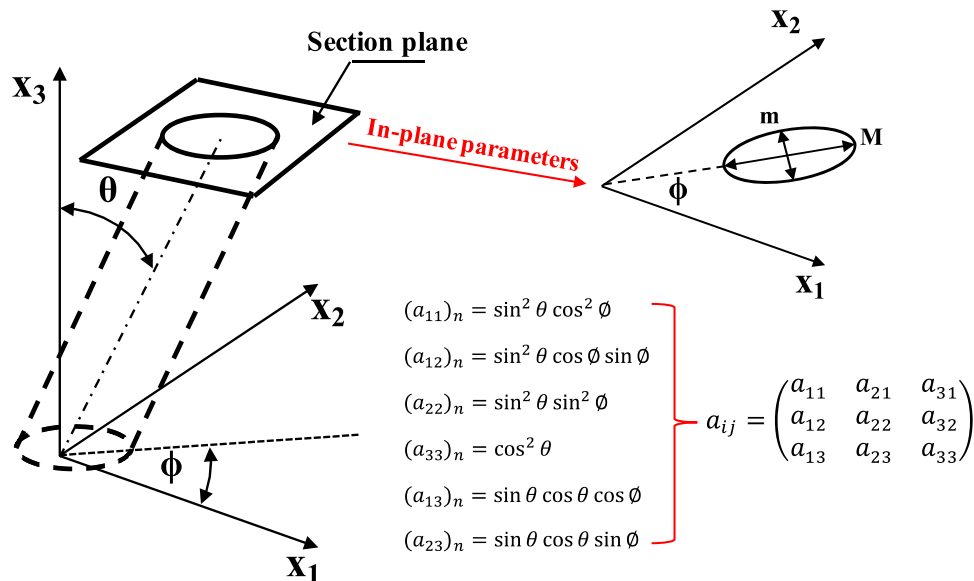


Figure 9. Schematic showing a single-fibre orientation parameters and the second-order orientation tensor (a_{ij}) components. The orientation angles of the fibre can be transformed into components of (a_{ij}) [195,196].

points. A $10 \times 5 \times 4 \text{ mm}^3$ sample scanned at a $3\text{-}\mu\text{m}$ resolution may result in 6–7 GB of image files [200]. Figure 10 shows the 3D Micro-CT scanned image of a 20 wt-% glass/PP LFT with a size of $1.8 \times 1.8 \times 0.6 \text{ mm}$ [202]. In spite of its current limitation in sample size, the Micro-CT is a method that can quantitatively characterise both the FOD and the FLD accurately and efficiently for LFT composites.

In addition to developing experimental methods for characterising the FOD and FLD of LFTs, different numerical models and simulation tools have been developed for predicting the fibre orientation [188,191,199,207–226] and fibre length [162,188,209–211,220,227–230]. Most, if not all, of the models in LFTs have adopted modelling techniques from short fibre composite, random oriented fibre composite and continuous fibre composites [188,199,215,220,221]. The Folgar-Tucker model initially developed for short fibre composites that accounts for fibre–fibre interaction through the isotropic rotary diffusion has been modified for better capturing the anisotropic characteristics of the FOD in injection-moulded LFTs [208,209,214,221]. One version of the modified model is Anisotropic Rotary Diffusion (ARD) and when combined with Reduced Strain Closure (RSC) models, it can be applied to accurately predict the orientation for injection-moulded LFTs [211,214,218]. However, the accuracy of the ARD-SRC model drops within the core layers of the moulded part. Tseng et al. [208,212,226] proposed an Improved ARD model that is coupled with Retarding Principal Rate Model (iARD-RPR) [208]. In their work, it was shown that the iARD-RPR model is capable of predicting long fibre orientation in the shell as well as core layers.

FLD is another important parameter that contributes to the properties of LFT, whereas it is normally neglected for SFT composites [209]. Both Phelps et al. [229] and Durin [230] independently developed complicated models for predicting the FLD in LFTs using similar approaches. Both of the models computed the time evolution of the full FLD and used the

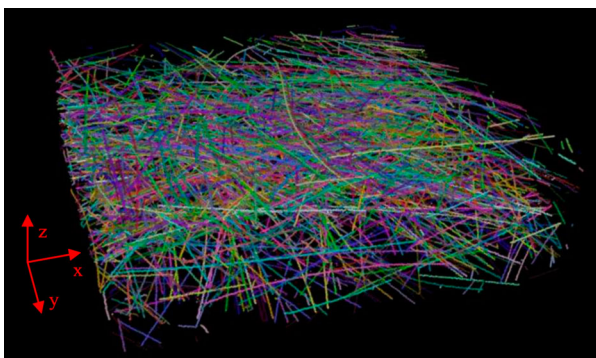


Figure 10. Micro-CT image of a 20 wt% glass/PP LFT with a dimension of $1.8 \times 1.8 \times 0.6 \text{ mm}$ [202]. Fibres are assigned with random colours for better distinction.

criterion that fibre breaks through buckling mechanism under compressive forces induced by hydro-dynamical pressure during moulding process [229,230]. Phelps verified the modelling results using injection-moulded glass/PP LFT, while the FLD verification experiments were conducted by blending glass fibres with PA12 using a twin screw extruder in Durin's work [230]. Nevertheless, satisfactory agreement was found between the modelling prediction and experimental results in both of the studies. A semi-empirical approach was also used to model the fibre length change for LFT composites. Bumm et al. [227] proposed a kinetic model that describes the glass fibre attrition in a co-rotating twin screw extruder for LFT composites based on experimental data and Euler buckling theory. Chen et al. [162] later validated the model with injection-moulded glass/PP and carbon/PP LFTs.

The ultimate goal of modelling the FOD and FLD is to use the modelling results to predict the mechanical properties of the LFT composites [220,231–250]. Two approaches have been normally used to model the elastic properties of LFT composites, namely, micromechanical modelling and numerical simulation of a composite representative volume element (RVE) [188]. The micromechanical model that was developed and proved to be accurate for short fibre composite properties, Eshelby–Mori–Tanaka model, is a base model for predicting the elastic properties of LFT composites [188]. Combined with the fibre orientation averaging method, it was able to model the elastic properties of an injection-moulded glass/PP LFT composite, including Young's moduli and shear moduli [188]. Furthermore, the elastic–plastic behaviour of LFT composites were modelled using a similar approach but combined with continuum damage mechanics and the nonlinear stress–strain response of injection-moulded LFT composites were modelled [237]. The RVE method is another powerful tool that has been used to predict the properties of LFTs [199,215,222–224,251]. The RVE, or unit cell, is required to be sufficiently large to be statistically representative of a heterogeneous material, such as LFT. Fliegenger et al. [199] developed a modelling procedure to construct the RVE for glass/PP LFTs that was based on the parameters describing the, the FLD, and the fibre volume content statistically. The finite element analysis was consequently used to numerically compute the material properties after the loading and boundary conditions were applied. An excellent agreement was achieved between the modelling results of elastic modulus obtained by the developed procedure and the experimental results of three glass/PP LFT with different fibre fractions varying from 10 to 30 wt-%. It was concluded that the RVE method is an effective way to model the complex microstructure of LFT [199]. The same approach has also been

successfully used for determining the effect of fibre curvature on the elastic properties of LFTs [220] and the uniaxial compression behaviour of LFTs [225]. It should be pointed out that although the RVE method is an effective method for modelling LFTs, its drawbacks such as insufficient packing failing to achieve higher fibre percentage such as 40–50% wt because of unavoidable fibre intersection could prevent it from extensive use for LFTs with high fibre percentages [224].

So far, the elastic properties, such as Young's modulus, shear modulus, or even nonlinear stress–strain behaviour of LFT composites have been modelled and the modelling results have been validated for injection-moulded LFT composites exclusively. Limited studies have been found on compression moulded LFTs though. With the benefit of longer fibres achieved in compression moulded LFTs compared with injection-moulded LFTs, it would be very beneficial to have more effort in modelling compression moulded LFTs in the future.

Properties of LFTs

The good structural performance of LFT composites has drawn great attention, especially from automotive industry. They have shown good performance in dynamic testing such as impact, creep, and fatigue and quasi-static testing such as tensile strength, tensile modulus, flexural strength, and flexural modulus. Some of the quasi-static testing results are summarised in Table 1 for LFTs with a different matrix, fibre, and/or fibre contents.

LFTs have often been compared to Glass Mat Thermoplastics (GMT), another discontinuous fibre-reinforced composite material. Generally, LFTs have comparable mechanical properties with GMTs [108,252–255]. However, it was reported that GMTs have higher strength [253,255] and toughness [256] than LFTs with the same fibre content. LFTs are

normally used in those application areas where stiffness and strength requirements are the top priorities, while GMTs would be used more in applications where high toughness and fatigue resistance are required [256]. It is still debatable which material prevails over the other because both of the GMT and LFT composite materials have their own advantages and disadvantages [257]. However, it seems that LFTs have increasingly gained market share because of their low cost, design flexibility, and ease of processing. The comparison of the European market share between GMT and LFT from the 1980s to 2009 (see Figure 11) shows an increasing growth of the LFT market and dwindling GMT share [107].

Thermoplastic polymers normally have good toughness and therefore impact performance. With the addition of reinforcement fibres, LFTs offer superior impact resistance [75,90,117,122,180,258–260]. With different additives added, the impact performance of LFT composites could vary. With the addition of compatibilizer, the impact properties of LFTs increase [261] but reduce with the addition of carbon black [262]. Impact testing was also carried out to investigate the ductile/brittle behaviour of LFTs. It was found there is no apparent ductile/brittle transition for glass/PA6 and glass/PP LFTs [180]. As a strain rate dependent material, LFTs show increased tensile and compression ultimate strengths and failure strains with increasing strain rate [263,264]. However, the modulus of LFTs could have a different trend in different ranges of strain rate [263]. The main failure modes for LFT composites under high strain rate testing, such as impact, are fibre fracture, matrix cracking and fibre/matrix debonding [4,258,263,265].

In addition to their quasi-static material properties and impact performance, the creep behaviour [266–271], fatigue behaviour [6,51,272–275], vibration behaviour [276], UV resistance [277], machinability [278,279], heat treatment [280], and rheological behaviour [56,58,96,199,281–284], of LFT composites have

Table 1. Mechanical properties of LFT composites.

| LFT Material | Fibre loading | Tensile Strength (MPa) | Tensile modulus (GPa) | Flexural strength (MPa) | Flexural Modulus (GPa) | Reference |
|---------------|---------------|------------------------|-----------------------|-------------------------|------------------------|--|
| Glass/PP | 30-40 wt% | 48-150 | 6.5-10.8 | 167-175 | 7.8-9.0 | (14, 62, 63, 143, 144, 166, 168, 172, 252) |
| Glass/PA | 25-50 wt% | 106-251 | 7.7-18 | 173-324 | 6.5-15.9 | (3, 9, 12, 15, 27, 149, 172, 175, 312) |
| Glass/PMMA | 10-30 wt% | 90-113 | -- | 120-182 | 4.8-8.2 | (32) |
| Glass/PBT/PC | 10-40 wt% | 70-137 | -- | 86-211 | 4.1-11.1 | (49) |
| Glass/ABS | 30 wt% | 78 | -- | -- | -- | (172) |
| Glass/PET | 30 wt% | 126 | -- | -- | -- | (172) |
| Carbon/PA | 18-35 wt% | 110-172 | 6.5-14.7 | 222-242 | 14.1-16.6 | (15, 27, 29, 146) |
| Carbon/PP | 18-50 wt% | 47-105 | 6.7-28.8 | 95-179 | 5.1-18.4 | (64, 141, 148) |
| Basalt/PA | 30 wt% | 136 | 7.2 | 158 | 4.8 | (66) |
| PET fiber/PP | 30 wt% | 15-29 | 2.1-2.3 | -- | -- | (70) |
| PET fiber/PET | 30 wt% | 52 | 3.3 | -- | -- | (70) |

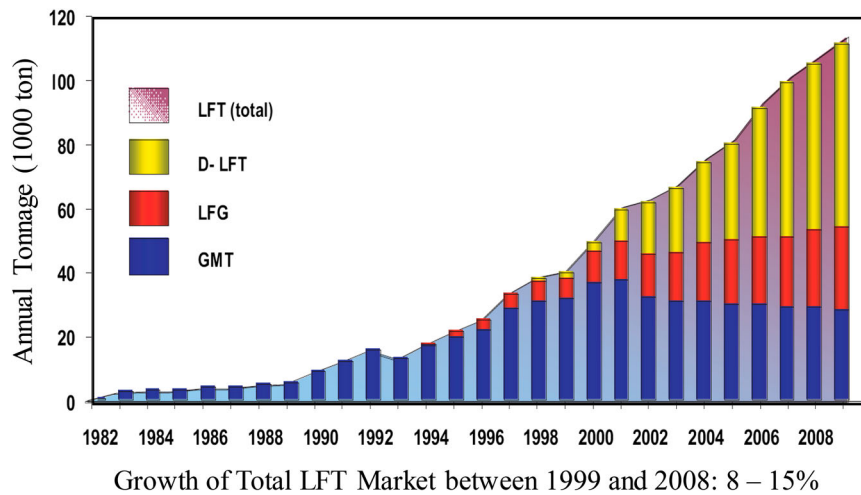


Figure 11. Market demand for LFT in Europe showing the increasing growth of the LFT market and dwindling GMT share [107].

also been studied. Chevali et al. [190,266,267] have extensively studied the creep performance for glass fibre LFTs, including glass/PP, glass/HDPE, and glass/PA66 LFT. It was confirmed that the fibre addition improves the creep resistance compared with the matrix for all the LFT composite [190]. Creep compliance of UV exposed glass/PA66 LFT decreased with increasing exposure time because of an increased degree of crystallinity leading to reduced polymeric segmental motion [267]. Fibre alignment in certain direction in LFT contributes to the reduced creep compliance in that direction [190]. The rheological studies by a number of research groups [281–283] have shown that LFT composites show shear thinning and higher fibre content causes more shear thinning. The viscosity of LFT suspensions increases with fibre length and fibre content [56,284]. The research findings from all these studies have provided useful information for LFT component design, material selection and processing.

LFT hybridising/joining

In cases where a single material cannot meet strict design requirements, the idea of hybridising different types of materials into one structure/component has gained significant attention. The integration of other materials into LFTs can be achieved by blending during impregnation/extrusion and/or co-moulding. Hybridising can improve the mechanical properties [17,285,286], electromagnetic interference (EMI) shielding [287,288], appearance [163,289], or acoustic emission [55], while maintaining a low density. Endless LFT (E-LFT) is an example of a common hybridised material. E-LFT combines LFT with unidirectional fibre composite, generally with the same polymer matrix for adequate bonding to enhance its rigidity, strength [290–293], and/or impact resistance [111,294]. Thattai parthasarathy et al. [291,295] studied the effect of different types of endless fibre composites on the strength of glass/PP LFTs by

compression co-moulding the LFT onto the endless fibre composite. The average flexural strength for endless E-glass, S2-glass, and carbon fibre E-LFTs were 137.4, 163.9, and 180.6 MPa, respectively, compared to an average of 106.5 MPa for glass/PP LFTs without any unidirectional fibre composite. Figure 12 shows a glass/PP LFT plate co-moulded with unidirectional glass fibre PP tapes [291]. In another study, a carbon/PA6 LFT was hybridised with a continuous fibre composite using injection moulding. It was found that a mould temperature of 190°C resulted in the highest interfacial welded strength of 19.2 MPa between the LFT and the continuous fibre composite [290]. The tensile, flexural, and impact performance of endless glass fibre composites co-moulded with glass/PP LFT increased with the fraction of endless fibre composite [294]. Fibre bundles were found to promote the toughness of E-LFTs as the failure mechanism of fibre breakage was replaced by fibre pullout which absorbs more energy. Woven long fibre hybrid thermoplastic composites (WLFT) are another hybridised LFT material in which pre-impregnated woven fibre composite sheets

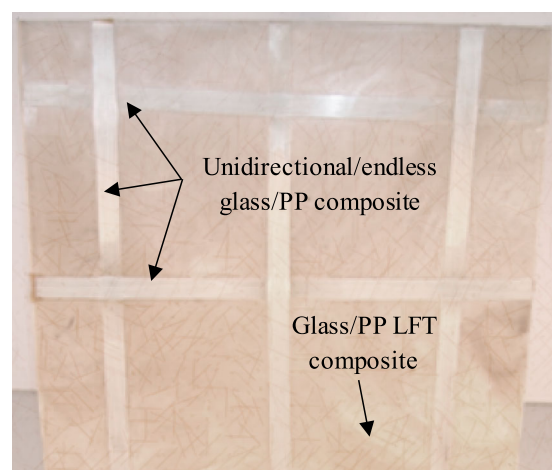


Figure 12. Co-moulded unidirectional/endless glass fibre PP composite with glass/PP LFT [291].

are co-moulded with LFTs. Overall, continuous fibres in different forms have been used to hybridise with LFTs and these hybridised LFTs with improved strength and rigidity provide more opportunities for weight saving as a structural material, especially in automotive industry. For example, a bumper back beam produced using the WLFT resulted in a 35% weight reduction compared to its steel counterpart [296]. Furthermore, this hybrid LFT composite is favoured by the automotive industry because the addition of the continuous fibre composite to LFT does not necessarily reduce the production rate, which is another important criterion in the automotive industry. Desirable properties at certain locations of an automotive component can also be readily achieved by strategic placement of the continuous fibre in the composite. It is expected that these advantages will enable continuously increasing use of the continuous fibre hybridised LFT composite in automotive and other applications.

Hybridising with metal is another approach to enhance the strength and rigidity of LFTs [131,288,297–299]. The bonding strength between the metal and the LFT relies on the interfacial mechanical interlocking. The design and processing of a hybridised tailcone consisting of aluminium and glass/PA66 LFT were reported [131,300,301]. The glass/PA66 LFT was co-moulded on the threaded aluminium to produce a hybridised tailcone with thermal resistance and superior mechanical properties. The performance of glass/PA LFT laminated with aluminium was studied in tension, bending, and impact [302]. The hybridised laminate possessed a much higher modulus and strength than pure LFT. The bonding between a glass/PA66 LFT and aluminium was found to be adequate to stand extremely high pressure (406 MPa) and temperature (1970 K) for a short period [131,303]. Not only the bulk and sheet metals were used to hybridise with LFTs, metallic wires have also been integrated with LFT composites to enhance

their rigidity and impact resistance [304]. The addition of steel wire grids has tripled the impact energy absorption for LFT. The process of hybridising other materials with LFT is similar to the processes for moulding LFT composites. The hybridising material is placed in a mould and LFT melt is injected onto (for injection moulding process) or LFT charge is placed onto the material and compression moulded to form a hybridised material. Figure 13 shows the typical co-moulding process for hybridising LFTs with unidirectional/continuous fibre composites, woven fabric composites, or metals.

In addition to hybridising LFTs with continuous fibre composites and metallic materials, polymer films have also been co-moulded onto the surface of LFTs to enhance their aesthetic appearance. This approach improves the surface smoothness such that the LFT can be adopted as a potential material for the exterior panels that meet 'Class A' finishes in automotive applications. In standard LFT processes, the temperature of the LFT charge is above the melting temperature of the polymer matrix while the mould temperature is much lower. Therefore, the skin of the charge freezes instantaneously when it touches the mould, which causes fibre imprints on the surface and therefore a high surface roughness. The arithmetic mean roughness of LFT surface at flow area is $0.38\ \mu\text{m}$, which is much lower than that of the lay-up position ($0.61\ \mu\text{m}$) due to the high cooling rates [305]. Co-moulding a film onto the LFT surface is the main approach that has been used to improve LFT surface finish. Geiger et al. [306] back-pressed films to LFTs using an extrusion compression moulding process. It has been proved possible to completely eliminate the known occurrence of fibre agglomerations or non-impregnated fibres on the surface of LFT components. Similar approach was used to co-mould films on the surface of a glass/PP LFT panel to obtain a good surface finish. It was found that co-moulding the film in an

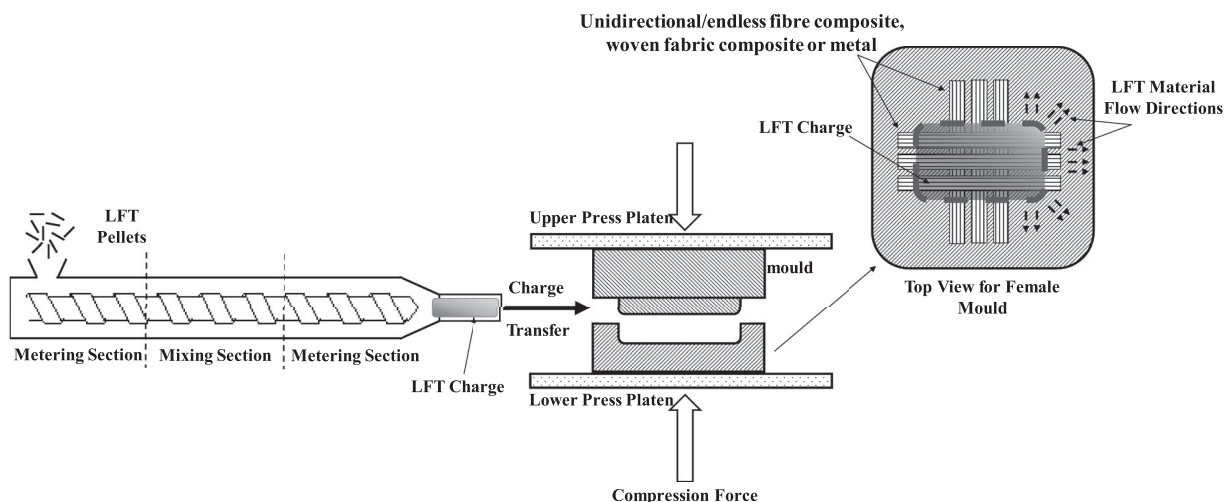


Figure 13. Schematic for hybridising of LFT and unidirectional/continuous, woven fabric composite, or metallic materials.

extrusion compression moulding process can be readily realised and a good surface finish was achieved [163]. Though more research and development work needs to be conducted to further improve the surface smoothness, there is a great potential for LFT composites to have surface finishes adequate for exterior components through the co-moulding or other methods.

LFT composites are thermoplastic polymer-based materials that can be re-melted and joined by different means such as resistance welding, ultrasonic welding, and friction welding. LFT glass/PP was successfully hybridised to continuous glass fibre-reinforced PP using resistance welding. A stainless steel mesh implant was used between the composites to provide a larger welding window [307,308]. The effects of several welding parameters, such as weld time, weld pressure, and electric current, were studied in relation to the bonding strength. A shear strength of 17–20 MPa, equal to the shear strength of the continuous fibre-reinforced composite, can be achieved [307]. Ultrasonic riveting and hot-air-sticking were also used to hybridise LFT glass/PP and glass/PA6 with steel. Hot-air-sticking was the preferred joining method to connect the LFT to metallic structures [309].

Additive materials for LFTs

Additives are a substance added to a certain material in small quantities to improve its properties. Additives have been added to LFT composites for several purposes, such as lowering the material cost, increasing the modulus [55], improving the appearance [289], and increasing flame retardancy [59,121,310,311]. Pigments have been blended into LFT to provide colorisation. They are usually added into the polymer by simple blending, wire coating, or hot melt impregnation [289]. A 0.5% loading of oxide pigment yielded higher mechanical performance than 5% pigment concentration while providing uniform colour dispersion [289]. Other additives, such as CaCO₃, can be added to the polymers to enhance the material modulus [55]. However, its fracture toughness decreased upon filler addition and the average fibre length decreases by 25% [55].

The flammability of LFT composites can be reduced through the addition of flame-retardant additives. Different additive systems, such as a brominated system composed of decabromodiphenyl oxide (DB) and antimonous oxide (AO) [121] and a halogen-free flame-retardant composed of a charring agent (CA), ammonium polyphosphate (APP) and organically modified montmorillonite (OMMT) [59], are used to improve the PP matrix LFTs. Both of these studies show that the flame-retardant materials added to glass/PP LFTs improved the fire rating from no rating to UL-94 V-0 with minimal sacrifice of mechanical properties. Similar trends have been observed when

adding decabromodiphenyl ethane (DBDPE) and antimonous oxide (AO) to glass/PP LFT. The fire retardancy of the glass/PP LFT increased, while its mechanical properties are marginally affected [121]. Besides PP, another commonly used matrix in LFT composites, nylon or PA, also have easy flammability [312]. In order to enhance its flame retardancy, Zn²⁺-modified melamine polyphosphate (Zn-MpolyP) flame retardant was added. UL-94 V-0 rating was achieved with a 25% loading of the flame retardant added. Meanwhile, the retardant improved the crystallisation degree and temperature of PA66 matrix and enhanced the mechanical properties of the composite by effectively improving the interfacial compatibility between the glass fibre and the PA66 matrix [312]. A different flame-retardant system, consisting of tris(tri-bromophenyl) cyanurate and antimony trioxide, was added to a glass/PA6 LFT to achieve UL-94 V-0 rating [313]. The influence of thermal-oxidative aging of the flame-retardant properties was also studied [313] and it was found that the thermal-oxidative aging enhanced the flame retardancy by improving the solid phase flame-retardant mechanism by a char-promotion function [313].

There are also a small number of studies on the addition of nanomaterials into LFT composites. Those studies mainly focused on improving the flame/thermal performance of LFTs. Nanoclay has been added to LFTs to enhance the flame retardancy and reduce thermal degradation [296,314–316]. Vaddi [316] used montmorillonite nanoclay to reduce the dripping of the molten glass/PP and glass/PE LFT composites. Nanoclay was also added to glass/PP LFT to enhance its resistance to thermal degradation [315]. The initial thermal stability of the modified LFT glass/PP at 5% weight loss was enhanced by 56°C compared to the conventional LFT glass/PP composite [314,315]. In spite of the benefits with nanomaterial added to LFTs, it is foreseen that the research effort in adding the nanomaterial to improve flame/thermal performance for LFTs will probably be still limited in the future because of its high material cost and the benefit of improvement can simply be achieved by adding lower cost flame-retardant additives as discussed previously. The difficulty of blending nanomaterials homogeneously and consistently in a highly viscous thermoplastic matrix might be another hurdle that prevents the nanomaterials from being widely adopted in LFT composites.

Recyclability

LFT composites consist of fibres and thermoplastics matrix, both of which can be recycled and reused. With more governmental regulations seeking a higher recycling percentage of automotive materials at the end of their life, LFTs have an advantage compared to

thermoset or thermoset composites. Vehicles are required to be made of 95% recyclable materials, of which 85% can be recovered through reuse or mechanical recycling and 10% through energy recovery or thermal recycling [317].

The LFT composite has been recycled as a whole and used as the core material of a sandwich structure [318]. Washed/cleaned LFT scraps went through a cutting mill before being pressed with continuous glass fabrics to form a sandwich structure. The recycled LFT was enclosed as the core in the middle by the glass fabrics on the surfaces. The process can be either a double belt process that can produce a flat sandwich structure with constant cross-section or direct compression moulding process that produce a sandwich structure with different configurations [318]. LFT machining residue or shredded LFT scraps have also been recycled to produce compression moulded components [319]. The main purpose of this work is to study the possibility of eliminating any scraps when producing LFT parts and achieving zero scrap rate by mixing all of the scrap material with virgin LFT for the part production. The effect of the percentage of the LFT scraps added to the virgin LFT composite on the resultant LFT properties was systematically studied [319]. It can be envisioned that the difference in fibre length and fibre content of the recycled LFT composites will pose challenges in the quality control of final LFT parts/products.

An effort has been exerted to use recycled fibres, especially carbon fibres, in LFTs. The carbon fibres are mainly recycled from large structures such as aircraft components or windmill blades made of continuous carbon fibre epoxy composites. The composite structure was chopped and discontinuous carbon fibres were extracted by pyrolysing the epoxy resin matrix [320–322]. The recycled carbon fibres were then combined with thermoplastic polymers in powder or fibre form and processed in injection moulding or compression moulding. The tensile and flexural properties of a recycled carbon fibre-reinforced PPS LFT were evaluated after several iterations of shredding–moulding–testing [320,321]. No definitive trends were found for the properties measured as a function of the number of iterations [320]. The vibration response of the recycled carbon/PPS at each iteration was also evaluated and there was a very little change in the vibration response of the recycled carbon fibre-reinforced PPS LFT [38]. In addition to the carbon fibre recycling, glass fibres have also been recycled and studies have been carried out on their interfacial bonding with polymers. It has been demonstrated that thermally recycled glass fibres needed a post treatment to act as effective reinforcement in PP composites [323]. The adhesion between fibres and PP can be regenerated by the addition of PP-g-MA, which is in good agreement with the findings by Zhang et al.

[147]. The post-treatment of the fibres with γ -aminopropyltriethoxysilane (APS) was even more effective in improving the composite performance. The composites with the post-treated fibres almost reached the performance of the composites with as-received fibres [323]. The use of recycled fibres in LFTs, especially carbon fibres, can largely reduce the raw material cost as extracting carbon fibres can avoid the time-consuming and energy-intensive manufacturing process from precursors. However, the variation in fibre grades due to different fibre sources could pose a challenge in quality control and maintaining consistency in LFT part properties.

Although there are only a limited number of studies on LFT recycling to date, it can be predicted that recycling of LFTs will become more important and prevalent in the near future. Large quantities of LFT composites are reaching the end of their service life and recycling would be a logic and effective way to avoid them from being sent to the landfills. The continuous growth of the LFT composite in various applications, raw material cost saving by using recycled LFT, and more strict environmental protection standards would also drive the demand for its recycling. It is expected that increased research and development work will be performed on the recycling of LFT composites in spite of the challenges previously mentioned.

Conclusions and outlooks

LFT composite materials have established a strong presence in various applications, especially within the automotive industry as semi-structural interior components because of their good mechanical properties, low density, good processability, and recyclability. The automotive market has been and will be the main market for the LFT composites in the foreseeable future.

With the improvement in the resolution of hardware (Micro CT or scanning techniques) and computing capability in analysing the FLD and FOD in LFT composites, more understanding will be achieved on how the processing conditions affect the FLD and FOD and the resultant LFT properties. An accurate prediction of the localised material properties in LFTs has the potential to provide a better estimation of the performance of the LFT components and result in better product design. More studies on the FOD and FLD of LFTs, experimentally and computationally, will enable the accurate description of the interrelationship of the processing, structure, and properties and therefore better design and manufacturing of LFT components.

Thus far, injection-moulded LFT composites have been predominantly investigated, experimentally or computationally. The study of FOD and FLD and the modelling and simulation are mostly focused on the

injection-moulded LFT composites. However, with the benefit of less fibre length attrition achieved in compression moulding process and its increasing popularity, it would be beneficial to have more research work be performed on compression moulded LFT composites in the future.

For applications with stringent requirements on material properties, LFTs may be hybridised with other materials to fulfil the tasks required by the application. Continuous fibre-reinforced composites, metallic materials, or plastic films can be readily integrated into LFTs to provide additional properties such as EMI shielding, improved strength, enhanced rigidity, greater wear resistance, or better appearance. However, the interfacial bonding between LFT and the hybridising materials, including continuous fibre composites or metallic materials, becomes crucial because it can determine the overall properties of the hybridised material. Nevertheless, it is expected that hybridising with other materials will become an important topic for the future developmental and research work related to LFT composites.

Overall, LFT composites have become an increasingly used class of high-performance lightweight engineering materials. The research work conducted to study the relationships among processing, structure, and properties of LFTs since the 1990s has resulted in a greater fundamental understanding of these materials and led to a great improvement of their properties. With the advantage of readily integrating other materials by the co-moulding process, LFTs can provide more versatility and design flexibility, which can open more avenues for applications. The use of LFT composites in scenarios with extremely high pressure, high temperature for a short period of time, and high corrosion and their capability of meeting the significant criteria show that they have a great potential for more unconventional applications with extreme conditions.

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