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Introduction

Man's odyssey on earth has actually passed through a succession of ages-stone, copper, bronze, iron, plastics and silicone before culmination in the present age of designed materials or composites. Composite materials combine more than one material, most commonly a matrix material and high strength fibres. Glass fibres have been one of the most common reinforcing materials for composites, but pose health and environmental problems and are energy intensive. Biological fibres and natural or synthetic matrix materials can be used to make ecocomposites that are equally strong and environment friendly [1-3].

1.1 Composite materials

One of the earliest known composite materials is adobe brick in which straw (a fibrous material) is mixed with mud or clay. The straw allows the water in the clay to evaporate and distributes cracks in the clay uniformly, greatly improving the strength of this early building material. Another form of a composite material is the ubiquitous construction material we call plywood. Plywood uses natural materials (thin slabs of wood) held together by a strong adhesive, making the structure stronger than just the wood itself. In nature, bamboo is often cited as an example of a wood composite structure, combining a cellulose fibre and lignin, with the lignin providing the adhesive to hold the fibres together [4-10]. Of course, we probably drive a car across a composite highway every day. Reinforced concrete is a combination of two remarkable materials, concrete (a composite by itself) and steel that takes advantage of the strengths of each material to overcome their individual limitations in each. Steel has very high tensile strength, while concrete has very high compressive strength. In combination, they make a superior material for road and bridge construction. The structure, properties and applications of various composites were reported by a number of researchers all over the world [11-26].

Today, when we speak of composite materials, or just "composites", we are referring to the highly engineered combinations of polymer resins and reinforcing materials such as glass fibres. A fibre glass composite structure is a combination of glass fibres of various lengths and resins such as vinyl ester or polyester. The term FRP is often used, meaning Fibre Reinforced
Plastic. FRP is a very general term for many different combinations of reinforcement materials and bonding resins. Thus, the term "composites" is used extremely broadly to describe many materials with many different properties targeted at an even larger number of applications.

Polymer fibre composites are based on thermosetting or thermoplastic polymers and contain fibres ranging in length from short to continuous. In addition to fibres, polymer composites may contain particulate fillers, pigments, fire retardants and other process aids and property modifiers. Together with the different types of matrices, i.e. thermoset or thermoplastic, and the need to retain fibre length, these fillers impose major constraints on recyclability. However, as an alternative to recovering the original material in a recycling operation, it is possible to recover the energy locked in the material and to use the composite as a source of fuel. Several problems exist in this respect. For instance, one of the most difficult composites to reprocess is automobile tyre. Retreading, pyrolysis and cryogrinding to produce crumb are possibilities. The main problems have been economics of production and the identification of suitable markets for the products. Incineration to recover inherent energy is currently the most promising route. There are similarities between tyres and thermosetting polymer composites. Incineration has been used extensively with plastics for some time. Considerable amounts of domestic refuse containing plastics are incinerated each year. However, the rapid introduction of legislation and public opinion is causing a far reaching analysis of the incineration route. Recycling is a much superior option to incineration.

1.2 Recycling

Today, composites are an integral part of everyone's lifestyle with application varying from common place articles to sophisticated scientific and medical instruments. However, there is downside: composite is one of the least friendly materials. Low-cost plastics such as single use packaging appear more frequently in the waste stream than the polymers used in making durable goods. Some of the plastic products other than packaging enter the waste stream one year or more after fabrication. The rapid growth of electrical and electronic equipment scan be attributed to the speed of new developments in technology, which has resulted in a reduction in product life to less than 2 years in some cases, for both domestic and commercial products. In 1998 the amount of waste electrical and electronic equipments, for example, in Europe reached
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an estimated 6 million tons, an amount expected to double over the next decade [27]. The
global figure of dismantled cars was around 24 million in 1995, generating 2.2 million tons of
plastic scrap [28].

Plastic is a non-biodegradable material, so we cannot eliminate plastic wastes either by
land filling or burning. Use of landfills to dispose plastic wastes prevents plant roots from
growing and negatively affects the agricultural enterprises. Burning of plastic wastes produces
great amounts of harmful gases, which harmfully affects all kinds of organisms. Currently there
is increasing worldwide interest in biodegradable polymers and composites, which are viewed
as a major part of global efforts to overcome serious environmental problems in the 21st century.
Biodegradable polymers offer scientists a possible solution to waste disposal problems
associated with traditional petroleum derived plastics [29-41]. For scientists, the real challenge
lies in finding applications that would consume sufficiently large quantities of these materials to
allow cost reductions, thus allowing biodegradable polymers to compete economically in the
market.

Attention focused on polymer recycling has increased in the past decade [42] because
more efficient reuse of materials will reduce the quantities sent to landfills, as well as reduce raw
material extraction [42-52]. Recycling of waste plastics has been an interesting subject in the
field of environmental science and technology for a long time and several methods have been
proposed for recycling waste plastics. Recycling of plastics mainly includes three options:

- Mechanical recycling
- Chemical recycling by depolymerization
- Energy recovery

Polyolefins and poly esters which have been given significant attention in the research
and technology are the most frequently recycled polymers. De Winter presents a review on
recycling of PET film and Neumann on a co-injection technology, which allows one to use
recycled PET as an intermediate layer in bottles. Both processes are common in industrial
practice and are thus able to offer an overview of experience in plastic recycling which is of
interest in other areas of recycling as well. Other references to PET recycling are presented by
Sereni and La Mantia, Perrone and Bellio [53-74].
Recycling of polyethylene (PE) and other polyolefins are also reported. La Mantia and Curto propose methods of recycling of photooxidized polyethylene in blend with nylon 6. It is shown that the recycled PE behaves like a functionalized PE, having compatibilizing attributes due to which blends exhibit improved mechanical properties [75-76].

Recycling of urban wastes has been discussed by Gattiglia et al. and by Laguna et al. Generation source, separation possibilities, and cleaning technology are discussed in relation to blend properties, such as rheology, morphology and mechanical properties. Comparison is also made with blends having similar composition but made from virgin polymers [77-78].

The major problems in recycling of mixed plastic waste are due to their inferior processability, which results in materials having poor mechanical properties. La Mantia et al. and Vezzoli et al. present experimental results, which disclose the possibility of obtaining recycled materials with acceptable properties from mixed plastic waste [79].

Recycling of plastic components from car scrap is a very important challenge for the plastics industry and car manufacturers, since the plastic content in cars is systematically increasing [79-90]. Henstock and Seidl have discussed the recycling of plastic fuel tanks. Oliphant et al. have described the methods of application of ground discarded tires as a filler in polymer composite; Vezzoli et al. have presented new strategies of design of easily recyclable car interiors; while Heil and Pfaff have shown how battery recycling can utilize all initial components, offering quality assurance for recycled polypropylene [91-104].

1.2.1 Recycling of composites

Composite materials contribute to a significant weight saving per vehicle, translatable into a worthwhile fuel saving. Plastic composites make a valuable contribution but they feature more strongly in volume, high value production than in mass produced vehicles; this situation is likely to continue. The main components made from composites are body panels, structural members, suspension parts and bonnet components [105]. This situation is even more apparent in the aerospace industries where 65% of the structural weight of commercial aircraft is composed of composites and most of that is likely to be plastic based. The composites used in aerospace applications are generally more sophisticated and have higher property profiles than those used in automotive applications. At the same time, design lives are much longer, for
example 25 years compared with 10 years. The total consumption of aerospace composites is lower than automotive composites; therefore we are confronted with high value, low volume composites in aerospace that will not become available for recycling for 25-30 years. On the other hand, the automotive industry will generate large quantities of scrap plastics and composites from a much earlier date, although the inherent value per kilogram will be less. Careful economic analysis is necessary to identify appropriate strategies. In the automotive industries, margins are very narrow and environmental pressure is very great. There is an urgent need for a sophisticated recycling industry that must be developed to deal with plastics and composites as the quantities involved become higher. It is unlikely to be acceptable simply to use these materials as landfills or to incinerate them in an unsophisticated manner. Separation procedures must be developed so that metals can be separated from plastics and one type of plastic and composite separated from one another. It is becoming increasingly apparent that considerable thought must be given to component design in order to render the separation process workable at the recovery and recycling stage.

For certain components, recycling presents little problem. If they are composed of a single material and can be easily separated then recycling is straightforward. All that is necessary is a simple means of identification such as bar coding or a similar method. It has been proposed that a ‘closed loop’ approach is adopted where components are reprocessed into similar components at some future time. However, this entails a very long range approach to material selection, which is not likely to be very practical. Where components are constructed from several polymeric materials, it is sensible to ensure they are compatible. For example, a bumper system composed of a reinforced plastic, energy absorbent core and a flexible cover should be based on compatible polymers, e.g. polypropylene. Then recycling is simplified as the plastic components as a whole can be shredded and compounded to recover a reinforced compound with useful properties.

A significant proportion of composites production is in the form of thermosetting materials such as SMC and BMC. The merits of incineration as a means of recovering the inherent energy values of these materials, the energy values available in these materials and the problems involved in the incineration process are being investigated [106]. After incineration, a considerable quantity of inert reinforcement and filler is left; one objective of these studies is to find worthwhile uses for it. The calorific values of thermosetting plastics used in polymer fibre
composites such, as polyesters, vinyl esters and epoxies are approximately 30 MJkg\(^{-1}\). These values are generally reduced in direct proportion to their filler and reinforcement contents. Many thermosetting composites contain up to 80% fillers and reinforcements, so their calorific values are significantly reduced. But endothermic reactions can absorb considerable amounts of energy; when 1 kg of calcium carbonate decomposes at between 800 and 900 °C to yield lime, it absorbs 1.8 MJ. Some fillers and polymers may react to form sulphur dioxide, nitrogen oxides etc. Table 1 shows some typical calorific values for comparison purposes.

Table 1 Comparative calorific values

<table>
<thead>
<tr>
<th>Material</th>
<th>Approximate calorific value (MJkg(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermosetting plastics, e.g. polyester, vinyl ester and epoxy</td>
<td>30</td>
</tr>
<tr>
<td>Thermosetting fibre composite containing 80% fibre/filler</td>
<td>6</td>
</tr>
<tr>
<td>Tyres</td>
<td>31</td>
</tr>
<tr>
<td>Polyethylene</td>
<td>46</td>
</tr>
<tr>
<td>Domestic refuse</td>
<td>10</td>
</tr>
<tr>
<td>Polymers in domestic refuse (average)</td>
<td>38</td>
</tr>
</tbody>
</table>

Flue gas emissions are a possible problem but initial studies on polymer composites have not revealed major problems. The indications are that particulate and gaseous emissions should be within legislative limits [106]. Polyester, vinyl ester and epoxy based composites give low char yields and the ash yield depends on the resin content. Phenolics and urea based composites give much higher values. Work is in progress to find uses for the recovered fillers in, for example, the cement industry, where the energy recovered would be of considerable use. Lime produced by the decomposition of calcium carbonate described above is potentially useful in this respect.

Short fibre thermoplastic composites can be granulated and melt processed by injection moulding or extrusion. However, some mechanical reduction of fibre length is inevitable, together in some cases, with degradation of the matrix. In-house recycling at the initial production stage is straightforward. In other cases, the situation is less satisfactory although the presence of fibres is often a help in compatibilizing systems comprising mixtures of
polymers and composites. Thermosetting composites can be re-used by shredding them into fine particles using them as a filler in other polymeric materials.

In the case of long fibre polymer composites, it is an advantage to preserve fibre length as far as possible in a recycling processes in order to maximize properties and value. This is difficult to achieve but is worth considering in view of the probable high cost of the fibres and polymer matrix. Studies have been made on recycling a thermoplastic composite based on poly ether ether ketone (PEEK) with 68 % continuous carbon fibres [107]. In pattern cutting, the prepreg material utilization is unlikely to be more than 75 %. Thus re-use of the offcuts is desirable. Studies have been made on the use of controlled size pieces of offcut prepreg followed by reconstitution by hot pressing. Good properties are achievable as can be seen from Table 2. It is conceivable that this approach could be extended to pattern cutting offcuts of thermosetting composites but handling and shelf lives present considerable problems. Injection moulding of the reclaimed material after granulation and dilution with PEEK is also possible and typical results are included for comparison.

Table 2. Comparison of reclaimed composite, reconstituted and an original continuous fibre composite

<table>
<thead>
<tr>
<th>Property</th>
<th>Reclaim with PEEK (40% carbon fibre) injection moulded</th>
<th>Reconstituted single prepreg piles (25.4 mm) hot pressed</th>
<th>Original continuous fibre composite</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flexural modulus</td>
<td>30.4</td>
<td>37.2</td>
<td>40.9</td>
</tr>
<tr>
<td>Flexural strength</td>
<td>410</td>
<td>440</td>
<td>616</td>
</tr>
<tr>
<td>Tensile strength</td>
<td>242</td>
<td>290</td>
<td>704</td>
</tr>
</tbody>
</table>

1.3 Short fibre reinforced thermoplastic composites

Polymer composites are playing an increasing role as construction materials in a wide variety of applications. In particular, thermoplastic polymer composites are falling under increasing scrutiny due to their potential to be easily repaired and/or reshaped, making them easier to recycle and reuse compared with thermosetting matrix composites. Short fibre
reinforced thermoplastic moulding materials are very widely used in industry. They are attractive because the addition of short fibres to the thermoplastic results in some very cost effective property improvements whilst retaining the processability of the thermoplastic. The main applications are for relatively small intricate, load bearing components. These vary from small mechanical details, such as gearwheels, pawls and levers to castings for electric hand tools and electronic equipments.

There are now two main classes of these moulding compounds, those containing very short fibres and those containing longer fibres. The fibres are most frequently E-glass of 10-20 μm diameter, the short fibres are typically less than 1 mm long in the moulding compound, the long fibres are typically 10 mm long at this stage. In both cases, some fibre breakage occurs during moulding so the lengths will be further reduced. The short fibre material is manufactured by mixing either prechopped E-glass roving or continuous glass roving with the thermoplastic in a twin-screw compounding extruder. The most effective technology is to introduce the continuous roving at a venting port directly into the molten thermoplastic. The high shear in the extruder ensures the fibre and plastic are intimately mixed; in this type of materials the fibres are dispersed as individual filaments instead of bundles or strands, as is usual in bulk or sheet moulding compounds, for example. The compound is then extruded through a 'spaghetti' die then either chilled and chopped into pellets or chopped directly with a hot face cutter. The resultant pellets or chopped directly with a hot face cutter. The resultant pellets are dried and contain up to 30% by volume of fibre (up to 50 % by weight according to the density of the polymer).

Passing continuous roving through liquid polymer using a fluidized bed of polymer powder or a crosshead die on an extruder makes the long fibre material. The material is passed through a die to force the polymer to infiltrate the roving. Finally it is chopped into pellets, typically 10 mm long and 4 mm in diameter. The fibre runs the full length of these pellets. When moulded, some fibre breakage occurs but the overall fibre length distribution will be much higher than for the short fibre material. This allows greater reinforcement efficiency to be attained, together with greater relative toughness.

The attraction of these materials lies in a combination of enhanced mechanical properties coupled with good processability. In general, stiffness is strongly enhanced in
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proportion to the stiffness of the fibre used, the fibre fraction, the length distribution and the orientation distribution achieved in the moulding. Strength is also enhanced but not as much as the stiffness; this is due to a reduction in the fracture strain. This low fracture strain, often only 1-2 %, is sometimes an embarrassment but the impact energy is often enhanced by fibre reinforcement. A better balance of properties is often achieved by a judicious combination of fibre reinforcement and rubber particle toughening. There are two further important effects: the heat distortion temperature is raised and the coefficient of thermal expansion is reduced. This allows the fibre reinforced grade to be utilized at higher service temperatures, reduces in-mould shrinkage and generally improves dimensional stability. Dimensional stability is very important for intricate components, which need to be manufactured to close tolerances. Some typical properties are given in Table 3.

Processability is generally very good. Although the addition of the fibres tends to increase the melt viscosity and hence the mouldability, the pseudoplastic nature of thermoplastics means their apparent viscosity decreases with increased shear rate. The presence of rigid fibres in the melt has the effect of increasing the local shear rate so mouldability remains good up to quite high fibre loadings. The main processing problems arise from flow induced fibre orientation. In regiments of converging flow, the fibres tend to align in the direction of the flow; in regiments of divergent flow, the opposite is the case. Practical mouldings tend to be composed of thin shell-like sections so good heat transfer to the mould can be achieved with consequent reduction in the moulding cycle time. In these sections, the orientation is modified by interactions at the (cold) mould surfaces. This may affect the mechanical properties of the moulding, but the more important implication is that it can lead to distortion due to differential shrinkage between sections with different fibre orientations. This can destroy the advantages of the reduced coefficient of thermal expansion mentioned above. A further effect is the formation of knit or weld lines where melt fronts intersect. This occurs wherever there is bifurcated flow, e.g. around a cored feature, or when multiple gates are used (Figure 1). These can be controlled by multilevel feed technology.
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Thermoplastic polymers differ from thermosetting resins. They are not crosslinked and derive their strength and stiffness from the spatial arrangement of the monomer units that form high molecular weight chains. In general, fibre reinforcement is used in discontinuous or short fibre form to extend the mechanical property advantages which in turn depend on the average length of the fibres on moulding. While the property gain from adding fibre reinforcement may seem modest in comparison with continuous fibre systems, the improvements in either Young's modulus or toughness justify their use for many applications.

In amorphous materials, heating leads to polymer chain disentanglement and a gradual change from a rigid to a viscous liquid. In crystalline materials, heating results in the sharp melting of the crystalline phase to give an amorphous liquid. Both amorphous and crystalline polymers may have anisotropic properties resulting from molecular orientation induced during processing and solidification. In composite systems, however, the properties are largely dictated by the character of the fibre reinforcement.

These polymer composite systems are often termed 'engineering compounds' because their mechanical properties extend beyond the commodity levels expected from bulk polymers and they are used in multicomponent compounds for specific applications. Compounds may include colorants, viscosity modifiers, stabilizers, matrix modifiers, interfacial bond enhancers or secondary fillers.

Figure 1 Weld or 'knit' lines are formed wherever melt fronts rejoin after flow around a cored feature. In this case the flow is illustrated for a centre-gated plate with three circular holes.
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Table 3 Typical properties of selected short fibre reinforced thermoplastics

<table>
<thead>
<tr>
<th>Polymer</th>
<th>Fibre</th>
<th>V_1</th>
<th>E (GPa)</th>
<th>X_T (MPa)</th>
<th>Charpy impact (KJm²)</th>
<th>HDT (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Polypropylene</td>
<td>None</td>
<td>0</td>
<td>1.9</td>
<td>39</td>
<td>2.7</td>
<td>60</td>
</tr>
<tr>
<td>Polypropylene Glass</td>
<td>0.20</td>
<td>7.5</td>
<td>110</td>
<td>8.0</td>
<td>155</td>
<td></td>
</tr>
<tr>
<td>Polyamide 6,6 None</td>
<td>0</td>
<td>3.2</td>
<td>105</td>
<td>&gt;25</td>
<td>100</td>
<td></td>
</tr>
<tr>
<td>Polyamide 6,6 Glass</td>
<td>0.20</td>
<td>10</td>
<td>230</td>
<td>40</td>
<td>250</td>
<td></td>
</tr>
<tr>
<td>Polyamide 6,6 Carbon</td>
<td>0.20</td>
<td>20</td>
<td>250</td>
<td>10</td>
<td>255</td>
<td></td>
</tr>
<tr>
<td>Polycarbonate Glass</td>
<td>0.20</td>
<td>9.0</td>
<td>135</td>
<td>10</td>
<td>160</td>
<td></td>
</tr>
<tr>
<td>Polyoxymethylene Glass</td>
<td>0.20</td>
<td>9.0</td>
<td>140</td>
<td>9.0</td>
<td>165</td>
<td></td>
</tr>
<tr>
<td>Polyphenylenesulphide Glass</td>
<td>0.20</td>
<td>11</td>
<td>155</td>
<td>20</td>
<td>263</td>
<td></td>
</tr>
<tr>
<td>Polyphenylenesulphide Carbon</td>
<td>0.20</td>
<td>17</td>
<td>185</td>
<td>20</td>
<td>263</td>
<td></td>
</tr>
<tr>
<td>Poly ether ether ketone Carbon</td>
<td>0.20</td>
<td>16</td>
<td>215</td>
<td>-</td>
<td>310</td>
<td></td>
</tr>
</tbody>
</table>

V_1 = Volume fraction, E Young’s modulus, X_T = Tensile strength, HDT = Heat distortion temperature

These commodity polymers are typically used in conjunction with short fibre reinforcement; mineral fillers are also commonly used in lower performance applications. E-glass fibres are used in the vast majority of reinforced injection moulding compounds on cost grounds, but carbon fibres (usually high strength type) and Kevlar type fibres may be compounded for specialist applications. Conductive fibres such as steel are used to impart dielectric properties.

The importance of commodity polymers may be seen from Figure 2. The left triangle shows the prediction made in 1975 for 1995. It was presumed that commodity polymers would be more or less wiped out and engineering and specialty polymers will rule the market. The right triangle shows the actual situation for 1997 where commodity polymers still hold more than 80% of the polymer market. This clearly shows the importance and need for upgrading commodity polymers for more critical applications.
1.3.1 Fibres used in composites

The fibre contributes the high strength and modulus to the composite. It is the element that provides the resistance to breakage and bending under the applied stress or load.

The most common fibre reinforcement is glass, usually E-glass. Glass fibres are usually 5-20 μm in diameter and are round and fairly smooth, though their surfaces are never completely defect free. For some short fibre reinforced composites they are provided pre-chopped in length of a few millimeters. A coating is commonly applied to glass fibres to improve processability and to reduce damage during handling. Surface coatings may also be applied to improve the adhesion between the matrix and the fibre.

Carbon fibres, often called graphite fibres although full graphitization is not achieved in their manufacture, are achieving wide acceptance for aircraft applications because of their advanced properties. Two categories of carbon fibres have predominated, distinguished primarily by their elastic moduli: high-strength carbon fibres with a typical modulus range 207-241 GPa and high-modulus carbon fibres with a typical modulus range of 345-380 GPa. Other higher-modulus carbon fibres, more loosely categorized as very high-modulus carbon fibres and ultrahigh-modulus carbon fibres, with moduli up to 830 GPa are also available.

Metal fibres can be used to provide electrical conductivity. The major applications for metal fibres filled conductive thermoplastic composites is as housings for computers and other electrical goods requiring protection against electromagnetic interference and electrostatic
discharge. Stainless steel fibres are used and loadings of the order of 1% by volume (depending upon the application) are common. Commercial grades are available based on several polymers including acrylonitrile butadiene styrene (ABS), various nylons, polycarbonate and polypropylene.

The aliphatic polyamides or Nylons were the first fully synthetic fibres to achieve commercial success (1939). Nylon is a condensation polymer of a diamine and a dicarboxylic acid. Because a variety of diamines and dicarboxylic acids can be produced, there are very large numbers of polyamide materials available to prepare nylon fibres. The most common versions are nylon 6,6 and nylon 6. Nylon 6,6 which is widely used as fibre is made from adipic acid and hexamethylene diamine. The commercial production of nylon 6 begins with caprolactum. Fibres are produced commercially in various parts of the world but nylon 6,6 has been preferred in non American markets, nylon 6 is more popular in Europe and elsewhere. The polyamide is melt spun and drawn after cooling to give the desired properties for each intended use. The fibre has outstanding durability and excellent physical properties. The main features are exceptional strength, high elastic recovery, abrasion resistance, lusture, washability, resistance to damage from oil and many chemicals, high resilience, colourability, relatively insensitivity to moisture, smoothness and softness. Like polyester, nylon has high melting point which conveys good high temperature performance. Its toughness makes it a major fibre of choice in carpets. Because of excellent tear strength it is used as a blending fibre in some cases. In certain applications, the performance of nylon fibre is hard to beat. Because of its high cost it is used in specialized applications where its performance can justify the cost. Nylon fibres are used for the manufacture of apittatable pie fibres. Non wovens developed from nylon are used in automobile products, athletic wear and conveyer belts.

In the case of rubbery composites, cellulose fibres have been found to give better reinforcement than glass or carbon fibres. The reason for this is probably that the flexibility of cellulose fibres results in less breakage during processing than happens with the brittle glass or carbon fibres which have less resistance to bending. The fibre length used in the preparation of rubber composites is critical. It should not be too long for the fibres will get entangled, causing problems with dispersion; if it is too short the stress transfer area is too small and the fibres do not provide effective reinforcement.
1.3.2 Matrix materials used in composites

The main roles of the matrix are to transmit and distribute stress on to the individual fibres and to maintain the fibres separated and in the desired orientation. The matrix also provides protection against fibre abrasion as well as fibre exposure to moisture or other environmental condition and causes the fibres to act as a team in resisting failure or deformation under load. The maximum service temperature of the composites is limited by matrix.

The most common thermoplastic matrices for generating short fibre reinforced composites are based on polypropylene and nylon. Higher performance thermoplastic composites use poly (ether sulphone) or poly (ether ether ketone)(PEEK), giving higher stiffness and higher working temperature. Also with thermoplastic behaviour are the thermotropic liquid crystal polymers in which the self reinforcing property is further enhanced by the inclusion of fibres. Polyimides, which can show either thermoset or thermoplastic characteristics, are also available in reinforced form.

Thermoset matrices include epoxies and phenolics. Thermosets are generally less suitable than thermoplastics for mass production but the improved properties achieved by adding fibre reinforcement has provided added incentive to develop a suitable means of fabrication. Both natural and synthetic rubbers are candidates for short fibre reinforcement.

1.3.3 Preparation of short fibre thermoplastic composites

Short fibre reinforced thermoplastics are most commonly supplied in the form of granules suitable for use in injection moulding machines. The granules are roughly cylindrical, measuring 3-5 mm long and about 3 mm diameter and the fibres are dispersed fairly uniformly within them. To make the granules, chopped fibres and unfilled thermoplastic polymer powder or granules are fed into an extruder. Mixing occurs on the passage through the extruder and the melt is passed through a die to make a lace that is chopped into granules of the required length. Fibre breakage is a major problem during this process and the design of the screw is of some importance, deep flights being required. Twin screw extruders are often preferred and the fibres are sometimes fed into the barrel part way along so that they enter directly into melt: this is found to reduce fibre breakage.
In most of the common short fibre thermoplastic moulding materials, the original fibre length is around 3 mm but few fibres survive mixing and moulding intact, with most fibres present in mouldings measuring fractions of a millimeter. Another class of compound is available known as long fibre thermoplastic, in which the granules measure about 10 mm and contain parallel continuous fibres than span the full length. These granules are produced by chopping up pultruded rod in which a continuous tow of fibres is wetted by the polymer when forced through a heated die. The long fibre compounds are found to behave surprisingly well in conventional injection moulding machinery and the fibre lengths are preserved more completely than in the case with compounds in which the fibres are shorter to begin with.

1.3.4 Mechanical properties of fibre reinforced thermoplastics

Fibre loading levels can have a significant effect on mechanical properties, with higher concentrations of fibre providing an increase in modulus and strength. In general, loadings are typically in the 20-30 wt% range, with loadings up to 50% commercially available [108]. As the level of reinforcement is increased, the mechanical properties also rise, but this is not a linear relationship [109]. An excellent investigation of how loading level affects reinforcement was undertaken by Hiscock and Bigg [110] for reinforced polyamide 6 (nylon 6). Loadings of 10 and 25% were studied, using different types of glass fibre and various effects of silane treatment. 10 wt% glass fibre in PA6 gave a tensile strength of 101 MPa and a modulus of 5.1 GPa while PA6 with 25 wt% glass possessed a strength of 169 MPa and a modulus of 11.1 GPa. These results show that increasing the loading by two and one-half times does not produce a commensurate increase in any of the mechanical properties. This should be expected, because as the concentration of fibre increases, it allows more fibre-fibre interactions which decrease the average fibre size. Smaller fibre aspect ratios increase the importance of stress concentration at the fibre ends, resulting in earlier failure and lower mechanical properties. Another study relating loading level, mechanical properties, and efficiency of reinforcement was performed by Xavier and Misra [111]. Polypropylene was loaded with 10, 20, 28, and 35 wt% glass and injection molded into ASTM standard tensile bars. As the loading was increased from 10 to 35 wt%, the tensile modulus rose from 1.59 to 3.41 GPa. Meanwhile, the average fibre length decreased from 0.55 mm to 0.35 mm and the efficiency of reinforcement decreased from 0.26 to 0.22. This
again confirms the relationship that higher loadings produce both lower fibre lengths and a lower efficiency of reinforcement.

Using smaller diameter fibres can also influence final mechanical properties [112-113]. Watkins et al. [114] studied glass fibres with diameters from 13.5 mm to 6.5 mm blended in polyamide 6,6 (nylon 6,6), poly(butylene terephthalate) (PBT), poly(ether ether ketone) (PEEK), polycarbonate (PC), and poly(ether imide) (PEI) at loadings from 20 to 40 wt%. All materials were injection molded into ASTM test specimens, which were tested for tensile strength and unnotched impact strength. For every weight fraction of glass, both the tensile strength and impact strength was higher when smaller diameter fibres were used. A typical example is with PA 6,6 at 30 wt%. This showed an increase in tensile strength from 176.6 MPa to 198.7 MPa and in impact strength from 811.7 J/m to 1233 J/m, establishing a strong relationship between smaller fibre diameter and higher mechanical properties.

However, this relationship may not hold for very small fibre diameters. There may be an optimum fibre size to attain the highest possible mechanical properties. In another study, fibres with diameters of 13, 7, 4, and 0.5 microns were used in a PA 6,6 matrix [115]. This investigation showed optimal properties at 7 mm, with 4 mm giving properties equal to the 13 mm fibres and 0.5 mm fibres yielding the lowest tensile and flexural values.

It was speculated that the existence of an optimum fibre size is due to two competing relationships. Loading polymer melt with fibres having smaller diameters results in a larger number of fibres in the melt at the same weight fraction. For example, the number of 6.5 mm diameter filaments would be four times the number of 13 mm diameter fibres at the same weight fraction of reinforcement. This provides more surface area per unit volume of reinforcement, which is beneficial because of the potential for better stress transfer. However, having more fibres also means having more fibre ends, which serve as stress concentrators and lower mechanical properties. Therefore, there may exist a fibre diameter which maximizes the benefits of high surface area while minimizing the detrimental effects associated with the number of fibre ends.

Fibre length has a substantial effect on mechanical properties, with longer fibres providing more reinforcement to the matrix. The best illustration of this is provided by comparing short fibre reinforcement with long fibre reinforcement [116-117]. Using PA 6,6 with 50 wt% glass loading, the short glass fibre had an average length of 0.33 mm while the long fibre had an
average length of 2.9 mm. The higher aspect ratios of the long fibre reinforcement consistently provided mechanical properties superior to those measured from short fibre reinforced composites. The most dramatic improvement was observed in notched Izod testing, where the impact strength was 261 J/m for the long fibre case and 139 J/m for short fibre reinforcement. In order to accurately correlate mechanical properties to fibre alignment, it is necessary to produce composite plaques where the fibre alignment has been well controlled. Often, this is accomplished by compression molding plaques using strands with a high degree of uniaxial alignment. For example, McNally [118] extruded 30 wt% glass-reinforced PBT to obtain highly oriented strands. After confirming that the glass was highly oriented by using scanning electron microscopy, the strands were then uniaxially compression molded into plaques. The plaques were cut at angles of 0°, 22°, 45°, 67°, and 90° with respect to the fibre orientation to determine how tensile properties changed. The tensile strength, tensile modulus, flexural strength, and flexural modulus were all observed to decrease by about one-half as the testing proceeded to 90° alignment. Impact testing was even more sensitive to fibre alignment. The highest notched Izod impact strength was 69.9 J/m while the lowest was 32.5 J/m. The reversed notched Izod tests showed similar results, with an impact strength of 265 J/m when the fibres were at a fibre orientation angle of 0°, while just 99.8 J/m when the fibre orientation angle was 90°.

Blumentritt et al. [119-120] also investigated compression molded samples, comparing random alignment with uniaxial alignment using a variety of different resins, types of fibre, and loading levels. These studies showed that with glass fibre, a random-in-plane alignment gave significantly lower tensile properties, but the magnitude of the decrease varied from material to material. For instance, loading high density polyethylene (HDPE) with 20 vol% glass produced composites with a tensile strength of 142.7 MPa in unidirectional alignment but only 42.13 MPa in the random mode.

Meanwhile, polycarbonate using the same vol% glass had tensile strengths of 114.4 MPa and 61.36 MPa under the same two methods of alignment. This indicates fibre alignment is not the only factor which affects mechanical performance; interfacial adhesion and how the fibre influences matrix properties may also have a significant effect. The influence of interfacial adhesion on the mechanical properties of glass fibre filled PA6 was examined by Bader and Collins [121]. The test samples were prepared by injection molding, using both an end-gated as
well as a side-gated test bars. For dry endgated samples containing 25 wt% glass fibres (12 mm in diameter), one set possessed fibres coated with a silane coupling agent while the second was not. The coated glass had a tensile modulus of 11.1 GPa, a tensile strength of 169 MPa, a notched Charpy impact energy of 19.7 KJ/m², and an interfacial shear strength of 44 MPa. Meanwhile, the glass fibres without the silane coupling agent possessed lower mechanical properties, with a stiffness of 10.7 GPa, a strength of 102 MPa, an impact energy of 16.8 KJ/m², and an interfacial shear strength of 35 MPa. These results demonstrate that interfacial adhesion can play an important role in maximizing mechanical properties.

One investigation which examined the influence of flow kinematics on the mechanical properties of filled polymers was undertaken by Darlington et al. [122], using an end-gated circular disk. The diameter and thickness of the disk was varied to determine the effect those parameters would have on mechanical behavior. It was found that making the disk thinner caused less mechanical anisotropy and that increasing the diameter both reduced anisotropy and improved the measured properties significantly. They attributed this to a balance between the fibre orientation in the core and the surface, with the core's orientation being transverse to the major flow direction. It was also noted that in order to create this balance, the flow behavior of the fluid had to be considered.

Pipes and coworkers [123] moulded end gated tensile bars for their examinations of fibre orientation. The bars were then cut into different sections to examine how the orientation in each layer is reflected in mechanical properties. The edge section was determined to have an orientation parameter of 0.8 and the core a parameter of -0.5. The edge showed a longitudinal tensile modulus of 18.3 GPa and a transverse modulus of 9.0 GPa while the core had moduli of 9.9 GPa and 15.2 GPa in the same two directions. This again shows that the flow kinematics creates fibre orientation in the bars and the change in orientation through the thickness has a measurable effect on mechanical properties. Notch sensitivity between the two sections was determined by drilling holes of different diameters through the test samples. It was found that the more highly oriented skin section was more sensitive to the holes, indicating that strength reduction between machined notches and molded notches will not be equivalent.
1.4 Short fibre reinforcement-stress transfer in discontinuous fibre composites

A discontinuous fibre composite is one that contains relatively short discrete lengths of the fibre dispersed within the matrix. The fibres may be aligned in one direction but are more usually in a random, or semirandom configuration. When an external load is applied to the composite, the fibres are loaded as a result of stress transfer from the matrix to the fibre across the fibre-matrix interface. The degree of reinforcement that may be attained is a function of the fibre fraction, the fibre orientation distribution (FOD), the fibre length distribution (FLD) and the efficiency of stress transfer at the interface. In general the reinforcement is more in the principal stress direction and the interface is 'strong'.

One of the earliest theories of reinforcement developed by Cox [124] is based on shear-lag mechanism observed in fibrous composites. According to Cox, in shear lag analysis, the main aspects of controlling the properties of a composite are critical length of the fibre and interfacial shear strength between fibre and matrix. The critical length of the fibre ($l_c$) in composites is a parameter, which determines the amount of stress transferred to the fibre. That is, if the length to diameter ratio is higher than the critical aspect ratio, composites show superior properties. When the aspect ratio is smaller than critical aspect ratio, composites show inferior properties. In Cox's treatment, interfacial shear strength is produced on the surface of the fibre due to the 'shear lag' between the fibre and the matrix during the failure of the composite.

Cox theory deals with the net tensile load across the fibre of length $l$ and radius $r$ which must be balanced by the shear force and the fibre-matrix interface. Shear stress $\tau$ at the fibre-matrix interface will vary along the fibre, so also will the tensile stress in the fibre. A schematic representation of Cox-shear lag analysis is shown in Figure 3.

Figure 3 The representative element used in the Cox analysis. The inner cylinder represents the fibre and the outer annulus the matrix.
According to this theory, longitudinal Young’s modulus $M_t$ is given by the Equation 1.a

$$M_t = M_f V_f \left(1 - \frac{\tanh \beta l/2}{\beta l/2}\right) + M_m V_m$$

(1.a)

where $M_m$ and $M_f$ are Young’s moduli of matrix and fibre respectively, $r$ is the radius of the fibre, $G_m$, the shear modulus of matrix $R$, the centre to centre distance of the fibres, and $A_f$, the area of the fibre.

$$\beta = \left[\frac{2 \pi G_m}{M_f A_f \left(\frac{r}{r_f}\right)}\right]^{1/2}$$

(1.b)

For hexagonally packed fibres,

$$R = \left[\frac{2 \pi r^2}{3^{2/3} V_f}\right]^{1/2}$$

(1.c)

For square packed fibres,

$$R = r\left[\frac{\pi}{4 V_f}\right]^{1/2}$$

(1.d)

According to Cox’s model, tensile strength ($T_c$) is given by

$$T_c = T_f V_f \left(1 - \frac{\tanh \beta l/2}{\beta l/2}\right) + T_m V_m$$

(1.f)

$\beta$ is given by the Equation 1.b.

But Cox’s shear-lag analysis has two major disadvantages. The first one is that the stress amplification effects at the fibre ends are not taken into account, and the second is that the matrix tensile stress possesses no radial dependence.

The alternative model, due to Kelly and Tyson [125], is based on the concept of frictional stress at the interface. It is considered that a constant shear stress is induced from the fibre ends, this results in a linear stress build up. The frictional stress may be regarded as the
interface shear strength ($\tau_i$); this concept is often used for the experimental estimation of interface shear strength by the fragmentation or pull out test. The model is useful in that it allows a precise definition of the transfer aspect ratio $R_t$. It should be noted that this transfer region increases as the applied strain is increased. If the fibre aspect ratio exceeds $2R_t$, there will be a plateau region along the central portion of the fibre. The reinforcement efficiency is obtained from a similar ratio of areas, as for Cox model and efficiency increases with fibre aspect ratio in a similar manner.

Most discontinuous fibre composites contain fibres with a wide distribution of lengths distributed in a semi random orientation. However, flow processes during fabrication often result in more complex distributions, dependent on component geometry and moulding parameters. To treat the problem of length variations, or more properly aspect ratio distribution. Then, if the interface shear strength is known, the efficiency of each fibre may be determined using the Kelly-Tyson model and the overall efficiency may be computed. Likewise, if the fibre orientation distribution is determined, a further efficiency factor may be computed using standard angle ply theory. This has been attempted by several workers [126] who have obtained quite reasonable predictions for the stiffness of short fibre systems. The simplest procedure is to use the aspect ratio and orientation data to produce two constants which may be applied to the Voigt equation.

$$E_c = \eta_0 \eta_1 E_f V_f + E_m V_m$$

where $\eta_1$ and $\eta_0$ are the length and orientation constants, respectively. They have a maximum value of unity (long aligned fibres) when the reinforcement efficiency is equal to that of continuous fibres. For short fibre reinforced thermoplastic moulding compounds, value of 0.3-0.5 may be considered typical.

The Bowyer and Bader methodology can be used to predict the stress strain response of short fibre reinforced plastics. According to Bowyer and Bader model, tensile strength of short fibre reinforced thermoplastic composites is the sum of contributions from subcritical and supercritical fibres and that from the matrix [127]. Tensile strength is given by

$$T_c = T_f K_1 K_2 V_f + T_m V_m$$

where $K_1$ is the fibre orientation factor. Depending on fibre orientations, $K_1$ also changes [128]. $K_2$ is the fibre length factor.
For fibres with $1 > l_c$

$$K_1 = 1 - \frac{l}{2l_c} \quad (1.i)$$

For fibres with $l < l_c$

$$K_2 = \frac{l}{2l_c} \quad (1.j)$$

where $l$ is the length of the fibre and $l_c$ is the critical length of the fibre. Young's modulus also can be calculated using the same equation.

$$M_c = M_f K_1 V_f + M_m V_m \quad (1.k)$$

### 1.5 Fabrication of short fibre thermoplastic composite - Injection moulding

One of the most common processing methods for thermoplastics is injection moulding [129-131]. The list of artefacts manufactured using this process is almost endless and includes electric drill castings, gearwheels, business machine housings, telephones and brief-cases. The process has been in existence for well over 100 years, although the development of the technique did not really get under way until the 1920s. In essence, the original concepts of the process were based on the pressure die casting of metals.

In principle, the injection moulding process is very straightforward. The polymer, in either granular or powder form is fed from a hopper into a heated barrel, where it softens and becomes a viscous melt. It is then forced under high pressure into a relatively cold mould cavity. When the polymer in the cavity has had sufficient time to solidify (at least partially), the mould is opened and the fabricated part is ejected. The cycles of operations are then repeated. Correctly controlled, this process is very versatile and is capable of fabricating very complex shaped components with considerable speed and precision.

The earlier injection moulding machines were of the plunger variety and there are still many of these machines in use today. The process of melting the polymer relies entirely on heat conduction from the barrel walls. In view of the low thermal conductivity of polymers, this results in a very non-uniform temperature distribution throughout the melt. This implies that any additives, e.g. pigments or antioxidants remain poorly dispersed with consequential problems in the final artefact. However, for certain applications where it is desirable to minimize deleterious effects on the additives, e.g. where processing fibre reinforced thermoplastics, the simple plunger machine does offer some advantages.
Many of the disadvantages associated with the plunger type injection moulding machine are overcome in the screw injection moulder, which now largely dominates the market. Basically, this machine uses an extruder type screw which acts in a dual role; it is initially used for the injection process itself. The arrangement of the screw in the barrel is shown schematically in Figure 3. The mould is initially closed and melt is injected into the cavity using the screw as a plunger. The pressure on the screw is maintained until solidification at the gate(s) has occurred. The screw is then allowed to rotate so it conveys fresh polymer towards its front. But the moulded part is still in place, so the screw moves backwards against a predetermined back pressure and the melt is fully homogenized, ready for the next shot. During this operation, the fabricated part has cooled sufficiently so the mould can be opened and the part ejected. The mould then closes and the whole cycle repeats. The overall cycle time is typically a few minutes, although this depends on the dimensions of the part. The briefest part of the cycle is injection, which often takes only a few seconds; much of the time is spent in waiting for the moulded artefact to solidify.

The size of an injection moulding machine is usually defined by its capacity to mould in a single shot, e.g. a medium sized machine would be rated 200 g. Machines used for the production of very large items, e.g. rubbish bins, are physically very large pieces of engineering equipment and demand considerable care in operation. The pressure required to inject the polymer melt into the mould can be very high (up to 200 MPa) and this demands the use of high tensile steels for both the injection unit and the mould.

The properties of the moulded part are highly dependent on the processing conditions employed. Barrel and mould temperatures, injection speed and pressure, screw back speed and pressure all influence the properties of the moulded artefact. Especially with some of the newer ‘engineering’ thermoplastics, minor changes in processing conditions can greatly influence part quality; consequently many of the new generation of injection moulding machines are equipped with ‘process controllers’. They allow the continuous monitoring of certain key parameters and enable corrective actions to be taken by means of feedback controllers. Process controllers have done much to develop the injection moulding process into a rapid fabrication route for precision parts.
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Figure 3 (a) Screw injection moulding machine
(b) Cycle of operations in injection moulding

1.6 Parameters influencing the characteristics of short fibre thermoplastic composites

Fibre aspect ratio, fibre-matrix interaction, short fibre length, fibre orientation and barrel residence time are the major factors which affect the properties of the injection molded thermoplastic composites.

1.6.1 Fibre aspect ratio

Aspect ratio is the l/d ratio of the fibre and is of great significance in deciding the level of reinforcement that can be effected by a fibre.

1.6.2 Fibre-matrix interaction

Once the manufacturing process has successfully achieved a uniform dispersion of matrix material around the reinforcing filaments, the fibre-matrix surface interaction must be considered. Fibre-matrix adhesion is widely considered a necessary condition to ensure good composite mechanical
properties [Drzal and Madhukar, 1993]. If there is no adhesion between the two, the composite will respond as if it were the bulk matrix material with voids retaining the shape of the included fibres (at low strains). At higher strains, Poisson's effect may bring about mechanical friction forces between the fibre and matrix phase, thus causing the fibres to bring about a greater influence in material properties.

Adhesion in thermoplastic composite systems is usually enhanced using fibre surface treatments. Itoi and Yamada studied the effect of carbon fibre surface modification by oxidation on adhesion with polyetherimide [1992]. Nitric acid and hydrogen peroxide were used as oxidation agents. Treated fibres were powder impregnated by the polyetherimide after which unidirectional laminates were obtained. Improvements in interfacial adhesion were monitored using interlaminar shear strength (ILSS) and transverse flexural strength. Interfacial bonding quality improvements were noted in both cases. Both ILSS and transverse flexural strength increased two-fold with fibre treatment. Microscopic examination of fracture surfaces showed excellent bonding after fibre treatment.

Grafting reaction of maleic anhydride onto polypropylene by reactive processing involves reacting the polymer melt with maleic anhydride, in the presence of organic peroxides. Investigations regarding such reactions have been carried out in equipments like torque rheometers, single screw extruders and in twin screw extruders [132-141]. Y.Li et al. reported that the addition of styrene as comonomer to the melt grafting system of maleic anhydride onto polypropylene could greatly improve the graft degree of maleic anhydride [141-145].

1.6.3 Short fibre length

When the fibres are of finite length, stress is assumed to be transferred from the matrix to the fibre by a shear transfer mechanism. For a given fibre, there is a minimum fibre length required to build up the shear stress between fibre and resin to the value of tensile fracture stress of the fibre. Over or equal to this length, the maximum value of the load transfer from the matrix to the fibre can occur. If the fibre length is less than this length, the matrix can not effectively grip the fibre to take the strain and the fibres will slip and be pulled out, instead of being broken under tension. The composite will then exhibit lower mechanical performance. This shortest fibre length (pull-out length) is called the critical fibre length (or the maximum value of load transfer length). This fibre length is an important system property and affects ultimately the strength and elastic modulus of composites.
1.6.4 Fibre orientation

The properties of short fibre-polymer composites are strongly dependent on the fibre orientation and/or orientation distribution. Enormous benefits would be possible, if methods could be developed for exercising tight control over the fibre orientation distribution in moldings made from short fibre polymer composites. In extruded products, the average alignment along the extrusion direction for short fibres is 10-20°, while in injection-molded products the orientation distribution is much more complicated. Several layers of different orientation may develop, depending on the mold geometry and processing conditions, but it is difficult to control. Variables affecting fibre orientation are,

- Flow area reduction/expansion ratio
- Angle of convergence
- Flow Channel diameter (relative to fibre length): wall thickness
- Barrel Temperature, matrix viscosity
- Pressure
- Plunger/ Screw speed
- Flow instabilities, flow rate
- Fibre loading
- Fibre length/ aspect ratio (L/D)
- State of fibre aggregation
- State of compaction
- Residence Time in the mould

1.6.5 Barrel residence time

There is time and temperature dependence for the rate at which thermoplastic materials will degrade. Plastics may degrade when exposed to "high" temperature for a short period of time, or degrade when exposed to "low" temperature for a long period of time. During processing, temperature settings and the amount of time, material is in the injection cylinder are important. The actual residence time may be determined experimentally, or roughly estimated from standard formula.
1.7 Prediction of composite properties by simulation

For the effective design of short-fibre reinforced polymer-based composites, computer simulation can be used. Because of highly nonlinear and complex flow characteristics of polymer and particle-contained suspensions, only numerical solutions including appropriate models are manageable. This economic technique offers a detailed understanding of the process and aids in identifying the cause of the problems.

The mechanical performance of injection moulded short-fibre reinforced thermoplastic components is anisotropic and is highly dependent on the fibre orientation and distribution. Short-fibre reinforced composites are widely used for their high strength to weight ratios and remarkably enhanced physical properties compared to pure polymer products. Compression moulding, extrusion and injection moulding are some of the processes often used. The fibres are suspended in the polymer matrix, and they orient themselves in response to the interactions among kinematics of the flow, other neighbouring fibres and mould cavity. Fibre reinforced composite typically shows anisotropic mechanical, thermal and rheological properties. Prediction of thermo-mechanical properties with given fibre orientation has been well developed to some extent. Therefore, prediction of fibre orientation during the transient mould filling is important for the prediction of such anisotropic properties of final plastic part.

1.7.1 Finite Element Analysis (FEA)

One of the most widely utilized numerical methods for solving engineering problems is finite element analysis. The basic idea behind finite element modelling is dividing a given geometry in a mesh of much smaller elements, hence the name. Each element consists of a number of nodes, which are shared with other adjacent elements. The elements also have defined properties such as modulus of elasticity, Poison's ratio, and any other physical properties that are necessary for the model. Boundary conditions such as loads and torques are added to the mesh to simulate the real world application of the geometry. The FEA program then solves for stress, strain and any other desired output using a stiffness matrix that is generated from the mesh and boundary conditions. Hence, FEA is a very useful design tool that allows initial design analysis to be done with minimal time and expense.
FEA simulation can show how solid materials (including rubber) will deform under stress, including applied forces, pressures and temperatures. Analysis that can be performed include, static stress/displacement analysis, dynamic stress/displacement analysis, transient or steady state heat transfer analysis, transient or steady-state mass diffusion analysis, steady state transport analysis, coupled thermo-mechanical and coupled thermo-electrical analysis, flow inside mould etc.

1.8 Objectives and scope of the work

In the automotive industry, polymers have made a major inroad in the past decades to make parts such as body panels, underbody structures and dashboards, seating components, front ends and bumpers. At present polypropylene (PP) is used for a large number of such kind of applications. It is cheap, can be reprocessed several times without significant loss of properties and can be easily modified to achieve specific requirements. In order to compete with standard engineering plastics such as polyamides, in terms of the high demands on stiffness and strength, PP has to be reinforced and glass fibre is the major reinforcing agent used for this purpose. Although both PP and glass are recyclable, when combined they are not that easy to recycle, neither in mechanical recycling nor in the end-of-life, viz. thermal recycling (incineration). Current trends toward environmentally friendly composite systems focus on the use of natural fibres like flax and hemp as alternatives for glass fibres. Although these fibres do have some ecological advantages over glass fibres since they are renewable and can be incinerated, natural fibres do not have advantages with respect to mechanical recycling. In fact, next to mechanical degradation, the relatively poor thermal stability of these ligno-cellulose fibres may lead to severe additional thermal degradation during subsequent recycling or reprocessing steps. Especially in the case of a polymer like PP, which has the lowest environmental impact of all polymers because of its excellent recyclability, the addition of natural fibres may significantly lower its eco-performance. Hence it is proposed to reinforce standard plastics like PP and HDPE with polymeric fibres to generate a new class of recyclable polymer composite.
Chapter 1

The specific objectives of the work are,

- Generate recyclable PP and HDPE composites by reinforcing them with short nylon fibres.
- Investigate methods for enhancing the properties of the composite by improving the fibre-matrix interaction.
- Characterise the composites using mechanical (both static and dynamic), thermal and rheological measurements.
- Suggest methods for obtaining the optimum properties of these composite by simulation technique.
- Evaluate the recyclability of the composites.
- Use process-waste nylon fibres for reinforcement.
1.9 References

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