MECHANICAL BEHAVIOUR AND FRACTURE TOUGHNESS OF UNFILLED AND SHORT FIBRE FILLED POLYPROPYLENE BOTH DRAWN AND UNDRAWN

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Experimental investigation the effect of fibre content and draw ratio on the mechanical properties of unfilled and short glass fibre filled polypropylene

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Abstract

The goal of this research is to investigate the combined effects of glass fibre reinforcement and molecular orientation in polypropylene-short glass fibre composites. Specimens have been fabricated using the injection moulding process and drawn using a small die drawing rig. The effects of die drawing on the fibre composites are complex, with the drawing process orienting both the polymer molecules and the glass fibres. This may be accompanied by the creation of voids in the polymer matrix and their destruction in the compressive stress field thus restoring the interfacial contact area between fibre and matrix.

Unfilled and short glass fibre filled polypropylene specimens, with fibre content 7% wt, 13%wt, 27%wt, and 55%wt, were injection moulded prior to the die drawing process. An experimental program of die drawing within an oven at elevated temperature was conducted for polypropylene filled to various levels and at different strain rates. The specimens drew to draw ratios in the range \( \lambda=1.41 \) to \( \lambda=5.6 \).

Mechanical characterization of the test materials has been conducted by examining the tensile stress strain and fracture behaviour under uniaxial conditions.

The influence of glass fibre content and drawing conditions (draw ratio) on the fracture toughness and crack propagation was investigated using the double edge notched fracture test. The notch lengths ranged from 1.5 to 2.5 mm for 10 mm wide specimens. The critical stress intensity factor increased as the fibre content increased up to a limiting filler level. The fracture toughness of both unfilled and fibre filled polypropylene were found to be highly dependent on draw ratio.

The results were analysed to find out the optimal draw ratio and fibre content that yielded the maximum modulus, strength and fracture toughness. Data showed that, at a given draw ratio, modulus, strength and fracture toughness increased with increasing fibre content to a maximum and then decreased. The optimum material was obtained at a draw ratio of 2.5 and filler loading 13wt%.

**KEYWORDS:** polypropylene, fibre composite, glass fibre, die-drawing, mechanical properties, molecular orientation, fracture toughness, critical stress intensity factor, finite element method, finite width correction factor
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I would like to dedicate this work to whom their guidance help me to achieve my goals in the life

Mum and Dad
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1 Introduction

1.1 General

Polymer materials have found increasing use in different sectors of manufacturing in the past decades. Their low cost and lightweight or ease of processing are of primary interest when compared to conventional structural materials. However, from the mechanical point of view they cannot be used to replace high performance materials such as metals without special modification.

Polypropylene represents one of the most interesting large volume thermoplastics with wide application in the industry (Dufton, 1992). Polypropylene is a semi crystalline polymer characterized by many interesting properties such as low density, relative high thermal stability, good processability and resistance to degradation, which has wide application in automotive, appliances, house-hold fields, and bottles, food packaging, textile, plastic parts, electrical parts, and containers.

Polypropylene can be made by the addition polymerisation process, has a melting point of about 165°C, and glass transition temperature $T_g$ about -10°C. for most commercial polypropylenes the levels of crystallinity, are between 40-60% (Joseph and Thomas, 2002). Depending on their crystallinity, density ranges from 0.85 g/cm$^3$ to 0.95 g/cm$^3$. Its Young's modulus is also intermediate, although it is less tough than high density polyethylene (HDPE) and less flexible than low density polyethylene (LDPE), it is much more brittle than HDPE. Polypropylene has very good resistance to fatigue (Joseph and Thomas, 1999).
The traditional method used to enhance polypropylene properties is to mix with reinforcing fillers such as glass fibres, and carbon fibres. When appropriate fillers are incorporated into polypropylene, stiffness, strength and damage tolerance can be enhanced to fill the gap between commodities and engineering thermoplastics. (Karger Kocsis, 1995).

Fibre-reinforced composite materials consist of high strength and modulus fibres bonded to a matrix with a distinct interface between them. Generally, the fibres filler are used as load carrying capacity, while the surrounding polymer acting as a load transfer medium between filler and holds fibre in the desired location and orientation. The incorporation of glass fibre into polymer can result in outstanding property improvement in terms of increasing the strength and modulus in injection moulded parts. During the injection moulding process the orientation of short fibre is a function of the way the polymer flows through the mould, which is affected by such factors as the rheology of the material, moulding conditions and the geometry of the mould. It is very difficult to control the fibre orientation within the part. Filled fibre and polymer molecules can be reoriented and aligned in same direction by deforming the structure in solid state to enhance their mechanical properties. Great efforts have been directed towards the orientation of fibre in polymers structure in the last decade, the use of drawn polypropylene short glass fibre filled in new structures is still limited to few demonstration projects. The innovation of short glass fibre filled drawn polypropylene is effective in facing the great demand for high stiffness strength components. In this work the drawn and undrawn polymer
filled specimens consisted of a polypropylene and reinforcing short glass fibres were studied and investigated to improve their mechanical properties in drawing and traverse direction.

A laboratory-small scale die drawing rig was developed and used to solid state deform polypropylene. Tensile and fracture tests were conducted on uniaxially oriented and isotropic polypropylene.

The aim of this work was to investigate the effects of the die drawing process through constant width dies on the final mechanical properties of the drawn polypropylene both short glass fibre filled, and unfilled.

The influence of process parameters, and fibre content on fracture toughness was investigated.
1.2 Objective:

A commonly used method of enhancing the properties of polymers is the introduction of reinforcing elements such as glass fibre to produce composite material. Molecular orientation of the polymer, such as by drawing, also has beneficial effects. This work describes attempts to combine these two approaches to property enhancement by die drawing of short glass fibre reinforced polypropylene.

The main objectives of this study are to investigate and examine drawing behaviour of unfilled and short glass fibre filled polypropylene specimens drawn under different drawing rates using a small rig die drawing process. Broad objectives are:

- Investigate the drawability of filled polymer
- Investigate the influence of the draw ratio on the mechanical property enhancement (modulus, yield stress) of drawn unfilled and drawn fibre filled polypropylene
- Investigate the influence of the draw ratio on the fracture toughness behaviour of unfilled and fibre filled polypropylene

The specific objectives of this thesis were to study:

1. The effects of fibre contents on mechanical properties of short fibre filled polypropylene:

- Evaluation of the stress strain response of drawn polypropylene glass fibre filled materials.
• Assessing the effects of fibre contents on mechanical properties of polypropylene glass fibre filled materials

• Comparison of the mechanical properties tensile strength and modulus between filled and unfilled specimens

2. **The effects of draw parameters on mechanical properties of short fibre filled polypropylene:**

• Evaluate the effects of draw ratio on the specimen’s properties.

• Investigate the drawing behaviour of filled polypropylene under different drawing speed conditions

3. **The Effects of draw ratio and fibre contents on fracture toughness**

• Investigate the fracture behaviour of drawn and undrawn unfilled and fibre filled polypropylene based on the method of Linear elastic fracture mechanics (LEFM)

• Investigation of the effects of fibre contents on critical stress intensity factor.

4. **Finite element simulation:**

• Finite element modelling to determine finite width correction factor for double edge notched anisotropic unfilled and fibre filled polypropylene
• Effect of increasing mesh elements mesh density for drawn and undrawn specimens to the double on fracture reaction forces, and finite width correction factor.
1.3 Thesis layout

The study consists of an experimental investigation, and finite element modelling. The experimental program is designed to provide better understanding of the behaviour of polypropylene short glass fibre filled under axial drawing loads, as well as to examine the effects of different draw ratio, and fibre contents. The experimental results of this study are used to examine the proposed finite element models. The experimental program includes four processes.

*The first process:* is die drawing process of polypropylene short glass fibre filled and unfilled drawn under different draw ratio, different fibre content ranging from 0 %wt to 55 wt %.

*The second process:* is focused on uniaxial tensile test under fixed cross head speed and test temperature for filled unfilled undrawn and drawn specimens to determine stress strain performance of drawn specimens.

*The third process* is to evaluate the fracture behaviour of drawn and undrawn short glass fibre filled polypropylene with double edge notch and different ligament length subjected to uniaxial load.

*The fourth process:* is a finite element simulation, the finite element study is focused on the development of finite element models to determine correction factor Y for oriented material.
The following is a brief description of the contents of this thesis:

**Chapter 1:** introduction. To the nature and requirements of the work

**Chapter 2:** Presents a literature review on semicrystalline polymers and glass fibre composites, background of polypropylene filled materials and die drawing process in general with more emphasis on drawing process.

**Chapter 3:** Describes samples preparation from injection moulding process together with test methods, tensile tests, and die drawing method.

**Chapter 4:** Presents the tensile test results of injection moulded specimens. The experimental data are analyzed and discussed in this Chapter. Die drawing results of injection moulded unfilled and short glass fibre filled polypropylene samples are presented in this chapter.

**Chapter 5:** In this chapter a tensile test program to investigate the effect of fibre content (0%wt, 7%wt, 13%wt, 27%wt, and 55%wt) and draw ratio on mechanical properties is presented. The outstanding properties of the fibre filled polypropylene specimens will be shown.

**Chapter 6:** This chapter cover the fracture behaviour of drawn, undrawn, filled and unfilled specimens, critical stress intensity factor measured by double edge notch specimens, and finite element models to determine correction factor Y for oriented material.
Chapter 7: This chapter provides a summary and leads to some conclusions of the study. Recommendations and a few propositions for future work are also given in this chapter.

Appendices: present tensile test, fracture test curves and finite element input files, for the correction factor model.
2 Literature Review

2.1 Background

This chapter describes the physical and mechanical properties of oriented polymer, the benefits of polymer and fibre orientation, some methods of solid phase orientation processing, and the role of the drawing process in orientation. Major factors controlling the performance of composites are briefly described. Special emphasis is given on the methods of modification of fibre orientation as it plays an important role on mechanical properties of composites. Both fibre and polymer orientation behaviour of composites are assessed mentioning some previous work in these fields.

2.1.1 Structure of semi crystalline polymers

Most of the standard polymers in the industry contain amorphous regions and crystalline regions; this means that they have a semi-crystalline structure. The degree of crystallinity for such materials can reach a maximum of about 90% (Griskey, 1995). Crystalline material such as Polypropylene and Polyethylene, possess the ability to crystallise, below the melting point $T_m$. A crystal structure formed by, polymer chains aligning with each other through a chain fold process.

*The crystalline state* is much more difficult to describe and still not completely understood. There have been two main theories of the structure of polymer crystals. The fringed micelle theory states that each polymer molecule passes
through successive amorphous and crystalline regions, that is, ordered and disordered areas as shown in Figure 2.1 (Leverme, 1975).

Polymer micro crystals are formed by folding a single polymer chain back and forth upon itself in a folded lamella structure, as proposed in recent studies. Figure 2.1 shows various folded chain models. The crystalline regions or crystallites are usually small and often rod like. They can form aggregates called spherulites in spherical order structure shape (Callister, 2006) as shown in Figure 2.3. Polymer properties are influenced by spherulite size and shape (Deanin, 1972). In a non-oriented semi-crystalline polymer the crystalline areas are randomly oriented giving to the overall material isotropic properties. To enhance the properties of these polymers many techniques have been developed in recent years based mainly on the solid deformation of the material.

All crystalline polymers contain amorphous regions due to long chains. Mechanical process affects polymer crystallisation, crystallinity and orientation increase in the direction of shearing and extensional process forces. Crystallinity is affected by cooling rate. A high degree of crystallinity for crystalline polymer can be achieved by cooling the material slowly, fast cooling for the material in processing stage minimise the crystallinity. High crystalline material is stiffer but brittle, whereas a high amorphous more tough and ductile than crystalline polymer.

When a molten polymer is cooled from the liquid to the solid state the molecules lie in a random orientation in the sample. When there is a stress the molecules tend to rotate into the position parallel to the direction of the applied stress. Molecular orientation, as a result of the solid state deformation, causes a high level of property enhancement in the oriented products. It has long been
recognized that molecular orientation in the polymer leads to a significant enhancement in the stiffness and strength along the orientation direction. Many researches (Imada and Takayanagi, 1971, Weeks and Porter, 1974, Hoffman and Sachs, 1953, Southern and Porter, 1970) in the past have studied the effect of orientation on mechanical properties of polymer by showing large enhancement in modulus and toughness for several polymers.

2.1.2 The amorphous state

Is characterized by a random distribution of the polymer molecules. These giant molecules are all intertwined and entangled with each other and form a disordered region as shown in Figure 2.2, the resulting structure has isotropic properties.

The amorphous polymers such as, poly vinyl chloride, and polycarbonate, the structures of these polymers have no order and the chains are random orientation. They behave as glassy solid at temperature below glass transition $T_g$, showing brittle and stiff structure, because the molecule in the material have no energy to move. Above $T_g$ the material becomes rubbery and the molecules easily move around each other, with increasing temperature more malleable materials are formed.
Figure 2-1: Schematic diagram of the fringed

Figure 2-2: Various folded chain
2.1.3 Molecular orientation and crystallinity

The temperature applied to the polymer materials during solid state deformation allows the molecule to have some degree of freedom. As stated before these molecules respond to the processing stresses and start to slip past each other. In the amorphous zone the long chains begin to untangle and the number of loops and free chains decreases (Salem, 1998a). In the crystalline region the crystallites start to orient themselves in the stretched direction. Salem shows the increase of molecular orientation with increasing draw ratio at a constant drawing force and different temperatures. This increase is caused by anisotropic structure of linear macromolecules. The influence of temperature can be seen. Decreasing draw temperature results in a higher orientation. However for higher temperatures molecule orientation decreases. There is also a linear increase of the orientation function with the draw ratio, for the amorphous zone. (Salem, 1998b)
Cole et al (1996) have studied roller drawn polymers. They found that the orientation shows the same increase versus the draw ratio, studied crystallinity for high density polyethylene specimens using the roller drawing process. A decrease in crystallinity is observed, up to draw ratio of 3 to 6. For higher draw ratios a constant increase of crystallinity is observed. At the beginning of the stretching process folded chains unfold, the spherulites will eventually break at a certain degree of orientation. Then the stretched crystals and the amorphous molecules pack closer together causing an increase in the degree of crystallinity, and the amorphous chains produce additional taut tie molecules.

Vigny et al. (1996) Confirm this behaviour and show the influence of the process conditions on the onset of crystallization. By changing the drawing temperature or the strain rate this onset can be shifted to higher or lower draw ratios. As the stretching process continues the crystal regions begin to slip past one another and the amorphous molecules reach their maximum orientation.

Cole (1999) Confirm that the orientation increase with increasing draw ratio using front-surface specular reflection IR spectroscopy on uniaxially and biaxially oriented polyethylene terphthalate specimens. At the same time as the molecular chains orient themselves in the direction of stretching changes occur in the crystallinity of the polymer.
2.1.4 Deformation behaviour of polymer

The deformation behaviour of polymer material can take different forms. One typical response of polymers under uniaxial tension is shown in Figure 2.4A. Deformation behaviour can be divided into three regions.

First region (X1) elastic deformation, region (X2) the material after elastic deformation yields and necking occurs, the stress remain constant while the strain increases. Region (X3) hardening region. However, elongation and necking processes do not occur in all type of polymers. Another type of polymer in which the stress never decreases and no yield occurs, the specimen fractures before the material yields as shown in Figure 2.4B.

![Figure 2-4: Typical stress-strain curves of polymers under uniaxial tension](image_url)
There are many important factors control the mechanical behaviour of polymers.

**The first factor** is the testing temperature $T$ relative to the material’s glass transition temperature $T_g$. When $T_g$ is higher than $T$, polymers tend to be brittle as shown in Figure 2.5 curve A, while when $T_g$ is lower than test temperature polymers shows ductile behaviour curve D. It can be seen that, if the testing temperature $T$ is much lower than the material’s glass transition $T_g$ as in curve A, specimen fractures occurs in elastic region before yielding. Curve B show with increasing testing temperature $T$ the stress reaches a maximum, after the yields the material, stress goes down till fracture occur. If $T$ is close to $T_g$ curve C, the strain keeps increasing after yielding occurs without the increase in stress, then work hardening occurs till material fails. This is similar to the typical curve as shown in Figure 2.4a. Curve D show when testing temperature $T$ is a lot higher than $T_g$, the material does not show an obvious neck and dramatically increases in strain with a slight increase of stress, showing a long plateau in the stress-strain curve. The fracture occurs after the curve goes up rapidly.
The second factor is the strain rate. Many experimental works have shown that strain rate has great effect on the polymer’s deformation behaviour (Gilat and Roberts, 2002, Teratsubo and Saeki, 2002, Tay et al., 1995), (Li and Lambros, 2001). The modulus and the yielding stress of polymers increase with the increasing in the strain rate, while the ultimate strain decreases the ductility and the polymers behaviour becomes more brittle, as shown in Figure 2.6. The increasing in the strain rate has the similar effect of the temperature decrease in a tensile test. In addition, specimen temperature may increase under very high strain rate tests which consequently change the polymer’s stress-strain curves the material showing thermal softening at large strains. (Spitzig and Richmond, 1979).
Polymers after yield can show localised necking. Necking is a local reduction in cross sectional area followed by drop in tensile load at the yield point. There are three types of deformation illustrated in Figure. 2.5, (A) no neck, (B) stable neck, and (C) unstable neck. In the stable neck, the load will remain steady and the neck will traverse the specimen length. Strain hardening will take place when the whole specimen has necked, and the load rises until fracture occurs. In the unstable neck original neck continues to get thinner until fracture occurs.

The conditions for necking and cold drawing are best shown by plotting the true stress $\sigma$ against the strain, $\varepsilon$. Considère construction a special criteria used to
shows necking occur point as in Figure 2.7. A tangent to the true stress-strain curve from the point $\varepsilon = -1$, intersects the curve when the above condition is satisfied. The construction also allows the condition for a stable neck to be determined. This is the case only when a second tangent can be drawn to the curve, the point of intersection corresponding to a minimum in the stress-strain curve. The Considère construction can therefore be used as a criterion to decide whether a polymer will neck, or will neck and draw.

**Figure 2-7:** Types of true stress-strain curves for polymers (a) No neck; (b) Unstable neck; (c) Stable neck
2.1.5 Nature of yielding in polymers

Stress-strain curve of a polymer tensile test is similar to metal tensile test curve as shown in Figure 2.8. As the strain is increased, the polymer material passes plastic region through elastic region which by contrast to the tensile behaviour to metals is usually also a non-linear region. The peak value of stress used to define the yield stress $\sigma_y$. A polymer yield strain $\varepsilon_y$, lies in the range 5-10% compared with 0.1% for metals. The yield point of the material should be described as the point at which permanent set takes place; it is very difficult to define yield point in polymers as it is sometimes plastic deformation possible to recover beyond the yield point by raising the temperature of the material. In fact, the distinction between recoverable and irrecoverable deformation depends on the time scale and temperature of the experiment. However, despite this, one can still define a yield stress as the peak value reached by the nominal stress.

Yield point definition is the main problem in characterising plastic deformation in polymers. Unlike metals, it is very sensitive to the experimental conditions and, in particular, sensitive to strain rate, temperature, and hydrostatic pressure.
2.2 Factors effecting the mechanical properties of polymer composite

The mechanical properties of short glass fibre filled polymer are largely dependent on the follow factors; fibre orientation in the load direction, and the interfacial strength of the bond between the fibre and the polymer. Incompatibility between fibre and polymer is a major concern for polymer composite mechanical properties. The details of the effective factor are as follows.
2.2.1 Fibre orientation

Orientation of fibres relative to one another and local direction plays an important role in polymer fibre filled materials. The strength of the polymer with oriented filler particles along the direction of fibre orientation is higher than that of the randomly oriented fibre filled polymer. However the fibres are oriented in transverse direction perpendicular to the stress direction, the fibres no longer reinforce the matrix to increase the strength of the composite. (Joseph and Thomas, 1999). Short fibre composites rarely consist of fibres oriented in a single direction. During extrusion and injection moulding, the fibre will rotate during polymer melt shear flow and oriented during elongation flow. Thus, it is possible to achieve some degree of fibre orientation by using extrusion and injection moulding (Fu and Lauke, 1996).

Short-fibre filled polymer product can be manufactured by using many manufacturing processes such injection or compression moulding. During these processes, the fibres and the polymer are transported into the cavity of the mould. As the polymer deforms to achieve the desired shape, the orientation of the fibres is changing. Change in fibre orientation terminate when the matrix solidifies.

There have been extensive investigations of the factors affecting the fibre orientation during the moulding process. Critical factor are fibre volume fraction $V_f$ and fibre aspect ratio $S$, defined as the ratio of the fibre length to fibre diameter. In the dilute concentrations, low $V_f$, the fibres are free to rotate due to the space between the fibres. The space is greater than fibre length. On the contrary high $V_f$ composites, the interaction of fibre-fibre becomes significant. The mould geometry can influence the fibre orientation in various sections of the mould (Papathanasiou and Guell, 1997), (Phan-thien and Zheng, 1997).
For short-fibre composites, image analysis is the most successful method to evaluate the distribution of fibre orientation. Light microscope equipped with a video camera can be used to capture cross sections of well-polished composite surfaces. The fibres appear in polished surface as ellipse shown in Figure 2.9. The fibre position is defined by the coordinates of centre gravity of its elliptical image and its orientation by Θ angle and φ angle as shown in Figure 2.10A. Θ is defined as the angle the fibre makes with the drawing direction(X). The angle between fibre and (Z) axis is φ. It is possible to determine Θ and φ directly from elliptical shape as shown in Figure 2.10B. Θ orientation angle determine by inverse cosine of the ratio of the semi-minor axis to semi-major axis of the sectioning ellipse.(Fischer and Eyerer, 1988) have used this method to examine short glass-fibre reinforced.

Figure 2-9: Schematic of fibre orientation when viewed on the polished specimen surface
(Phan-thien, 1997)
\[ \Theta = \cos^{-1} \left( \frac{b}{a} \right) \]

- \( \Theta \) = orientation angle
- 2a = major axis
- 2b = minor axis
- \( \phi \) = orientation angle

Figure 2-10: Calculation of orientation angle (Fischer and Eyerer, 1988)
2.2.2 Fibre volume fraction

The content of reinforcing fibre is one of the most significant factors determining the mechanical properties of composite. Tensile strength is usually decreased at low fibre volume fractions. This is due to the introduction of flaws created by the fibre ends. These flaws act as stress concentrations, and cause the bond between fibre and polymer to break. The matrix is sufficiently restrained at higher volume fractions and the stress is more evenly distributed. Hence, the tensile properties gradually improve with increasing fibre volume fraction. The fibre volume fraction at which the strength of the material starts to increase is known as the critical fibre volume fraction. The strength of composites starts to decrease at very high fibre volume fractions, due to insufficient filling of the matrix materials (Bibo and Hogg, 1996).

During the injection moulding and extrusion process of short fibre reinforced polymer, because of fibre-polymer interaction and fibre to fibre interaction, fibre damage takes place. This could decrease composites mechanical properties. At high fibre volume fractions, there is an increase in fibre-fibre interaction, leading to the reduction in mean fibre length, and if the mean fibre length is much smaller than the critical fibre length the reinforcing efficiency would be reduced. (Fu et al., 2000).
2.3 Solid deformation of semi-crystalline polymers

The solid deformation of polymer at temperatures just below the melting point was started in the early 1970s by the works of IM. Ward (UK), R.S. Porter (US) and M. Takayanagi (Japan) and their co-workers. The main goal of these researches was to produce highly oriented polymers parts such as sheets, rods; pipes or any other shapes by introducing orientation in processes. Polymer materials are thermally softened during solid state deformation at temperatures between the glass transition temperature and the melting point and then worked by rolling, stretching and extruding at temperatures below melting point. Large segments of molecules under applied mechanical stress and temperature have enough freedom to slip past each other. Stretching temperature must not be too high to avoid rapid thermal motions of large segments of molecules, rapid motion of molecules will effect the level of orientation achieved in the material. In consequence, industrial processes involving molecular orientation are usually carried out at moderate temperatures below the melting point, and then the stretched film or fibre is cooled down to freeze in the orientation produced.

Ajji (1996) presents a roll drawing solid state process Figure 2.11. Even if this process has limited applications for engineering polymers it gives a good example of solid state deformation. Through a set of rolls the thermally softened polymer is drawn. Roll drawing process control by many parameters such as the roll speed, the gaps between the rolls, and the temperature, polymer temperature being maintained above the glass transition temperature. In the industry, many different processes are based on solid state deformation. They can produce either uniaxially or biaxially oriented articles.
Figure 2-11: Solid state roll-drawing process (Ajji, 1996)
2.3.1 How to achieve orientation

Conventional fibre filled polymer are well-known for their superior stiffness, strength and light weight properties with relatively high market values compared to neat polymers. However, high fibre content is normally used in processing such composites, resulting in the lack of a good fibre distribution and the debonding or fracture issues at some thinning areas of the final manufacturing products. Accordingly, since the pioneering work of Ward (1985), solid phase processing of polymer, has focused interest on the replacement of conventional polymer fibre composites by solid state drawing technology to enhance mechanical properties through orientation of both polymer molecule and fibre filler.

The orientation of molecular structure of polymer and the orientation of fibre reinforcement material in a given direction is influenced greatly by the deformation imposed in that direction. The deformation of polymer material can be achieved by many solid phase forming techniques including drawing (Farrell and Keller, 1977, Griswold et al., 1978), (Kanamoto et al., 1983), hydrostatic extrusion (Porter et al., 1994, Ryoukei Endo et al., 1998), (Appelt and Porter, 1981), (Pereira and Porter, 1983), and die drawing (He and Porter, 1987),(Anagnostis and Porter, 1979). Solid-phase deformation of polymers as a method of obtaining high stiffness materials has been the main focus of much research (Ball and Porter, 1977), (Farrell and Keller, 1977), (Buckley and Long, 1969), (Alexander and Wormell, 1971), (Nakayama and Kanetsuma, 1974).
2.3.1.1 Cold drawing

The cold drawing process can be used for ductile thermoplastics. This process is normally conducted at room temperature. The stress rises steadily with increasing strain with plastic deformation concentrated in the neck, and the neck forms after the sample reduces to a smaller cross-section.

2.3.1.2 Hot drawing

Thermoplastics, which are brittle at normal temperature, can be oriented at elevated temperature by hot drawing process. In the hot drawing process the polymer is oriented at temperature above ambient temperatures sometimes close to the polymer melting point. Most of technological processes for oriented polymers operate above ambient temperature and the stretching process maybe homogeneous rather than drawing through a sharp neck.

The polymer molecule orientation can be achieved by using a die drawing process or hydrostatic extrusion. Both these processes are based on the drawing of polymer at a temperature above its glass transition temperature. Die drawing and hydrostatic extrusion offer the potential of producing oriented polymers with larger dimensions. Both die drawing and hydrostatic extrusion are process involving a billet which is made to pass through a convergent die by the application of either a tensile force (die drawing) or back pressure (hydrostatic extrusion). In both cases the billet is heated to a sufficiently high temperature to allow flow, but it is below its melting point in order to obtain a high degree of molecular orientation.
2.3.2 Hydrostatic extrusion process

Hydrostatic extrusion is a solid phase forming technique. In this process the billet was forced through the die by pressurized hydraulic fluid. First research dealing with hydrostatic extrusion of polymers early in 1969 were given by (Buckley and Long, 1969), (Alexander and Wormell, 1971), (Nakayama and Kanetsuma, 1974), the results were not very interesting and the mechanical properties of extrudated specimens were very moderate because of the low orientation of the extrudates specimens.

Figure 2.12. Shown a schematic of hydrostatic extrusion. The billet is surrounded with a suitable fluid and hydrostatic pressure is produced using piston. The fluid eliminates the friction between wall and specimen and the lowers the die friction. Hydrostatic extrusion has the particular advantage of being capable of producing oriented products from brittle materials, because deformation occurs in a totally compressive stress field.
Figure 2-12: Schematic of hydrostatic extrusion (Buckley and Long, 1969)
2.3.3 Die drawing process

Die drawing was developed from a hydrostatic extrusion technique, essentially by applying a pulling force on the specimen at the exit side of the converging die and by discarding the pressure feed on the specimen entering the die. An important difference is that the billet is free to neck down and follows an optimum strain and strain rate path through the die. Leaving the die wall at an appropriate point, a product smaller in cross-section than the die exit may be obtained. This is in contrast to hydrostatic extrusion where the polymer remains in contact with the die so that a die exit size product is produced. Strength and stiffness of the drawn structure is enhanced in drawing direction by achieving the molecular orientation. Gibson and Ward (1978) using a conventional conical die got some enhancement in the axial directions for the drawn rod. Effect of die drawing on strength and stiffness of drawn sheets and tubes drawn through standard taper dies and drawn over conical mandrel was investigate by Coates and Ward, (1980) and Hope and Ward (1981b).

The reduction in area for any drawing process ranges from 10% to 40%. The strain and the drawing load increases with reduction in cross sectional area. Material flow is affected by die geometry and distribution of the effective strain and flow stress in the deformation zone. The optimum die angle value depends on the reduction and the existing friction conditions for the process. Studies in this work found the suitable die angle for the drawing process is 4° to 14° (Hope and Ward, 1981b).

The die drawing process is shown schematically in Figure 2.13. In this process the billet of solid polymer is drawn through a heated conical die solely by the action of haul-off force applied to the product. Successful drawing can only
occur in a narrow temperature range with the solid phase. Too high a temperature results in deformation without orientation whilst too low a temperature results in premature fracture of the material during drawing. The main advantage is that the polymer experiences the highest strain rates at the exit of the die where the plastic strain is greatest.

Coates and Ward have shown the strain rate sensitivity of flow stress in solid state hydrostatic extrusion increases rapidly with plastic strain. This situation occurs when very high flow stresses are produced in the polymer as it reaches the die exit. High extrusion pressures are therefore being required. By contrast, in die drawing the polymer necks down and follows an optimal strain rate field. This strain rate field is such that the highest strain rates are encountered at low levels of plastic deformation, consistent with a constant load at all section of final product (Coates and Ward, 1978).

The die drawing process is shown schematically in Figure 2.13. A heated polymer billet is drawn through a heated conical die by applying a pulling force on the billet at the exit side of the die. The polymer billet is free to neck down and follows an optimum strain and strain rate path through the die, leaving the die wall at an appropriate point, hence reducing the required flow stress considerably. This leads to three distinct deformation regimes:
**Zone one**: Isothermal conical die flow. In this region the material billet remains in the contact with die wall.

**Zone two**: Free tensile isothermal flow; in this region the material necks down free of the die wall but should remain substantially at the die temperature.

**Zone three**: In this region the material necks down further beyond the die under nonisothermal conditions. The deformation continues outside the die and the polymer reaches its final deformation ratio on cooling.
Figure 2-13: Schematic of die drawing process (Gibson and Ward 1978)
The actual draw ratio $R_A$ is used to characterise the material degree of deformation by the die drawing process. Actual draw ratio is expressed in term of the initial and final cross sectional dimensions of the product.

$$R_A = \frac{\text{initial billet cross section}}{\text{final product cross sectional area}}$$  \hspace{1cm} (2.1)

For circular cross-section rods,

$$R_A = \left(\frac{d_0}{d_f}\right)^2$$  \hspace{1cm} (2.2)

Where

$d_0 =$ original billet diameter.

$d_f =$ final billet diameter.

The nominal draw ratio, $R_N$ is defined as the ratio of the billet cross sectional area to the billet die exit:

$$R_N = \left(\frac{d_0}{d_l}\right)^2$$  \hspace{1cm} (2.3)

Where $d_l =$ die exit diameter.

Coates and Ward (1979) demonstrated the first successful die drawing rig on the large scale for polyoxymethylene, and then on a small scale rig designed for use on an Instron tensile testing machine for polypropylene. The small die drawing rig equipment apparatus is shown in Figure 2.14.
Figure 2-14: Schematic diagram of small-scale die drawing assembly (Coates and Ward 1979)
Die-drawing process results for the polypropylene (Coates and Ward, 1979) are shown in Figures 2.15 and 2.16. From Figure 2.15 it can be seen that the actual deformation ratio increases, with increasing in draw speed from 10 mm/min to 50 mm/min. In the case of the die designed to give $R_N=7$, the actual deformation ratio $R_A$ rises to 20. There is unique relationship between the axial Young’s modulus and the actual deformation ratio result. This is shown in Figure 2.16, where it can be seen that the modulus increase with increasing draw ratio.

![Dependence of maximum steady deformation ratio $R_A$](image)

*Figure 2-15: Dependence of maximum steady deformation ratio $R_A$ (Coates and Ward, 1979)*
Gibson and Ward (1989) obtained similar polypropylene results. Such data is necessary for the die-drawing polyethylene were to ensure the capability of a large scale die drawing rig to draw large rod, sheet and tube cross-sections. The die drawing rig can be readily adopted to draw sheet products from rectangular cross-section billets.

![Graph](image)

**Figure 2-16: Axial modulus versus draw ratio for polypropylene (Coates and Ward, 1979)**
2.4 Solid phase deformation previous work

The axial draw load produced an alignment of the molecular and isotropic material. Such material becomes anisotropic. Axial mechanical properties are enhanced downstream. Coates and Ward (1979), Taraiya and Ward (1987) Richardson and Ward (1987), developed the initial work in this area for round tubes and bars on a small scale rig mounted in tensile testing machine, which provided the load required to pull the material through the die. The small scale equipment accepted specimens up to 14mm diameter, which after drawing produced rod as small as 4mm diameter at comparatively low haul-off loads.
This process was used to produce oriented polypropylene rod with room temp elastic modulus of up to 20 GPa. The orientation processes also increase the ductile brittle temperature up to at least 40°C.

These results clearly demonstrate that the die drawing is very successful method for the manufacture of high stiffness polypropylene rod. The application of die drawing to produce high oriented polymer was also considered by Gibson and Ward (1980b) It was shown that a variety of product rod, sheet, and tubes of relatively high stiffness could be obtained with elastic modulus value for polypropylene Up to 20GPa

Coates and Ward (1979) studied hydrostatic drawing behaviour of polypropylene using conical die angle semi angle of 15° with two exit 7mm and 15.5mm.Specimens were drawn at draw temperature of 152°C. Different methods were used to form a nose. The first involved hydrostatic extrusion of a nose $R_N=5$ to draw a billet of normal deformation of 5 or 7.
The second method employed stepped specimens. Specimens had steps in diameter along its length. Products were evaluated by optical inspection and by measurement of the axial modulus. A draw ratio of 19.9 samples were opaque and white possibly due to internal voids. Other draw ratio had very smooth surfaces and were quite transparent.

They found the process increased the modulus to about 20 GPa compared to the isotropic specimens (1.1 GPa). The relation between modulus and draw ratio appears approximately to be linear. The optimum drawing temperature of polypropylene was 152°C. There was excellent agreement between results compared with Cansfield and Ward (1976) for polypropylene drawn at draw temperature of 100°C and Williams (1973) for polypropylene rods extruded at 100°C.

Coates and Ward (1979) discuss the advantage of the die drawing process compared with conventional tensile drawing and hydrostatic or ram extrusion. They found die drawing to be a controllable process for the production of very high stiffness polypropylene. The higher the designed draw ratio the greater is the production rate at a given nominal temperature. There is no significant adverse pressure effect unlike hydrostatic extrusion. The strain rate field in the deformation region is not imposed totally by the geometry of the die due to specimens free drawing after exit from the die.

A. J. Wills (1980) studied the influence of temperature on the tensile drawing behaviour of polypropylene to produce an ultra-high modulus oriented polymer. Results showed that optimum draw temperature depends on molecular weight and is also related to the draw ratio. Low temperature resulted in higher modulus
typically of 25-27GPa with draw ratio of 15, at drawing temperature of 110°C. These results were identical to those observed by Cansfield and Ward (1976)

Gibson and Ward (1980a) investigated processing several grades of polyethylene and polypropylene to obtain higher modulus. They found that polypropylene, with a 20% w/w glass fibre, filled gives moduli up to 14.2 GPa. They concluded that orientation of both glass fibre and polymer matrix contributes to stiffening. The actual achievable draw ratio of filled specimens was lower than for unfilled specimens. The maximum stiffness was therefore lower than that attainable with the unfilled polypropylene.

Hydrostatic extrusion die drawing was used in the study of oriented filled polymer material. Richardson and Ward (1982) investigated the solid phase forming of glass fibre polyoxymethylene. They used cylindrical billets for die drawing studies containing 20% by of short glass fibre. Drawing was performed at a temperature of 152°C at drawing speeds up to 400 mm/min. Attempts to increase the filled polymer drawing speeds above 80mm/min resulted in product fracture beyond the die exit. Significant matrix orientation was developed in the die drawing process of unfilled materials. Significant fibre orientation was developed also due to the convergent die used. There was less enhancements of properties by the incorporation of glass fibre in addition to the orientation of the polymer. The result showed that the moduli of glass fibre filled product was no higher than for unfilled product. In die drawing the fibre consequently does not appear to be effective as a reinforcing phase in filled specimens drawn to a maximum draw ratio of 11. However in unfilled polyoxymethylene the deformation ratio continued to rise until fracture occurred at draw ratio of 14.
Products surface finish was free of flaws but filled specimens finish was considerably rougher than unfilled specimens. In die drawing debonding of fibre from matrix occurs. This is accompanied by extensive void formation. Internal voids were present mainly in filled specimens but to a lesser extent in unfilled specimens. Axial modulus of polyoxymethylene was found to be more nearly linear with a draw ratio for both filled and unfilled. The fibre did not act as reinforcing phase after die drawing. This could be due to either to shortening of the glass fibre or to debonding of the fibres from the polymer matrix. The densities measurement of drawn specimen’s glass filled were much lower than the undrawn specimens, thus indicating substantial void formation had occurred during drawing process. Scanning electron microscopy revealed that extensive voids had formed during processing consistence with densities drop from 1500 to 500 Kg/m$^3$.

The effect of uniaxial deformation on fibre and matrix orientation of short glass fibre polyoxymethylene was studied experimentally by Curtis et al (1982). Quantitative measurements of both fibre and matrix orientation were presented for a series of samples of short-glass-fibre-reinforced polyoxymethylene copolymer, processed, to various substantial deformation ratios, by solid-phase hydrostatic extrusion. Results showed that there was alignment of glass fibre in addition to alignment of polymer. The polymer matrix becomes highly oriented at modest deformations, but the glass fibre orient in a slower pseudo-affine manner.

The production of oriented polypropylene specimens has been studied comprehensively by Taraiya and Ward (1987) using the die drawing process The
die drawing behaviour of polypropylene specimens drawn at different draw temperatures over a wide range of drawing speeds were comprehensively examined. Results show that the draw ratio increases with drawing speed. The maximum draw speed was limited by fracture of the specimens in certain cases or by machine maximum speeds of 500mm/min. in other. Fracture occurred beyond the die exit. Applying drawing temperature of 155°C for nominal deformation ratios R_N 3, 5, 7, and 9 drawn at 500mm/min resulted in maximum draw ratios of 7.1, 9.1, 12.7, and 21.5 respectively, when R_N 11 specimen was drawn a maximum speed of 100mm/min was achievable beyond which fracture occurred, with a maximum draw ratio obtained being 17.2

Under a set of conditions specimens draw up draw ratio of 23.2 were obtained giving tensile modulus up to 20GPa in the draw direction. This represents a substantial enhancement over isotropic value of 1.5GPa. The effect of draw temperature, haul speeds, and initial billet size on mechanical properties of polypropylene polymer material was studied comprehensively. Draw ratios up to 23.2 were obtained giving 20GPa bend moduli at room temperature. Again this represents a substantial enhancement over isotopic values of 1.5 GPa. The researchers found it possible to perform drawn speeds of 2000 mm/min at a draw temperature up to 155°C giving draw ratios up to 19.3. Capaccio and Ward (1980) studied the effect of drawing temperature on draw ratio and tensile modulus, over a drawing temperature range 75°C to the melting point, using a constant drawing speed of 10cm/min. They found that increasing the draw temperature led to substantial increases in the draw ratio. Measured modulus of drawn material showed it increased with draw ratio to draw ratio of 20 or more.
Taraiya and Ward (1991) showed experimentally that the uniform biaxial oriented tubular products can be produced by a process which involves drawing the tubular billet over the expanding mandrel. They found it possible to produce uniform biaxially oriented tubes of various draw ratio and thickness with enhanced mechanical properties. Biaxially oriented samples had higher tensile strength compared with isotropic material. In comparison to uniaxially drawn, biaxially drawn samples have higher strength in hoop direction. The impact strength of biaxially drawn sample is much better as a consequence compared to that of isotropic samples.

Cook (1992) investigated the orientation of glass fibre filled polypropylene manufactured by a number of processing routes including extrusion, injection moulding and die drawing. Voids were observed in drawn samples. Increasing draw temperature resulted in less voids.

Ward and Craggs (1993) analysed the stress in small elements of isotropic polymer undergoing the drawing process. Samples were in the form of circular rod. Using a force equilibrium approach stress strain rate characterization were used from uniaxial tensile test. Good agreement was obtained between experimental and axial stress predicted distributions when a value of 0.1 was assumed for friction coefficient.

Taraiya and Ward (2000) developed continuous die drawing process, to manufacture oriented polypropylene products. The process has been successfully applied to the manufacture of fluted cores for wire ropes.
Mourad and Barton (2005) investigated the effect of process parameters on the mechanicals behaviour of die drawn polypropylene. A single stage hot die drawing test rig was used to produce oriented Polypropylene rod. The influence of drawing process parameters such as nominal draw ratio, drawing temperature, and drawing speed on drawing load, final area reduction, elastic moduli and yield strength was studied. They found that tensile modulus of elasticity and yield strength are improved substantially by increasing the draw ratio. Further improvement can be obtained by increasing the drawing speeds, however increasing the drawing temperature reduces the tensile strength and moduli. In contrast, the compression modulus and yield strength both increased with processing temperature but decreases with processing speed. The degree of deformation attainable depends strongly on the draw velocity as found with elastic modulus increased up to 23GPa highly oriented polymers.

A comparison between the mechanical properties and physical structure of oriented polyoxymethylene produced by two solid state processes; hydrostatic extrusion and die drawing, has also been conducted by Ward et al.

Mohanraj and Ward (2004) demonstrated the effects of die drawing process on specimen tensile stress. They found macro-voids were produced in the oriented sample through die drawing whereas the macro-voids are suppressed due to the compressive field in the case of hydrostatic extrusion.

Finite element simulation work published by Mirza et al (2003) simulates the production and properties of highly oriented polyoxymethylene by die drawing. They have used the experimental data to provide validation of their numerical model. This FE model has been used to gain a better understanding of the die
drawing process and its controlling parameter. The influence of process parameters explored such as die half-angle reduction, die wall friction on the draw loads and the amount of free tensile drawing that takes place outside the die. They validated a finite element model using experimental stress strain rate data. Data were measured from uniaxial tensile test and applied directly to the finite element analysis. Uniaxial test tensile data utilized in numerical simulation with finite element analysis results show good agreement between the model and measured drawing load. The model can be used to study the die drawing process of polymer.

Die drawing process profiles were studied by Mohanraj and Ward (2004). They analysed strain rate distribution in a wire die drawing process using conical dies using finite element simulation. It has been shown that profiled dies can be constructed to reduce the strain rate at the die exit and, hence, the possibility of fracture, enabling the process to become more commercially variable.

Most previous studies have been focused on unfilled polymer, with many types of polymer studied. Initial trials with short glass fibre filled polyoxymethylene by Hope and I.M. Ward (1982) result showed that extensive voiding occurred around the fibres and the modulus of the filled drawn specimens was only comparable to the unfilled drawn specimens. They concluded debonding of fibre from matrix and subsequent void formation, occur because of incompatibility between fibre and matrix interface when strained in solid phase drawing process.

The solid phase forming of short glass fibre reinforced polymer has been investigated using the technologies of die drawing and hydrostatic extrusion by, Richardson and Ward (1973), Hope and Ward (1981a), Hope and I.M. Ward (1982). Although considerable orientation of the glass fibre and the polymer
matrix occurs in process, there are very appreciable differences between the stiffness of the glass filled product from the two processes. For hydrostatics extrusion, the moduli of glass filled products are significantly higher than those of the unfilled products. In the die drawing, however the absence of hydrostatic pressure allows debonding of the fibre from the matrix to occur, accompanied by extensive void formation around the fibre and consequently, are no longer effective as a reinforcing phase. This result in the moduli of the glass fibre filled products being no higher than those of the unfilled products.

Recently the effect of impact modifier on the die drawing behaviour and mechanical properties of Polypropylene, was investigated by Mohanraj and Ward (2003). They found that addition of modifier particles reduced the draw stress, allowing the blend to be easily oriented at low temperatures parallel to the draw direction.

Recently Foster et al (2009) investigated the properties and structure characteristics of nanocomposite polypropylene carbon nanofibre. The modulus was measured at various stages of blending, with a blending temperature of 200°C -230°C. Samples were taken at three individual mixing zone and several extrusion times. Comparisons are made between the measured modulus of the material and micromechanical modelling prediction. They found optimum tensile modulus is obtained when the material is mixed through four zones at 200°C. the modulus of 2.15GPa was obtained.

More recently wood polymers composite have been studied by Polec et al (2010). Polymer with 40%by weight concentration of soft and hard wood, have been prepared and processed using drawing process. Materials with significantly increased in stiffness from 1.9GPa to 8.2GPa, and strength from 13GPa to 127
GPa were obtained for both wood types. However drawn filled moduli were lower than the equivalent unfilled. Specific moduli were very similar for unfilled and filled. Again the filled material has a lower density compare to drawn material due to void formation. Unfilled exhibits an $R_A$ to be much higher than $R_N$ while for wood filled $R_A$ is much closer to $R_N$.

Many attempts have been made to improve the mechanical properties of polymers by die drawing. However, there is a need for further studies that might widen the scope of knowledge on the influence of drawing speeds and introducing short glass fibre filler in polymer matrix on the mechanical behaviour of die drawn polypropylene. This is the area of study to be covered in this thesis.
2.5 Fracture Background

Fillers such as fibres are added to polymers to increase stiffness and for high fracture resistance. Incorporation of glass fibre can offer great enhancements in tensile properties of polymers. The theory of fibre reinforcement is well documented in the literature Hull and Clyne (2000). The fracture toughness of short glass fibre reinforced toughened polymer was investigated by Laura et al (2000). They examined the effect of short glass fibre on fracture toughness and found that the tensile properties improved and modulus increased with increasing fibre content, with a short glass fibre content of 20%wt showing substantially higher modulus. Short fibres can also improve fracture toughness for brittle matrix composites. Akay and Bailey (1995) studied the effect of short glass fibre filler on fracture toughness of polyamide 6.6 and found that the fracture toughness was improved and total work of fracture increased by 25-37%. On the other hand, addition of short fibres usually reduces the toughness in ductile matrix composites. The effect of fibre content using essential work of fracture under quasi static loading rate researched by Ching and Mai (2000) showed that the addition of 10 %wt of short glass fibre improved the fracture toughness due to the synergistic effect of matrix yielding and fibre energy absorption during fibre debonding. However, with increasing fibre content to 20%wt and 30%wt, the process zone was smaller and this caused reduction in fracture toughness. Fu et al (2000), studied the effect of fibre volume fraction on tensile strength and modulus. Increasing fibre volume fraction led to decreased fibre efficiency and more fibre corresponded to decreases in tensile strain and failure stress.
The influence of filler particle on the fracture mechanism of polypropylene has been investigated by Zebarjad et al (2004). Their results show an increase in calcium carbonate content leads to a decrease in yield strength, elongation at break and fracture toughness due to crazes occurring at the interface.

### 2.6 Fracture toughness

Fracture toughness approach assumes that the failure in the polymer material occurs as a result of initiation and propagation of material cracks. Linear elastic fracture mechanics (LEFM) is used for the characterization of materials with elastic deformation or materials with small scale yielding near the tip of the crack. It is assumed that radius of the crack (r) is much smaller than the initial length of flaw (c). The useful LEFM variables include the critical stress intensity factor (K_c) and critical strain energy release rate (G_c). The LEFM is developed by Irwin based on the (Irwin, 1957) previous work of Griffith (Griffith, 1920). The fracture toughness can be measured by K_c, which implies the stress at fracture (σ_b) and is given by

\[
K_c = \sigma_b \sqrt{\pi c}
\]

(2.4)

Failure occurs when the local energy release rate exceeds the critical value (G_c). Polymer materials have a threshold limit of this energy dissipation (G_0) about 50 J/m^2, where the crack cannot grow below this limit. G_c can be related to K_c by knowing the Young’s modulus (E)

\[
G_c = \frac{K_c^2}{E}
\]

(2.5)
Basic to fracture mechanics is the understanding of the state of stress near the tip of a sharp crack and the relationship between gross stress and flaw geometry. The stress fields near crack tips can be divided into three basic modes, each associated with a local mode of deformation, as described below.

### 2.6.1 Crack deformation modes

The crack deformation modes, also known as symmetry modes, were introduced by (Irwin, 1960). For linear problems, any kind of the deformation can be represented as a linear combination of the three deformation modes which are:

- **Opening mode**: The applied loading tends to open the crack surfaces and is associated with a local displacement in which the crack surfaces move directly apart as shown in the Figure 2.16 (a). This mode is traditionally known as mode I.

- **Shearing mode**: This mode also known as sliding or in-plane shearing is characterized by displacements in which the crack surfaces slide over one another as shown in Figure. 2.16 (b). This mode is traditionally referred to as mode II.

- **Tearing mode**: This mode is also known as anti-plane shearing mode. In this mode the crack surfaces slide with respect to one another parallel to the leading edge, as indicated in the Figure. 2.16 (c). This mode is traditionally referred to as mode III.
Figure 2-17: Three loading modes that can be applied to a crack (Irwin, 1960)

The application of fracture mechanics to crack growth in polymers has received considerable attention. The main, inter-relatable, conditions for fracture were proposed by Irwin (Irwin, 1961) who found that the stress field around a sharp crack in a linear elastic material could be uniquely defined by a parameter named the stress-intensity factor, $K_I$, and stated that fracture occurs when the value of $K_I$ exceeds some critical value, $K_{IC}$. Thus, $K_I$ is a stress field parameter independent of the material whereas $K_{IC}$, often referred to as the fracture toughness, is a material property.

When measuring the fracture toughness of polymer materials, subjected to uniaxial tensile loading, a large localized stress region develops near the vicinity of a crack tip. At this localized stress region, a plastic zone is created, and the material near the crack tip is at its yield stress.
2.6.2 Linear elastic fracture mechanics

Linear elastic fracture mechanics (LEFM) originally developed for metallic material is valid for crack growth with little or no plastic deformation at the crack tip, and to provide proper fracture toughness values for non-ductile polymers because these polymers have small plastic zones that occur at the crack tip of the samples. The stress intensity factor $K_I$ is an important parameter in linear elastic fracture mechanics. Cracks, if present in the region experiencing the modes of deformation, increase the stress amplitude significantly and this high stress may lead to premature failure of the engineering components. Knowing the value of the $K_I$ one can predict if the crack will propagate or not.

2.6.3 Stress intensity factor $K_I$

The actual stress-intensity factor $K_I$ is the loading parameter used to describe the crack driving force. The stress state near the tip of a crack caused by a remote load or residual stresses can be predicted accurately by using the stress intensity Factor $K_I$. When this stress state becomes critical a small crack grows and the material fails.

For the geometry shown in Figure 2.17, which is only mode-I, the crack is normal to the applied load, and the stress-intensity factor for isotropic material is calculated by Rooke and Cartwright (1976)

With the stress intensity for an infinite body containing a crack of length $2a$ given by $K_a$
\[ K_0 = \sigma \sqrt{\pi a} \] (2.6)

The stress intensity modification factor is the right hand side of the equation below

\[ \frac{K_1}{K_0} = \frac{((1.12*(1-(\frac{1}{2}\frac{a}{b}))) - 0.015*(\frac{a}{b})^2 + (0.091*(\frac{a}{b})^3))}{\sqrt{(1-\frac{a}{b})}} \] (2.7)

to give the actual stress intensity factor \( K_1 \)

Here \( \sigma \) is the remote stress, \( a \) is the crack length, \( b \) the specimen half width.

In general, crack propagation is assumed to occur when the \( K_1 \) actual stress-intensity factor is equal to the material’s critical fracture toughness \( K_{1c} \).
Figure 2-18: Double edge notch specimen


2.6.4 Stress analysis of cracks

Generally there are three modes to describe different crack surface displacement in Figure 2.18. Mode I is the most common load type encountered in engineering design. The value of the stress intensity factor $K_I$, is a function of the applied stress, the size and the position of the crack as well as the geometry of the solid piece where the cracks are detected. The tensile stress in $X$ and $Y$ directions, and the shear stress in the $Y - X$ plane as shown in Figure 2.19 can calculated in terms of $K_I$ and position can be written as:

\[
\sigma_x = \frac{K_I}{\sqrt{2\pi r}} \cos(\frac{\theta}{2}) \left[ 1 - \sin(\frac{\theta}{2}) \sin(\frac{3\theta}{2}) \right] \quad (2.8)
\]

\[
\sigma_y = \frac{K_I}{\sqrt{2\pi r}} \cos(\frac{\theta}{2}) \left[ 1 - \sin(\frac{\theta}{2}) \sin(\frac{3\theta}{2}) \right] \quad (2.9)
\]

\[
\tau_{xy} = \frac{K_I}{\sqrt{2\pi r}} \sin(\frac{\theta}{2}) \left[ \cos(\frac{\theta}{2}) \cos(\frac{3\theta}{2}) \right] \quad (2.10)
\]
Polypropylene has remarkable growth in the last years. The reason for this growth is that the ability to modified to specific applications because of thermal stability, mechanical, chemical resistance and a competitive price.

Polypropylene is characterised by high tensile strength, high stiffness and high heat deflection temperature under load. However the major weakness of polypropylene is its very low tensile strain and impact resistance especially at low temperature.

Because of the high fibre mechanical properties, filling polypropylene with short glass fibre will improve material tensile and impact strength.
The choice of fibre filler with polymer due to enhancing in material mechanical properties, low cost, high resistance to heat and chemical resistance.

Short glass fibre increased isotropic material stiffness toughness in random fibre orientation, fibre reorientation for anisotropic material stiffness increase in the orientation direction.

In the most manufacturing process such as injection moulding it’s very difficult to control specimen’s fibre orientation using die drawing process to reorient fibre in the flow direction.

Many researchers have studied the effect of drawing process on mechanical properties of polymers these studies concentrate on polymer molecular reorientation.

Research work related to the drawing behaviour of polymer short glass fibre filled and their behaviour under axial (tensile) drawing loading conditions is, however, very limited to date. The fibre effect on molecular orientation under different drawing speeds has not been extensively investigated. Hence this study focused on study the effect draw rate and fibre contents on mechanical properties of polypropylene fibre filled by applying different draw speeds and different fibre contents.

Many studies have investigated the enhancement of undrawn polymer and polymer filled in tensile properties and fracture toughness. Stiffness and strength properties enhancement of PP can be produced by solid-state molecular orientation (Coates P D and Ward I M, 1981). What needs to be investigated is the effect of filler, such as short glass fibre, and filler concentration on drawing speed and draw ratio. This represents an important area that has not been investigated for polypropylene short glass fibre filled. Hence, the present study
focuses on the tensile and fracture behaviours of polypropylene with short glass fibre of different loading, die-drawn at various speeds. Orientation in the draw direction is likely to increase the strength and stiffness while there is expected to be a reduction in the transverse direction. For this reason, fracture behaviour of drawn material is studied to quantify drawing effects in a transverse direction.
3 Die Drawing and Tensile Specimens Preparations

3.1 Die drawing specimens preparations

3.1.1 Sample fabrication

Injection moulding process was used to fabricate die drawing and tensile test specimens. Injection Moulding is the process of forcing molten plastic into a mould cavity where it cools and hardens. The moulded shape produced is a reverse image of the mould tool. Injection moulding is often used in mass-production and prototyping. Injection moulding is an extremely versatile process for producing a wide range of simple or complex plastic parts—economically and with a good surface finish.

All specimens were fabricated using a FANUC injection moulders as described in the next section.

3.1.1.1 Material mixing

The material investigated in this study was a commercial grade of unfilled Polypropylene from SABIC. This was used as master batch compounded with 55% fibre to produce the filled composites. The polypropylene data sheet for unfilled and 55% short glass fibre filled are listed in appendix A. Mixing was achieved using normal rotating mixer as shown in Figure 3.1. To produce a homogenous mix, the blend was mixed for 1hr in square drum rotating at 40rpm. Once the master batch was created it was further blended, with pure polypropylene to give composites of lower fibre content. The composites produced by this blending method are listed in Table 3.1. The weight percentages of the composites range from 7% to 55% fibre content.
Figure 3-1: Electric rotating mixer

Table 3-1: Polypropylene fibre mixing concentration

<table>
<thead>
<tr>
<th>No</th>
<th>Mixing material by weight</th>
<th>Final mixture by weight</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0% Wt Polypropylene</td>
<td>55% Wt filled PP</td>
</tr>
<tr>
<td>1</td>
<td>1 Kg</td>
<td>0.125 Kg</td>
</tr>
<tr>
<td>2</td>
<td>1 Kg</td>
<td>0.25 Kg</td>
</tr>
<tr>
<td>3</td>
<td>1 Kg</td>
<td>0.5 Kg</td>
</tr>
<tr>
<td>4</td>
<td>0 Kg</td>
<td>1 Kg</td>
</tr>
</tbody>
</table>
3.1.2 Injection moulding process

After mixing of polypropylene with short glass fibre to create filled compositions. The samples were injected into a tensile test specimens using a 100 ton FANUC injection moulding machine equipped with ASTM mould. The injection machine is Model S-200i100A, is shown in the Figure 3.2. The screw diameter is 32 mm and L/D ratio is 22:1. The pellets were introduced into the hopper without any preconditioning.

With injection moulding, granular plastic is fed by gravity from a hopper into a heated barrel. As the granules are slowly moved forward by a screw-type plunger, the plastic is forced into a heating chamber, where it is melts. As the plunger advances, the molten plastic is forced through a nozzle that rests against the mould, allowing it to enter the mould cavity. The mould remains cold so the plastic solidifies almost as soon as the mould is filled. Dumbbell samples of gauge length 90 mm, width 10 mm and thickness 4 mm were produced for each unfilled and filled polypropylene. These dimensions of the produced specimen are according to ASTM D638 standards of type I.
3.1.2.1 Major steps in the injection moulding process

Major steps in injection moulding are:

- Clamping: An injection moulding machine consists of three basic parts; the mould, the clamping unit and injection unit. The clamping unit is what holds the mould under pressure during injection and cooling.
- Injection: During the injection phase, plastic material, usually in the form of pellets, are loaded into a hopper on top of the injection unit. The pellets are fed into the cylinder where they are heated until they reach molten form. Within the heating cylinder there is a motorized screw that mixes
the molten pellets and forces them to end of the cylinder. Once enough material has accumulated in front of the screw, the injection process begins. The molten plastic is inserted into the mould through a sprue, while the pressure and speed are controlled by the screw.

- Dwelling: The dwelling phase consists of a pause in the injection process. The molten plastic has been injected into the mould and the pressure is applied to make sure all of the mould cavities are filled.
- Cooling: The plastic is allowed to cool within the mould.
- Mould Opening: The clamping unit is opened, which separates the two halves of the mould.
- Ejection: An ejecting rod and plate ejects the finished piece from the mould.
• The pellets are fed into the machine.

• The pellets is worked and warmed by an auger screw in a temperature controlled barrel

• As the pellets stock accumulates in the front of the screw, the screw is forced backwards. When the screw has moved back a specified amount, the machine is ready to make a shot

• With the mould held closed under hydraulic pressure, the screw is pushed forward. This forces the polymer into the mould

• While the polymer cures in the heated mould, the screw turns again to refill.

• The mould opens and the part can be removed. The machine is ready to make the next shot, as soon as the mould closes

Figure 3-3: Injection moulding process
3.1.3 Tensile specimens

Test specimens manufactured using injection moulding process. The specimens used for this investigation were based upon ASTM D638 standards for type I specimens. The schematic below Figure 3.4 shows such a produced injection moulded specimen with gage length 90mm, width 10 mm and thickness 4mm.

![ ASTM D638 standard type I specimen ]

- $W$: width of narrow section
- $W_O$: width overall
- $R$: radius of fillet
- $D$: distance between grips
- $L$: length of narrow section
- $L_O$: length overall
- $t$: thickness

Figure 3-4: ASTM D638 standard type I specimen

3.1.4 Procedure

The material used in this study was 0 %wt, 7 %wt, 13 %wt, 27% wt, and 55%wt, glass fibre reinforced polypropylene Tensile test specimens were produced on a FANUC injection moulder Model S-200i100A as shown in the Figure 3.5, equipped with a standard ASTM mould into drawing specimens. The melt processing temperature was set to 240 °C, in accordance with the material technical data sheet. The mould temperature was set to 50°C The typical injection moulding processing settings conditions process for unfilled and fibre
filled parameters Elsheikhi (2007) were listed in Table 3.2. These parameters selected by trial and error to optimise against the effect of condition on specimen’s geometry shrinkage in width and thickness and material flashing.

![Injection moulding tensile specimen](image)

**Figure 3-5: Injection moulding tensile specimen**

**Table 3-2: Injection moulding setting parameters**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Injection moulding Machine Setting</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fibre contents</td>
<td>0%</td>
</tr>
<tr>
<td>Barrel temperature</td>
<td>210</td>
</tr>
<tr>
<td>Nozzle temperature</td>
<td>210</td>
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<tr>
<td>Back pressure</td>
<td>100</td>
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<tr>
<td>Holding pressure</td>
<td>100</td>
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<tr>
<td>Cooling time</td>
<td>20 sec</td>
</tr>
<tr>
<td>Holding time</td>
<td>45 sec</td>
</tr>
<tr>
<td>Shot Size</td>
<td>36 mm</td>
</tr>
<tr>
<td>Screw rotation speed</td>
<td>150 rpm</td>
</tr>
<tr>
<td>Injection velocity</td>
<td>80 mm/sec</td>
</tr>
</tbody>
</table>
3.2 Die drawing process

Dumbbell specimens were injection moulded from unfilled polypropylene and 7%wt, 13%wt, 27%wt, and 55%wt short glass fibre filled as described previously in Figure 3.15. Line marked injection polypropylene unfilled and short glass fibre filled samples were drawn at fixed oven temperature (155°C) over wide range of draw ratio controlled at haul-off speeds of; 5mm/min, 10mm/min, 20mm/min, and 50mm/min.

3.2.1 Constant width die fixed at top of air oven.

Die drawing process was performed on a Messphysik tensile testing machine using the small scale die at top of an environmental chamber, as shown in Figure 3.6. Unfilled polypropylene and 7%wt, 13%wt, 27%wt, and 55%wt short glass fibre filled composite were drawn. The rig was fixed at the top of oven using supports as shown in Figure 3.7. Under this test condition the die and specimens are heated by the oven blower until they reach the required temperature, followed by a dwell time of 1 hour to ensure complete heating of specimen and die. The specimens were drawn through a die then outside the oven at room temperature, from a hole placed at the top of the oven.

Die temperature, die holder temperature and air temperature vary from point to point. To ensure the specimens are drawn at the required temperature thermocouples were fixed on six places in rig apparatus; upper, inside, bottom die, air, heater to monitor the temperature.

A constant width small rig die with 15° half angle was used as shown in Figure 3.8. The die thickness at the exit is 2 mm, the die width is 20 mm and the
die length is 7 mm. The set die temperature was 155 °C. This is just 10 °C below the melting temperature. However the thermocouple shows an actual temperature of 154°C during tests.

A tapered section was machined on each billet with a tag of 1 mm thickness and 20 mm length to allow gripping and to assist the start-up procedure for the process. All specimens were marked with horizontal lines every 10 mm to calculate the longitudinal draw ratio. Specimen tags are pulled out through the die with gradually increasing draw rate from 1 mm/min to 5 mm/min for 50 mm. The test then commenced, drawing specimens at an appropriate draw rate, using the drawing apparatus as shown schematically in Figure 3.9.
Figure 3-6: Die drawing apparatus

1-Mesphysik  
2-machine control  
3-Temperature control  
4-Load cell  
5-Electric blown oven  
6-Clamps - Grips  
7-dumbbell  
8-PC  
9-PC Monitor
Figure 3-7: Die at top of oven

Figure 3-8: A schematic diagram of constant width small rig
Figure 3-9: Small scale die apparatus environmental chamber
3.3 Drawn and undrawn specimens tensile test method

3.3.1 Sample preparation

Undrawn tensile test specimens were fabricated by injection moulding, and drawn tensile test specimens were cut from drawn samples. Specimens were drawn at different draw ratio and different fibre contents. Figure 3.10 illustrate the dimensions of the drawn anisotropic specimens and undrawn isotropic specimens.

![Figure 3-10: Tensile test specimen’s dimensions](image-url)
3.3.2 Tensile test method

Uniaxial tensile test of the drawn and undrawn unfilled polypropylene and short glass fibre filled specimens were carried out using an Instron tensile testing machine as shown in Figure 3.11. Uniaxial tests were performed with a cross head speed 10mm/min, at room temperature. Specimens were randomly selected from approximately one hundred and fifty samples. For tensile test, three specimens were tested for each condition to check the reproducibility of the results. Load-displacement data are used to calculate stress-strain, so comparison can be made between undrawn isotropic materials and drawn anisotropic material with different ratio of fibre contents.
Figure 3-11: Tensile test machine

1-Instron
2- Specimen
3-Load cell
4- Clamps –Grips
5- machine control
6- PC
7- PC Monitor
3.4 Fracture toughness test

In this study, double edge notched tensile specimens were used to derive the critical stress intensity factor $K_{IC}$. The specimen was cut with a saw, and a notch was cut using a band saw and sharpened blade. Fracture tests were conducted on an Instron test machine with the cross head speed of 5mm/min.

3.4.1 Drawn and undrawn specimens fracture test method

3.4.1.1 Sample preparation

Undrawn fracture test specimens were fabricated by injection moulding. Drawn tensile test specimens were cut from drawn test specimens drawn at different draw ratio and different fibre contents. Figure 3.12 illustrate the dimensions of the drawn anisotropic specimens and undrawn isotropic specimens.
3.4.2 Experimental details

Experimental fracture tests were performed on drawn and undrawn polypropylene filled with short glass fibre at contents 0% wt, 7% wt, 13% wt, 27% wt, and 55% wt. Failure stress, failure strain and fracture toughness were determined for double-edge-notched (DEN) specimens. All test samples of drawn polymer were cut with the longitudinal axis parallel to the drawing direction. They were cut from central positions in the drawn billets in order to have similar fibre orientation distribution for the individual specimens. Fracture specimens geometry can be calculated using Hashemi’s suggested equation (Hashemi and Williams, 1984) They found that polypropylene can give satisfactory value of thickness and widths down to half the minimum values using:

- A-Undrawn specimen

- B-Drawn specimen

Figure 3-12: Fracture test specimen’s dimensions
Chapter 3  
Die Drawing and Tensile Specimens Preparations

\[ B = 2.5 \left( \frac{K_{IC}}{\sigma_y} \right)^2 \]  \quad (3.1)  

\[ w_{\text{min}} = 6.25 \left( \frac{K_{IC}}{\sigma_y} \right)^2 \]  \quad (3.2)  

For the DEN specimen, the specimens width and length are 10 and 100 mm respectively and thickness, \( t = 1.8 \text{ mm} \) as shown in Figure. 3.13., while the span (distance between grips) is equal to 70 mm, the crack length \( a \), was set at 1.5mm, 2.0mm and 2.5 mm.

![Figure 3-13: Geometry of specimens with edge notches](image_url)
3.4.3 Fracture test method

Since preliminary tests indicated anisotropy in the mechanical properties, the notches were introduced perpendicular to the drawing direction. Pre-notching was done by cutting with a sharper cut machine. All double-notch of undrawn and drawn specimens were carefully machined by Perfecto sharper-cut machine number 1476/4 as shown in Figure 3.14 to ensure parallelism and symmetry. This type of Perfecto sharper moves up/down, forward/backward and right/left, with an adjusting knife holder. A sharp knife position is then controlled precisely by an indicator to make the notches exactly in the middle of the samples.

![Figure 3-14: Perfecto sharper- cut machine](image-url)
Uniaxial fracture test of the drawn and undrawn unfilled polypropylene and short glass fibre filled specimens were carried out using an Instron tensile testing machine model 5564 as shown in Figure 3.15. Uniaxial fracture tests were performed with a cross head speed 5mm/min, at room temperature. Specimens were randomly selected from approximately one hundred and fifty for test specimen. Load displacement data were used to calculate stress-strain, so comparison could be made between undrawn isotropic materials with drawn anisotropic material with different ratio of fibre contents. The fracture behaviour of the materials were analysed from load extension curves and the stress-stain curve. Five specimens for each fibre content and draw ratio were tested and the average values of the results were reported.

Figure 3-15: Instron fracture test machine
Figure 3-16: Fracture test machine
4 Die Drawing and Tensile Test Result

Introduction

In this chapter, the results die drawing process of unfilled and unfilled material drawn under different speeds and mechanical properties are presented and discussed.

4.1 Calculation of stress and strain

Testing was carried out on specimens under uniaxial loading conditions. True stresses and engineering strains were calculated for each data point using:

\[
\text{True stress } \sigma = \frac{F}{A} \quad (4.1)
\]

\[
\text{Strain } e = \frac{\Delta l}{l_0} \quad (4.2)
\]

Where \( F \) is load, \( A \) is the instantaneous cross sectional area, \( \Delta l \) is change in length, and \( l_0 \) is the original length.

The changing cross sectional area was calculated using the assumption that volume remains constant and so the area can be calculated using the following formula.

\[
V = lA \quad (4.3)
\]

Where \( V \) is the volume, \( l \) is the length, \( A_0 \) initial area and initial length \( l_0 \) this corresponds to

\[
V = l_0 A_0 \quad (4.4)
\]

The new area is
\[ A = \frac{A_0}{l/l_0} \]  

(4.5)

\( l/l_0 \) is the extension ratio \( \lambda \). Hence

\[ A = \frac{A_0}{\lambda} \]  

(4.6)

From equation (2.1) it now follows that

\[ \sigma_t = \frac{F}{A_h} = \lambda \frac{F}{A_0} = \lambda \sigma_e \]  

(4.7)

Where \( \sigma_e \) is the engineering stress, for the purpose of data analysis the true stress \( \sigma_t \) was calculated by multiplying the load by the extension ratio, obtained from lines drawn in samples before drawing and then dividing by the original area of the specimen.

For completeness, an explanation of true strain follows although this was not evaluated during the analysis. True strain \( e \) is the sum of all the instantaneous engineering strains

\[ d_e = \frac{dl}{l} \]  

(4.8)

Then true strain, \( e \) is

\[ e = \int_{l_0}^{l_f} dl = \int_{l_0}^{l_f} \frac{l_f}{l_0} = \ln \frac{l_f}{l_0} \]  

(4.9)

Where \( l_0 \) and \( l_f \) are the initial and final lengths.

This can be related to the engineering strain, \( e_e \) as
\[ e = \ln \frac{l_f}{l_o} = \ln \left( \frac{l_o + \Delta l}{l_o} \right) = \ln (1 + e) \] 

(4.10)

### 4.2 Die drawing results

Polypropylene molecular chains can align and rearrange by drawing below the melting point using die drawing process. This process is carried out at a temperature of 155 °C, just 10 °C below the T\text{m}, as suggested in the work of Coates and Ward (1979). Changes to the drawing process are discussed in the following section.

The final cross section of specimen is usually less than die exit cross section due to the free tensile drawing that occurs after die exit. Total deformation characterized by actual draw ratio R\text{A}. The draw ratio was calculated from the ratio before and after drawing of the spacing of lines marked along drawing specimens.

At the start of the drawing process the load reaches its peak value. This is because the material becomes softer and more ductile when it enters the high die temperature, since its temperature is higher than material at the beginning of the drawing process. In the die the specimen necks down and the draw load therefore decrease from its maximum to reach a steady state value.

The width dimensions of the drawn specimens were measured at different positions along the length actual. These reveal R\text{A} draw ratio range from 1.4 to 5.6 for die with exit thickness of 2.0 mm.
The general observations are that the draw ratio and mean draw load increased with increase in draw speeds for both unfilled and different fibre filled specimens.

Draw ratio decreased with increasing fibre content. The addition of 7%wt-55%wt fibre significantly decreases draw ratio. However higher fibre contents caused more appreciable draw ratio decreases. This decrease in draw ratio can be associated with the fibre that restricting the mobility of the polymer (Premalal et al., 2002). Unfilled material shows the highest draw ratio.

### 4.2.1 Die drawing of unfilled polypropylene

Unfilled polypropylene specimens were drawn at four different draw speeds from 5mm/min to 50mm/min. By increasing draw speed draw ratio increased and drawing mean load increased by 16% from 37 N for draw speed of 5mm/min to 44N for draw speed of 50mm/min. Mean load is the averaged drawing load taken during drawing process. Figure 4.1 show different drawn samples for each drawing speed. Mean load draw ratio values are listed in Table 4.1.

<table>
<thead>
<tr>
<th>Wt%</th>
<th>Draw speed mm/min</th>
<th>Mean load (N)</th>
<th>Draw ratio λ</th>
</tr>
</thead>
<tbody>
<tr>
<td>0%</td>
<td>5</td>
<td>37</td>
<td>4.6</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>39</td>
<td>4.7</td>
</tr>
<tr>
<td></td>
<td>20</td>
<td>42</td>
<td>5.0</td>
</tr>
<tr>
<td></td>
<td>50</td>
<td>44</td>
<td>5.6</td>
</tr>
</tbody>
</table>
The variation between drawing load for unfilled polypropylene drawn at different draw speeds and drawing extension is shown in Figure 4.2. The general observation here is that the draw load level and draw ratio increases with increasing draw speeds. Also, the load peaked at the beginning of the drawing process prior to dropping rapidly to an approximately constant and steady value. It can be seen that increase in the draw rate results in an increase between 57% and 80% in drawing load.
### Figure 4-2: Unfilled polypropylene drawn at different draw speeds

![Graph showing drawing load vs displacement for different draw speeds](image)

\[ \text{Displacement (mm)} \]

- 5mm/min
- 10mm/min
- 20mm/min
- 50mm/min

---

#### 4.2.2 Die drawing of polypropylene +7% wt short fibre filled

Polypropylene +7% wt short glass fibres filled drawn at different draw speeds from 5mm/min to 50 mm/min, is shown in Figure 4.3. The polymer draw ratio is shown to decrease by adding short glass fibre compared to unfilled material. At same drawing speed the draw ratio decrease by 42% from $\lambda=5.6$ for unfilled polypropylene to $\lambda=3.2$ for 7%wt filled. The figure4.3 show that draw load increases with draw speeds. The load increased by 23% from drawing speed of 5mm/min to 50mm/min.
Chapter 4  

Results  

Die drawing

Figure 4.3: Polypropylene 7% wt filled drawn at different draw speeds

Table 4.2: Draw ratio and draw load for different draw speeds

<table>
<thead>
<tr>
<th>Wt%</th>
<th>Draw speed mm/mi</th>
<th>Draw load (N)</th>
<th>Draw ratio $\lambda$</th>
</tr>
</thead>
<tbody>
<tr>
<td>7%</td>
<td>5</td>
<td>59</td>
<td>2.4</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>65</td>
<td>2.6</td>
</tr>
<tr>
<td></td>
<td>20</td>
<td>66</td>
<td>2.7</td>
</tr>
<tr>
<td></td>
<td>50</td>
<td>73</td>
<td>3.2</td>
</tr>
</tbody>
</table>

4.2.3 Die drawing of polypropylene +13% wt short fibre filled

Figure 4.4 show data for polypropylene +13% wt short glass fibre composites drawn at draw speeds of 5mm/min, 10mm/min, 20mm/min, and 50mm/min. It can be seen that increasing draw speeds increases the drawing load from 78N for drawing speed 5mm/min to 108N for drawing speed 50 mm/min.
4.2.4 Die drawing of +27% wt polypropylene short fibre filled

Data for polypropylene +27% wt short glass fibre filled drawn at draw speeds of 5mm/min to 520mm/min is shown in Figure 4.5. Drawing speed was limited of 20mm/min because fracture occurred in samples at the die exit when speeds were more than 20 mm/min. Increasing the draw speed results in up to 6% increase in the draw load. Increases in draw ratio from $\lambda=1.71$ to $\lambda=1.83$ resulted in drawing load increases from 107N to 114N. Also drawn specimens dimension increase in width to 11mm from 10mm for undrawn specimens.
Figure 4-5: Polypropylene 27%wt filled drawn at different draw speeds

Table 4-4: Draw ratio and draw load for different draw speeds

<table>
<thead>
<tr>
<th>Wt%</th>
<th>Draw speed mm/mi</th>
<th>Draw load (N)</th>
<th>Draw ratio $\lambda$</th>
</tr>
</thead>
<tbody>
<tr>
<td>27%</td>
<td>5</td>
<td>107</td>
<td>1.71</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>104</td>
<td>1.73</td>
</tr>
<tr>
<td></td>
<td>20</td>
<td>114</td>
<td>1.83</td>
</tr>
</tbody>
</table>
4.2.5 Die drawing of polypropylene +55% wt short fibre filled

Data of Figure 4.6 show load-displacement curves of polypropylene +55%wt short glass fibre specimens drawn at draw speeds of 5mm/min. and 10mm/min. Increasing short glass fibre content to 55%wt limits the speed to 10mm/min. Above 10mm/min results in failure of the material at die exit. Increasing the glass fibre to 55%wt results in a relatively brittle composite with a low fracture strength. The two draw ratio achieved are \( \lambda =1.41 \) and slightly higher draw ratio \( \lambda =1.43 \). The drawing load decreases from 120N to115N. Specimens thickness increased to 1.4mm in two draw ratios.

![Drawing load vs Extension graph](image)

**Figure 4-6: Polypropylene 55% wt filled drawn at different draw speeds**
### Table 4-5: Draw ratio and draw load for different draw speeds

<table>
<thead>
<tr>
<th>Wt%</th>
<th>Draw speed mm/mi</th>
<th>Draw load(N)</th>
<th>Draw ratio $\lambda$</th>
</tr>
</thead>
<tbody>
<tr>
<td>55%</td>
<td>5</td>
<td>120</td>
<td>1.41</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>115</td>
<td>1.43</td>
</tr>
</tbody>
</table>

#### 4.2.6 Draw ratio

Figure 4.7 shows draw ratio versus drawing speeds for all composites drawn at different speeds. There appears approximately to be a linear relationship between drawing speeds and draw ratio. It can be seen that clearly draw ratio increased with increasing draw speed and decreased with fibre content. The draw ratio achieved in at various drawing speeds and for different fibre contents are summarized in Tables 4.10. The unfilled polypropylene shows an approximate linear increase in draw ratio withdraw speed, reaching a maximum draw ratio of $\lambda = 5.6$ at 50 mm/min. The lowest draw ratio for polypropylene +55%wt short glass fibre filled is $\lambda = 1.43$. As short glass fibre content increases from 7%wt, 13%wt, to 27%wt. draw ratio decrease to $\lambda = 3.2$, $\lambda = 2.5$, $\lambda = 1.83$ respectively.
Figure 4-7: Draw ratio versus drawing speed of different fibre contents
Table 4-6: Average mean load and draw ratio for different fibre content

<table>
<thead>
<tr>
<th>Fibre contents (wt)</th>
<th>0%</th>
<th>7%</th>
<th>13%</th>
<th>27%</th>
<th>55%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Drawing speeds (mm)</td>
<td>5</td>
<td>10</td>
<td>20</td>
<td>50</td>
<td>5</td>
</tr>
<tr>
<td>Mean load (N)</td>
<td>37</td>
<td>39</td>
<td>42</td>
<td>44</td>
<td>59</td>
</tr>
<tr>
<td>Draw ratio $\lambda$</td>
<td>4.6</td>
<td>4.7</td>
<td>5.0</td>
<td>5.6</td>
<td>2.4</td>
</tr>
<tr>
<td></td>
<td>1.71</td>
<td>1.73</td>
<td>1.83</td>
<td></td>
<td>1.41</td>
</tr>
</tbody>
</table>
4.3 Draw ratio calculating using specimens area

Draw ratio of filled and unfilled specimens determined by calculating the distance between two lines that are drawn along the specimen lengths before and after drawing as shown in Figure.4.7.

Another method used to determine draw ratio is to compare specimen area before and after drawing. A specimen’s thickness and width decreases with increasing draw speed.

The deformation ratio or draw ratio was calculated from the ratio before and after drawing of the specimen’s cross section area. Results show no significant difference between areas and longitudinal draw ratio as listed in Table 4.7.

Figure 4-8: Draw ratio versus drawing speed
Table 4-7: Comparing between area and longitudinal draw ratio

<table>
<thead>
<tr>
<th>Fibre contents</th>
<th>Drawing speed</th>
<th>Thickness</th>
<th>Width</th>
<th>Area</th>
<th>$\lambda_L$</th>
<th>Initial area</th>
<th>Final area</th>
<th>$\lambda_a$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0%</td>
<td>5mm/min</td>
<td>1.23</td>
<td>7.2</td>
<td>8.86</td>
<td>4.6</td>
<td>39.9</td>
<td>8.86</td>
<td>4.51</td>
</tr>
<tr>
<td></td>
<td>10mm/min</td>
<td>1.21</td>
<td>6.9</td>
<td>8.35</td>
<td>4.7</td>
<td>39.9</td>
<td>8.35</td>
<td>4.78</td>
</tr>
<tr>
<td></td>
<td>20mm/min</td>
<td>1.16</td>
<td>6.7</td>
<td>7.77</td>
<td>5</td>
<td>39.9</td>
<td>7.77</td>
<td>5.13</td>
</tr>
<tr>
<td></td>
<td>50mm/min</td>
<td>1.10</td>
<td>6.4</td>
<td>7.04</td>
<td>5.6</td>
<td>39.9</td>
<td>7.04</td>
<td>5.67</td>
</tr>
<tr>
<td>7%</td>
<td>5mm/min</td>
<td>1.77</td>
<td>9.2</td>
<td>16.21</td>
<td>2.4</td>
<td>39.9</td>
<td>16.21</td>
<td>2.46</td>
</tr>
<tr>
<td></td>
<td>10mm/min</td>
<td>1.74</td>
<td>8.5</td>
<td>14.79</td>
<td>2.6</td>
<td>39.9</td>
<td>14.79</td>
<td>2.70</td>
</tr>
<tr>
<td></td>
<td>20mm/min</td>
<td>1.72</td>
<td>8.3</td>
<td>14.19</td>
<td>2.7</td>
<td>39.9</td>
<td>14.19</td>
<td>2.81</td>
</tr>
<tr>
<td></td>
<td>50mm/min</td>
<td>1.55</td>
<td>8.2</td>
<td>12.71</td>
<td>3.2</td>
<td>39.9</td>
<td>12.71</td>
<td>3.14</td>
</tr>
<tr>
<td>13%</td>
<td>5mm/min</td>
<td>1.89</td>
<td>10.1</td>
<td>19.13</td>
<td>2.1</td>
<td>39.9</td>
<td>19.13</td>
<td>2.09</td>
</tr>
<tr>
<td></td>
<td>10mm/min</td>
<td>1.84</td>
<td>10.1</td>
<td>18.55</td>
<td>2.1</td>
<td>39.9</td>
<td>18.55</td>
<td>2.15</td>
</tr>
<tr>
<td></td>
<td>20mm/min</td>
<td>1.80</td>
<td>10.0</td>
<td>18.00</td>
<td>2.3</td>
<td>39.9</td>
<td>18.00</td>
<td>2.22</td>
</tr>
<tr>
<td></td>
<td>50mm/min</td>
<td>1.78</td>
<td>9.2</td>
<td>16.41</td>
<td>2.5</td>
<td>39.9</td>
<td>16.41</td>
<td>2.43</td>
</tr>
<tr>
<td>27%</td>
<td>5mm/min</td>
<td>1.92</td>
<td>12.3</td>
<td>23.62</td>
<td>1.71</td>
<td>39.9</td>
<td>23.62</td>
<td>1.69</td>
</tr>
<tr>
<td></td>
<td>10mm/min</td>
<td>1.93</td>
<td>12.1</td>
<td>23.35</td>
<td>1.73</td>
<td>39.9</td>
<td>23.35</td>
<td>1.71</td>
</tr>
<tr>
<td></td>
<td>20mm/min</td>
<td>1.91</td>
<td>11.9</td>
<td>22.67</td>
<td>1.83</td>
<td>39.9</td>
<td>22.67</td>
<td>1.76</td>
</tr>
<tr>
<td></td>
<td>55%</td>
<td>2.00</td>
<td>14.2</td>
<td>28.40</td>
<td>1.41</td>
<td>39.9</td>
<td>28.40</td>
<td>1.40</td>
</tr>
<tr>
<td></td>
<td>10mm/min</td>
<td>1.95</td>
<td>14.2</td>
<td>27.69</td>
<td>1.43</td>
<td>39.9</td>
<td>27.69</td>
<td>1.44</td>
</tr>
</tbody>
</table>
4.4 Summary

4.4.1 Die drawing results

Both fibre filled polypropylene and unfilled polypropylene specimens have been drawn under different drawing speeds. Results show that the axial draw ratio increase with drawing speeds. The axial draw ratio is higher at lower draw temperature at any draw speed, which is the same result obtained by Capaccio and Ward (1980)

In fact draw ratio increases with increasing draw speed for both unfilled and filled samples, this is similar to the work of Cansfield and Ward (1976) the deformation of unfilled material increases with increasing drawing speed from 10mm/min to 20mm/min, with the actual draw ratio RA raising to $\lambda = 20$. In die drawn polypropylene is found the degree of deformation attainable depends strongly on the draw velocity. This is a similar finding to the work of Coates and Ward (1979) and Taraiya and Ward (1987).

Draw ratio is higher for unfilled material at same drawing speed than filled. It is thought this is because the filler fibre network restricts the polymer molecules from moving easily in the draw direction. As filler loading increased draw ratio decreased, reaching lowest value for 55%wt of fibre, due to fibre colliding with each other and voids increasing surround fibre. This is a similar result to that by Gibson and Ward (1980a) for polypropylene 20%wt glass fibre filled specimens giving moduli up to 14.2 GPa. Because the actual draw ratio of filled specimens achieved was lower than unfilled, the maximum stiffness (modulus) was lower than that attainable with the unfilled polypropylene. Specimens with higher filler contents, 27%wt and 55%wt failed at draw speeds above 20mm/min. similar
result for glass fibre polyoxymethylene containing 20% wt of short glass were obtained by Richardson and Ward (1982). Attempts to increase the drawing speed above 80mm/min. resulted the product fracture beyond the die drawing die exit. Composites could only be drawn to a draw ratio of $\lambda = 11$, while for unfilled the actual deformation ratio continued to rise until fracture occurred at draw ratio of $\lambda = 14$. Additionally in work by Taraiya and Ward (1987) on unfilled polypropylene, draw speed was limited by machine maximum speeds of 500mm/min.
5 Mechanical Behaviour of Polypropylene and Polypropylene

/Glass Composite both Drawn and Undrawn

5.1 Uniaxial tensile testing

This chapter describes the effects of draw ratio and fibre content on the mechanical properties of composites based on short glass fibre reinforced polypropylene. Injection moulded polypropylene specimens filled with 7 % wt to 55 % wt short glass fibres, were drawn using a small scale die drawing rig at different draw rates. The filler loading and draw ratios are summarized in Table 5.1 below. The materials were investigated using room temperature tensile testing to study the effect of draw ratio and fibre content on mechanical properties.

Table 5-1 Draw ratio and fibre contents

<table>
<thead>
<tr>
<th>Fibre %wt</th>
<th>Drawing speed mm/min</th>
<th>5</th>
<th>10</th>
<th>20</th>
<th>50</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Draw ratio</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>4.6 4.7 5.0 5.6</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>2.4 2.6 2.7 3.2</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>13</td>
<td>2.1 2.2 2.3 2.5</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>27</td>
<td>1.71 1.73 1.83</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
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<td>55</td>
<td>1.41 1.43</td>
<td></td>
<td></td>
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</tr>
</tbody>
</table>
Chapter 5

Results - Mechanical Behaviour

5.2 Unfilled polypropylene

The variation of tensile stress-strain for unfilled polypropylene in the undrawn and drawn condition at different draw ratios is shown in Figure 5.1 and Figure 5.2 respectively. It is clearly seen that the tensile stress increases with increasing draw ratio. The tensile stress increases from 20 MPa for $\lambda = 1$ draw ratio to 90 MPa for $\lambda = 5.6$ draw ratio as shown in Figure 5.3 Results of maximum strain and maximum stress are listed in Table 5.2

The stress strain curve for undrawn unfilled polypropylene is different to that of drawn material. In the undrawn specimens local necking was observed at a certain stress level and the neck progressed along specimen’s length eventually reaching its ends as stress increased. This is due to the polymer molecules orienting in the load direction.

The stress strain-curves of the drawn unfilled polypropylene are almost the same for all draw ratios. There is no necking and stresses increased to its maximum values. Polymer molecules undergo considerable orientation and this orientation has an effect on the polymer mechanical properties; toughness and stiffness.
Figure 5.1: Tensile stresses versus strain for 0% wt fibre undrawn specimens

In unfilled polypropylene specimens the die drawing process results in a high modulus and tensile strength enhancement. These enhanced mechanical properties resulted from high orientation in polymer molecules. Likewise inclusion of fibre filler in the material resulted in enhancement of mechanical properties in the draw direction but a decrease in the traverse direction.

From data in Figures 5.3 and 5.4 it is shown both stress at break and yield stress increase with draw ratio. The trend is linear from draw ratio $\lambda = 4.7$ to $\lambda = 5.6$.

Actual experimental data is summarized in Table 5.2

The enhancement of modulus with drawing has been interpreted in terms of morphology. It is believed extended chain crystals contributed to the improved properties along the drawing direction (Gibson. and Ward, 1978).

It can be seen that there is an enhancement of the modulus along the draw direction of approximately 300% for unfilled samples compared to undrawn polypropylene specimens at a draw ratio of $\lambda = 5.6$. 

103
The tensile modulus of drawn polypropylene is comparable to data obtained by Taraiya and Ward (1987).
Table 5-2 Unfilled polypropylene tensile modulus and stress at yield

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Yield stress (MPa)

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Stress at break (MPa)

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Figure 5-2: Draw ratio versus yield stress for unfilled
Figure 5-3: Draw ratio versus stress at break for unfilled
5.2.1 Tensile modulus

Tensile modulus was calculated by drawing linear trend line using Excel through the initial part of the tensile stress strain curve. Tensile modulus versus draw ratio curves are shown in Figure 5.4. From the figure it can be seen that the tensile modulus for unfilled polypropylene increased with increasing draw ratio. Specimens drawn at draw ratio of $\lambda = 5.6$ show the highest tensile modulus of 3.6GPa. Undrawn specimens $\lambda = 1$ show the lowest tensile stress of 0.95GPa. These data are comparable with trends found by Ward (1982), showing tensile modulus increases with draw ratio.
Figure 5-4: Draw ratio versus tensile modulus for unfilled polypropylene
5.3 Polypropylene +7% wt short glass fibre filled

5.3.1 Tensile stress strain

Figure 5.5 show true stress-strain curves for drawn and undrawn polypropylene filled with 7% wt short glass fibre. From the figures it can be seen that the tensile stress increases with increasing draw ratio from $\lambda = 1$ to $\lambda = 3.2$ to its highest value of 48MPa.

Stress at break, yield stress and tensile modulus increased with increasing draw ratio, as is shown in Figures 5.6-5.8. The results show drawing significantly enhances tensile properties compared with undrawn samples. There is an improvement in modulus of about 200% for the higher draw ratio compared to the undrawn specimens.

Much improvement is shown in Figures 5.6, and 5.7 for both yield stress and stress at break. Yield stress was increased up to 65% for the drawn material as compared to undrawn material and stress at break increased by 40%. All tensile results are listed in Table 5.3.
Figure 5-5: Tensile stresses versus strain for 7% wt fibre
Table 5-3: Polypropylene 7% wt tensile modulus and stress at yield

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Figure 5-6: Draw ratio versus yield stresses for 7% wt fibre
Figure 5-7: Draw ratio versus stress at break for 7% wt fibre filled
Figure 5-8: Draw ratio versus tensile modulus for 7% wt fibre filled.
5.4 Polypropylene +13% wt short glass fibre filled

5.4.1 Tensile stress strain

The effect of draw ratio on the tensile modulus of 13%wt filled material is shown in Figure 5.9. An increase in the tensile modulus values is observed. The results also indicate that the yield stress, stress at break and modulus all increase with draw ratio as shown in Figures 5.10-5.11-5.12. At a draw ratio of $\lambda=2.5$ the modulus increased to the highest value, 200% being greater than undrawn. The data show there is a higher modulus for the drawn material over the undrawn. This is thought to be due to the high modulus of glass fibre and its orientation. Observation of yield stress, stress at break, and tensile modulus results, show a remarkable enhancement by the addition of 13%wt fibre and on applying an increasing draw ratio from $\lambda=1$ to $\lambda=2.1$. Stress at break values were increased by 20% in specimens with draw ratio of $\lambda=2.5$ compared to undrawn specimens. Table 5.4 listed stress and modulus values for different draw ratios.
Figure 5-9: Tensile stresses versus strain for 13% wt fibre filled
Table 5-4: Polypropylene 13% wt tensile modulus and yield stress

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Figure 5-10: Draw ratio versus yield stress for 13% wt fibre filled
Figure 5-11: Draw ratio versus stress at break for 13% wt fibre filled
Figure 5-12: Draw ratio versus tensile modulus for 13% wt fibre filled
5.5 Polypropylene +27% wt short glass fibre filled

5.5.1 Tensile stress-strain

Figures 5.13 to 5.16 display stress-strain curves for polypropylene with 27% wt short glass fibre from the lower draw ratio of $\lambda = 1$ to highest draw ratio of $\lambda = 1.83$. The tensile stress values have been calculated for every draw ratio. Comparing the figures, it can be seen that the tensile stress decreased by 10% per cent when drawn at draw ratio of $\lambda = 1.83$ from the value of 52.6 MPa for the specimens drawn at draw ratio of $\lambda = 1$ (values of only 42.1MPa draw ratio of $\lambda = 1.83$). In general tensile stresses slightly decrease at intermediate draw ratio $\lambda = 1.73$ and $\lambda = 1.71$.

![Graph of Tensile Stress vs Strain for 27% wt fibre filled](image)

**Figure 5-13:** Tensile stresses versus strain for 27% wt fibre filled
Trends in tensile modulus against draw ratio are shown in Figures 5.16. It can be seen that drawing the 13% wt filled specimens reduce the modulus by 20% per cent when drawn to draw ratio of $\lambda = 1.83$. At the highest draw ratio of $\lambda = 1.83$, tensile modulus decrease substantially to a value of 3.40 GPa compared to an undrawn value of 4.25 GPa.
Table 5-5: Tensile modulus and stresses of undrawn drawn 27% wt filled polypropylene

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Figure 5-14: Draw ratio versus yield stress 27% wt fibre filled
Figure 5-15: Draw ratio versus stress at break 27% wt fibre filled
Figure 5-16: Draw ratio versus tensile modulus for 27% wt fibre filled
5.6 Polypropylene +55% wt short glass fibre filled

5.6.1 Tensile stress strain

In Figure 5.17 plots of the stress-strain for the undrawn polypropylene +55% wt short glass fibre drawn at $\lambda=1.41$ and $\lambda=1.43$ are shown. As expected tensile stress decreases with increasing draw ratio. The tensile stress decreased by 120% at the maximum draw ratio of $\lambda=1.43$. Undrawn specimens show the highest tensile stress value of 75MPa while specimens drawn at a draw ratio of $\lambda=1.43$ exhibit a tensile stress of 33.5MPa. The calculated tensile stress strain and tensile modulus are displayed Table 5.6.

![Figure 5-17: Tensile stresses versus strain for 55% wt fibre filled](image)
The tensile stress versus strain graphs are plotted in Figure 5.17. The calculated tensile modulus for each draw ratio is shown in Figure 5.20. These data show that the tensile modulus decrease to value of 4100MPa by increasing draw ratio from $\lambda=1$ to $\lambda=1.4$. This is a reduction by 40% in tensile modulus.
Table 5.6: Tensile modulus and stresses of undrawn drawn 55% wt filled polypropylene

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<tbody>
<tr>
<td>1</td>
<td>32</td>
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<td>30</td>
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<td>1.155</td>
</tr>
<tr>
<td>1.41</td>
<td>21</td>
<td>22</td>
<td>22</td>
<td>23</td>
<td>0.577</td>
</tr>
<tr>
<td>1.43</td>
<td>18</td>
<td>19</td>
<td>18</td>
<td>18</td>
<td>0.577</td>
</tr>
</tbody>
</table>
Figure 5-18: Draw ratio versus yield stress 55% wt fibre filled
Figure 5-19: Draw ratio versus stress at break 55% wt fibre filled
Figure 5-20: Draw ratio versus tensile modulus for 55% wt fibre filled
5.7 Uniaxial tensile test results analysis and discussion

Mechanical tests were conducted on both drawn and undrawn unfilled and short glass fibre filled polypropylene following the procedures described in previous section. A summary of the test results and discussion are given in this section. More detailed test results and curves can be found in Appendix C.

There is a strong influence of short glass fibres on drawing behaviour and the orientation in term of mechanical property enhancement. The effect of draw ratio and the effect of fibre contents are clearly seen in test specimens. Draw ratio influences the mechanical properties of the composite in two ways – via polymer molecules orientation, and via the fibre orientation. Increasing in fibre contents and the increasing in draw ratio make the material significantly stiffer compared with the unfilled undrawn polypropylene.

5.7.1 Effect of draw ratio and fibre content

5.7.1.1 Tensile modulus

Tensile modulus of the undrawn specimens increases continuously with increasing in fibre content, as shown in the tensile modulus of undrawn and drawn composite specimens plotted in Figure 5.21. A strong increase in modulus is observed with increase in fibre content to 55%wt at $\lambda =1$. Drawing resulted in modulus increase with increasing draw ratio for unfilled material. It clearly seen the modulus increased from 0.94 MPa for undrawn to 3.68MPa for draw ratio of $\lambda =5.6$. A similar trend of increasing modulus with draw ratio is seen for 7%wt filled. Again observation of the 13%wt filled composite shows tensile modulus increased from 2.09MPa to 4.63MPa for draw ratio $\lambda =2.5$. However for both
27% wt and 55% wt glass fibre filled composite the tensile modulus decreased with draw ratio.

Yield stress data for unfilled and short glass fibre filled polypropylene are shown in Figure 5.22. The maximum yield stress for unfilled polypropylene was 33.7 MPa for the specimens drawn at draw ratio of \( \lambda = 5.6 \).

Polypropylene 7%wt short glass fibre data showed that yield stress reaches its maximum value of 36.3 MPa at draw ratio of \( \lambda = 3.2 \).

Yield stress of polypropylene 13%wt glass fibre reaches its maximum value of 58 MPa for specimens drawn at draw ratio of \( \lambda = 2.5 \).

Data for polypropylene +27%wt glass fibre show yield stress decreases from a maximum value of 26.7 MPa for undrawn specimens to 20.1 MPa for those drawn a \( \lambda = 1.73 \). Similar data for polypropylene +55% wt glass fibre show significant decrease in yield stress from 50 MPa for undrawn condition to only 18.3 MPa at \( \lambda = 1.43 \).
Figure 5-21: Draw ratio versus tensile modulus for unfilled-7%-13%-27%-55% wt
Figure 5-22: Draw ratio versus yield stress unfilled-7%-13%-27%-55% wt
5.7.2 Test results of undrawn unfilled polypropylene and fibre filled composite

In comparing the tensile modulus results of undrawn unfilled and drawn short glass fibre filled composite we find the tensile modulus reaches its maximum for the undrawn 55%wt short glass fibre filled composite

Unfilled and moderate filled composite displayed a general trend of increasing tensile modulus and strength with an increase in fibre contents. Tensile modulus was enhanced by the order of 792% for 55%wt short glass fibre filled compared to unfilled polypropylene. Yield stress was found to increases by about 278% compared to unfilled specimens for the same filler contents.

5.7.3 Test results of drawn unfilled polypropylene and fibre filled composite

The polypropylene glass fibre filled composites fabricated with fibre weight fractions ranging from 7%wt to 55%wt display complex trends tensile modulus and tensile stress behaviour. At low weight fraction the drawn composites initially show a trend on increases in modulus. However above critical loading (13%wt) both the properties decrease with fibre contents. Tensile moduli of undrawn and drawn polypropylene unfilled and filled material are summarised in Tables 5.7, 5.8. Specimens filled 13%wt short glass fibre seem to be an optimal fibre filled for yield stress, and tensile modulus.

Tensile modulus reaches its maximum for specimens filled with 13%wt short glass fibre and drawn at draw ratio of \( \lambda = 2.5 \). The tensile modulus was
increased by 130% when compared with the undrawn specimen. Specimens filled by 7%wt short glass fibre drawn at draw ratio of λ=3.2, tensile modulus increased by 127% compared to undrawn specimens. While for 27%wt and 55%wt there was significant reduction in modulus with increasing draw ratio.

The mechanical behaviour of drawn filled specimens are unlike those of the undrawn specimens for undrawn specimens both modulus and yield stress increased with increasing fibre contents. However for drawn specimens modulus and strength show a continuous increase with an increase in fibre contents and draw ratio to a13%wt. there is significant reduction in these properties at higher fibre contents irrespective of draw ratio> λ of 1

The reason for the decrease in stress and modulus at high fibre filled and high draw ratio is the interactions between the fibres. Since the fibres distributed in core of specimens by injection moulding process, interactions between the fibres are inevitable. When drawing specimens using the die drawing process specimen thickness decreases which tends to expose fibre on the outer surface of specimens. It is believed this creates more interaction between the fibres, and this interaction becomes greater with increasing drawing ratio. The higher fibre contents may lead to increasing voids and poor bonding between the fibres and the polypropylene. Hence, the tensile modulus and stress start to decrease as fibre contents increases. When the fibre volume is low, the fibres play the role of reinforcement. This is why below a certain fibre contents, the tensile modulus and strength of the composite increase.
Figure 5.23: Draw ratio versus stress at break unfilled-7\% -13\% -27\% -55\% wt

Draw ratio

Stress at break (MPa)
### Table 5-7: Tensile properties of undrawn drawn unfilled and polypropylene filled

<table>
<thead>
<tr>
<th>Fibre contents (wt)</th>
<th>0%</th>
<th>7%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Draw ratio $\lambda$</td>
<td>1</td>
<td>2.4</td>
</tr>
<tr>
<td>Yield stresses (MPa)</td>
<td>13.7</td>
<td>20.3</td>
</tr>
<tr>
<td>Stress at break (MPa)</td>
<td>19.0</td>
<td>27.0</td>
</tr>
<tr>
<td>Tensile modulus (GPa)</td>
<td>0.94</td>
<td>1.40</td>
</tr>
</tbody>
</table>

### Table 5-8: Tensile properties of undrawn drawn filled polypropylene

<table>
<thead>
<tr>
<th>Fibre contents (wt)</th>
<th>13%</th>
<th>27%</th>
<th>55%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Draw ratio $\lambda$</td>
<td>1</td>
<td>1.71</td>
<td>1.73</td>
</tr>
<tr>
<td>Yield stresses (MPa)</td>
<td>23.0</td>
<td>26.67</td>
<td>24.67</td>
</tr>
<tr>
<td>Stress at break (MPa)</td>
<td>36.3</td>
<td>51.33</td>
<td>43.85</td>
</tr>
<tr>
<td>Tensile modulus (GPa)</td>
<td>2.09</td>
<td>4.28</td>
<td>3.87</td>
</tr>
</tbody>
</table>
Figure 5-24: Fibre contents versus tensile modulus for undrawn polypropylene.
5.8 Summary

Mechanical properties, such as modulus and stiffness, increase in the direction of orientation as a result of drawing material. Significant enhancement of modulus produced by (Coates and Ward, 1979), and (Gibson and Ward, 1980b). Modulus results of unfilled material for draw ratio from $\lambda=3.2$ to $\lambda=5.6$, show the highest values. As the drawing speed increased from 5mm/min to 50mm/min, a corresponding increase in modulus is observed for unfilled material. The percentage of increase in modulus is approximately 300%. Slower drawing speeds will permit the molecule to respond flexibly and demonstrate lower modulus, while faster drawing speeds will confer stiffer molecules and produce higher modulus. Polypropylene with $\lambda=5.6$ draw ratio shows the greatest improvement among all unfilled material with enhance of about 300% more than undrawn unfilled materials. The result compare favourably to polypropylene specimens studied by Taraiya and Ward (1987) drawn to ratio of $\lambda=23.2$ resulting in tensile modulus up to 20GPa in the draw direction. This represents a substantial enhancement over isotropic value of 1.5 GPa.

The 7%wt filled material showed an increasing for modulus to increasing with draw ratio $\lambda=3.2$. This showed improvement of about 100% compared with undrawn material.

The 13% wt filled composites, exhibits higher values of tensile modulus than the 27% wt and 55% wt composites. At the maximum draw ratio of $\lambda=2.3$ the modulus is improved by >100% compared to undrawn 13%wt material. This modulus, 58MPa is more than a 100%, and 200% improvement compared to the drawn 27% wt and 55% wt composite respectively. The lower moduli of the 27%wt and 55% wt composites maybe attributed to the formation of voids or fibre matrix incompatibility that probably build weak contact surfaces between polymer and fibre This mode of failure was not seen for the low fibre content composites at low drawing speeds where
it is believed the molecules are given more time to relax and there is lower stress at the interface

Stiffness enhancement through both orientation of glass fibre and polymer matrix stiffening is concluded by Coates and Ward (1979),

Enhancement of properties is less attributed to the incorporation of glass fibre than that of the orientation of the polymer matrix. The modulus of glass fibre filled product is no higher than that unfilled product. In die drawing the fibre consequently is no longer effective as a reinforcing phase, as found by Richardson and Ward (1982) for glass fibre polyoxymethylene containing 20% wt

A low level of fibre content has increased the tensile modulus for polypropylene. The work of Gibson and Ward (1980a) shows that 20%wt glass fibre filled specimens give moduli up to 14.2 GPa.

The tensile modulus increased with increasing fibre content for undrawn material. A 55%wt composite shows the highest tensile modulus being about 600% greater compared to an unfilled. The next improvement was for 27%wt about 400% compared with unfilled. There was also valuable improvement in modulus for 13%wt and 7%wt of about 100% and 120% respectively
6 Fracture toughness of Polypropylene and Polypropylene

Short Glass Fibre Composite Both Drawn and Undrawn

In this chapter we will highlight the fracture mechanics concepts which become significant in describing crack propagation. This is applied to injection moulded specimens of polypropylene, both drawn and undrawn and both unfilled and glass fibre filled. The main aims to be achieved are listed below:

- To develop experimental methods for the observation of fracture behaviour in tension.
- To interpret the results in terms of critical stress intensity factor.
- To study the effect of draw ratio and fibre orientation on fracture behaviour, in particular on the critical stress intensity factor.

6.1 Effect of fibre contents and draw ratio on fracture stress

Fracture test of the polypropylene with 0%wt, 7% wt, 13%wt, 27%wt and 55%wt content of short glass fibre were carried out using DEN specimens. Typical fracture stress strain curves for the DEN specimens with different notch lengths $a$ are shown in Figures. 6.1-6.22. It can be seen that irrespective of the crack length, all stress strain curves have similar shapes and the specimens fail in a brittle manner with little plastic deformation. This is an essential requirement to use linear elastic theory.
6.1.1 Drawn polypropylene +7% wt short glass fibre filled

Stress-strain curves for DEN Specimens of polypropylene filled with 7%wt short glass fibre and drawn at different draw ratios $\lambda = 2.4$, $\lambda = 2.6$, $\lambda = 2.7$, and $\lambda = 3.2$ for various notch lengths $a$, 1.5mm, 2.0mm, and 2.5mm are shown in Figures 6.1-6.4. Generally the curves show the remote stresses. The load divided by specimen’s unnotched cross section area is used to calculate the remote stress. For specimens drawn at draw ratio of $\lambda = 2.4$, and $\lambda = 2.6$, the fracture stress increased with increasing draw ratio. Specimens drawn at $\lambda = 2.4$ as shown in Figure 6.1 fracture stress increased with decreasing crack notch length, the values of fracture stress are 19MPa, 23MPa, 27MPa, and fracture strains are 0.0103, 0.0112, and 0.0122. The fracture stress values are 22MPa, 27MPa, and 32MPa, for 2.5mm, 2.00mm, and 1.5mm crack notch respectively for specimens drawn at draw ratio of $\lambda = 2.6$ as shown in Figure 6.2.

The fracture stresses for specimens drawn at draw ratio of $\lambda = 2.7$ are as shown in Figure 6.3 as 23MPa, 28 MPa, 33 MPa for notch length 2.5 mm, 2.00mm, and 1.5mm, respectively, corresponding to fracture strains 0.0126, 0.0136, and 0.0162.

DEN Specimens for drawn polypropylene 7%wt short glass fibre filled drawn with different draw ratio are shown in Figure 6.4. At the highest draw ratio of $\lambda = 3.2$ as shown in Figure 6.4, the specimens shows brittle behaviour. Fracture stress are 34MPa, 29 MPa, and 23 MPa for notch lengths 1.5mm, 2.00mm, 2.5 mm, at fracture strain 0.0149, 0.0131, and 0.0127, corresponding to extensions 1.04mm, 0.92mm, and 0.89mm.
Table 6-1: Fracture stress of drawn polypropylene 7% wt short glass fibre filled

<table>
<thead>
<tr>
<th>fibre contents</th>
<th>Draw ratio $\lambda$</th>
<th>Notch (mm)</th>
<th>Fracture Stress (MPa)</th>
<th>Fracture strain</th>
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<tbody>
<tr>
<td>7%</td>
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</tr>
<tr>
<td></td>
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<td>0.011</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1.5</td>
<td>27</td>
<td>0.012</td>
</tr>
<tr>
<td></td>
<td>2.6</td>
<td>2.5</td>
<td>22</td>
<td>0.012</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2</td>
<td>27</td>
<td>0.012</td>
</tr>
<tr>
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<td>32</td>
<td>0.014</td>
</tr>
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<td>2.7</td>
<td>2.5</td>
<td>23</td>
<td>0.013</td>
</tr>
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</tr>
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<td>1.5</td>
<td>33.8</td>
<td>0.015</td>
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</table>
Chapter 6

Fracture behaviour

Figure 6-1: Fracture stress vs strain 7% wt fibre filled 2.4 draw ratio for notch length of 1.5, 2.0 and 2.5mm

Figure 6-2: Fracture stress vs strain 7% wt fibre filled 2.6 draw ratio for notch length of 1.5, 2.0 and 2.5mm

Figure 6-3: Fracture stress vs strain 7% wt fibre filled 2.7 draw ratio for notch length of 1.5, 2.0 and 2.5mm

Figure 6-4: Fracture stress vs strain 7% wt fibre filled 3.2 draw ratio for notch length of 1.5, 2.0 and 2.5mm
6.1.2 Drawn polypropylene +13% wt short glass fibre filled

Fracture stress strain curves for Polypropylene +13% wt short glass fibre filled drawn to different draw ratio for different notch length are shown in Figures 6.5-6.8. As shown in the curves the fracture stress increased with increasing draw ratio until $\lambda = 2.5$. With increasing draw ratio to $\lambda = 2.5$ the fracture stress increase to the maximum values. The highest fracture stress values are 31 MPa, 35 MPa, and 40 MPa for specimens drawn at draw ratio $\lambda = 2.5$ with 2.5mm, 2.00mm, and 1.5mm notch depth respectively.

Specimens drawn at draw ratio of $\lambda = 2.1$ shows the lowest fracture stress value of 28 MPa, 32 MPa, and 37MPa for 2.5mm, 2.00mm, and 1.5mm notch length.

The values of fracture stress for specimen drawn at draw ratio of $\lambda = 2.2$ and $\lambda = 2.3$, notched with 2.5mm, 2.00mm, and 1.5mm, are 29MPa, 33MPa, and 38MPa, fracture stress for specimen drawn at draw ratio of $\lambda = 2.3$ are 30MPa, 34MPa, and 39MPa for 2.5mm, 2.00mm, and 1.5mm respectively. Table 6.2 summarizes the fracture behaviour.
Chapter 6

Fracture behaviour

Figure 6-5: Fracture stress vs strain 13%wt fibre filled 2.1 draw ratio for notch length of 1.5mm, 2.0mm and 2.5mm

Figure 6-6: Fracture stress vs strain 13%wt fibre filled 2.2 draw ratio for notch length of 1.5mm, 2.0mm and 2.5mm

Figure 6-7: Fracture stress vs strain 13%wt fibre filled 2.3 draw ratio for notch length of 1.5mm, 2.0mm and 2.5mm

Figure 6-8: Fracture stress vs strain 13%wt fibre filled 2.5 draw ratio for notch length of 1.5mm, 2.0mm and 2.5mm
Table 6-2: Fracture parameters fracture load and fracture stress of drawn polypropylene 13% wt short glass fibre filled

<table>
<thead>
<tr>
<th>Fibre contents</th>
<th>Draw ratio</th>
<th>Notch (mm)</th>
<th>Fracture Stress (MPa)</th>
<th>Fracture strain</th>
</tr>
</thead>
<tbody>
<tr>
<td>13%</td>
<td>2.1</td>
<td>2.5</td>
<td>28</td>
<td>0.011</td>
</tr>
<tr>
<td></td>
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<td>2</td>
<td>32</td>
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</tr>
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<td></td>
<td></td>
<td>1.5</td>
<td>37</td>
<td>0.012</td>
</tr>
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<td>2.2</td>
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<td>29</td>
<td>0.012</td>
</tr>
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<td></td>
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<td>0.012</td>
</tr>
<tr>
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<td>1.5</td>
<td>38</td>
<td>0.013</td>
</tr>
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<td>40</td>
<td>0.013</td>
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</table>
6.1.3 Drawn polypropylene +27% wt short glass fibre filled

Fracture stress strain curve for double edge notched drawn Polypropylene 27% wt short glass fibre drawn with different draw ratios and different notch lengths are shown in Figure 6.9-6.11. As shown in the curves the fracture stress decreased with increasing draw ratio until $\lambda = 1.83$ draw ratio. With increasing draw ratio to $\lambda = 1.83$ the fracture stress decreases to the minimum value. Highest fracture stress values are 30 MPa, 34 MPa, and 42 MPa for specimens drawn at draw ratio $\lambda = 1.71$ with 2.5mm, 2.00mm, and 1.5mm notch length respectively. Specimens drawn at draw ratio of $\lambda = 1.83$ shows the lowest fracture stress value of 26 MPa, 29 MPa, and 35MPa for 2.5mm, 2.00mm, and 1.5mm notch length.

The values of fracture stress for specimens drawn at draw ratio of $\lambda = 1.73$ notched with 2.5mm, 2.00mm, and 1.5mm, are 28 MPa, 32 MPa, and 39MPa respectively, fracture parameters are summarize in Table 6.3.
Figure 6-9: Fracture stress vs strain 27% wt fibre filled 1.71 draw ratio for notch length of 1.5mm, 2.0mm and 2.5mm.

Figure 6-10: Fracture stress vs strain 27% wt fibre filled 1.73 draw ratio for notch length of 1.5mm, 2.0mm and 2.5mm.

Figure 6-11: Fracture stress vs strain 27% wt fibre filled 1.83 draw ratio for notch length of 1.5mm, 2.0mm and 2.5mm.
Table 6-3: Fracture parameters fracture load and fracture stress of drawn polypropylene 27\%wt short glass fibre filled

<table>
<thead>
<tr>
<th>Fibre contents</th>
<th>Draw ratio</th>
<th>Notch (mm)</th>
<th>Fracture Stress (MPa)</th>
<th>Fracture strain</th>
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<tr>
<td>27%</td>
<td>$\lambda=1.71$</td>
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</tr>
<tr>
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<td>$\lambda=1.73$</td>
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<td>39</td>
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<td>32</td>
<td>0.0076</td>
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<td>28</td>
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<td></td>
<td>$\lambda=1.83$</td>
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<td>35</td>
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<td>2.0</td>
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<td></td>
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<td>2.5</td>
<td>26</td>
<td>0.0053</td>
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6.1.4 Drawn polypropylene +55\% wt short glass fibre filled

Stress strain curves for double edge notched drawn polypropylene 55\%wt short glass fibre filled specimens drawn with different draw ratio $\lambda=1.40$, $\lambda=1.43$ and various notch length (a), 1.5mm, 2.0mm, and 2.5mm are shown in Figures 6.12-6.13. Generally the curves show the fracture stress is highest for specimens with long ligament lengths.

Double edge notched specimens drawn at $\lambda=1.40$ show brittle behaviour. Fracture stress was 30 MPa for the small 1.5mm notch, and 27 MPa, 22 MPa for the notch length of 2.00mm, 2.5mm respectively.

Fracture stress decreases with increasing draw ratio. Specimens drawn at $\lambda=1.43$ give fracture stress values as shown in Figures 6.13 as 25MPa, 21MPa, 17MPa, MPa for notch lengths of, 1.5mm 2.00mm and 2.5mm, respectively.
Figure 6-12: Fracture stress vs strain 55% wt fibre filled 1.41 draw ratio length of 1.5mm, 2.0mm and 2.5mm

Figure 6-13: Fracture stress vs strain 55% wt fibre filled 1.43 draw ratio length of 1.5mm, 2.0mm and 2.5mm
Table 6-4: Fracture parameters fracture stress of drawn polypropylene 55% wt short glass fibre filled

<table>
<thead>
<tr>
<th>Fibre contents</th>
<th>Draw ratio</th>
<th>Notch (mm)</th>
<th>Fracture stress (MPa)</th>
<th>Fracture strain</th>
</tr>
</thead>
<tbody>
<tr>
<td>55%</td>
<td>( \lambda = 1.41 )</td>
<td>1.5</td>
<td>30</td>
<td>0.0057</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2</td>
<td>27</td>
<td>0.0049</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2.5</td>
<td>22</td>
<td>0.0037</td>
</tr>
<tr>
<td></td>
<td>( \lambda = 1.43 )</td>
<td>1.5</td>
<td>25</td>
<td>0.0051</td>
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<td></td>
<td></td>
<td>2</td>
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<td>2.5</td>
<td>17</td>
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</table>
6.1.5 Drawn unfilled polypropylene

Figures 6.14-6.17 show remote stress strain curves for double edge notch specimens of drawn polypropylene unfilled with various notch lengths drawn at draw ratios of $\lambda=4.6$, $\lambda=4.7$, $\lambda=5.0$, and $\lambda=5.6$. The highest fracture stress is for specimens with long ligament length as expected. From the figures we can see the fracture stress increased with increasing draw ratio. Specimens drawn at 5.6 draw ratio shows the highest fracture stress, with values of 10MPa, 16MPa, and 23MPa, for notch length of 2.5mm, 2.00mm, and 1.5mm respectively, with fracture strains 0.013, 0.014, 0.016. Fracture stress for specimens drawn at $\lambda=4.6$, $\lambda=4.7$, and $\lambda=5.0$, are 9.5MPa, 13MPa, and 18MPa. For 2.5mm, 2.00mm, and 1.5mm notch lengths the strengths are respectively, 9.7MPa, 14MPa, and 18MPa. For $\lambda=4.7$, for specimens drawn at draw ratio of 5.0 fracture stress are 9.8MPa, 14.9MPa, and 21MPa for 2.5mm, 2.00mm, and 1.5mm crack notch respectively. Experimental fracture data fracture stress for the different draw ratio and different crack notch are summarise in Table 6.5
Figure 6-14: Fracture stress vs strain 0% wt fibre filled 4.6 draw ratio for notch length of 1.5mm, 2.0mm and 2.5mm

Figure 6-15: Fracture stress vs strain 0% wt fibre filled 4.7 draw ratio for notch length of 1.5mm, 2.0mm and 2.5mm

Figure 6-16: Fracture stress vs strain 0% wt fibre filled 5.0 draw ratio for notch length of 1.5mm, 2.0mm and 2.5mm

Figure 6-17: Fracture stress vs strain 0% wt fibre filled 5.6 draw ratio for notch length of 1.5mm, 2.0mm and 2.5mm
Table 6-5: Fracture parameters fracture stress of drawn unfilled polypropylene

<table>
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<tr>
<th>Fibre contents</th>
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<th>Notch (mm)</th>
<th>Fracture stress (MPa)</th>
<th>Fracture strain</th>
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<tbody>
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<td>0%</td>
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</tr>
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</tr>
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<td></td>
<td></td>
<td>1.5</td>
<td>22</td>
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6.1.6 Undrawn unfilled polypropylene

Remote stress-strain curves for undrawn double edge notch, specimens of unfilled polypropylene with various notch lengths 1.5mm, 2.0mm, and 2.5mm, are shown in Figures 6.18. Specimens show ductile behaviour. Fracture stress values for all different notch length are 9MPa, 12MPa, and 16MPa fracture strains are 0.010, 0.012, and 0.015 for specimen notched with 1.5mm, 2.0 mm, and 2.5mm. Fracture parameters are summarised in Table 6.6.

6.1.7 Undrawn polypropylene +7% wt short glass fibre filled

Stress strain curves for undrawn 7%wt polypropylene short glass fibre filled are shown in Figure 6.19 from the curves we can see that the fracture strain increased with increasing notch length. Fracture stresses are 15 MPa, 20 MPa, and 25 MPa for the three notch lengths. The values of fracture strain for specimen notched with 1.5mm, 2.00mm, and 2.5mm, are 0.0102, 0.0137, and 0.0146 respectively. Table 6.6 summarises experimental fracture data fracture stress for different notch lengths.

6.1.8 Undrawn polypropylene +13% wt short glass fibre filled

Result for undrawn 13%wt short glass fibre filled polypropylene with notch lengths 1.5mm, 2.0mm, and 2.5mm are shown in Figures 6.20. Specimens shows brittle behaviour fracture stresses for specimens with notch length of 1.5mm, 2.0mm, 2.5mm are 26MPa, 21MPa, and 16MPa, and fracture strains are 0.0094, 0.0112, and 0.0134, for 1.5mm, 2.00mm, and 2.5mm respectively.
6.1.9 Undrawn polypropylene +27% wt short glass fibre filled

Fracture stress is 44 MPa, 37 MPa, and 31 MPa for undrawn specimens with 27% wt short glass fibre filled polypropylene with different notch lengths as shown in figure 6.21. The fracture strain increased with decreasing notch lengths. Fracture strain values for specimens notched at 1.5mm, 2.00mm, and 2.5mm, are 0.0104, 0.0092, and 0.0074 respectively.

6.1.10 Undrawn polypropylene +55% wt short glass fibre filled

Figure 6.22 shows fracture stress of undrawn 55% wt short glass fibre filled Polypropylene as 36 MPa, 30 MPa, and 25 MPa. For the three notch length values of 1.5mm, 2.00mm, and 2.5mm. Fracture strain decreased with increasing notch length, with values of 0.0140, 0.0087, and 0.0077, for 1.5mm, 2.00mm, and 2.5mm respectively.

Table 6-6: Fracture parameters fracture stress of undrawn filled polypropylene

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<th>Draw ratio</th>
<th>Notch (mm)</th>
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<th>Fracture strain</th>
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<tr>
<td>7%</td>
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<td></td>
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<td>20</td>
<td>0.014</td>
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<td>0.009</td>
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<td>2.5</td>
<td>25</td>
<td>0.008</td>
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Chapter 6

Fracture behaviour

Figure 6-18: Fracture stress vs strain 0% wt fibre filled ratio for notch length of 1.5mm, 2.0mm and 2.5mm

Figure 6-19: Fracture stress vs strain 7% wt fibre filled ratio for notch length of 1.5mm, 2.0mm and 2.5mm

Figure 6-20: Fracture stress vs strain 13% wt fibre filled ratio for notch length of 1.5mm, 2.0mm and 2.5mm

Figure 6-21: Fracture stress vs strain 27% wt fibre filled ratio for notch length of 1.5mm, 2.0mm and 2.5mm
Figure 6-22: Fracture stress vs strain 55% wt fibre filled ratio for notch length of 1.5mm, 2.0mm and 2.5mm
6.2 Experimental results and discussion

6.2.1 Fracture toughness measurements $K_{IC}$

The critical stress-intensity factors $K_{IC}$ or fracture toughness are determined by employing a testing speed of 5mm/min to specimens with double edge notch geometry. The notches are cut in the midsection of the specimen perpendicular to the draw direction, the notch lengths being 1.5mm, 2.00mm, and 2.5 mm deep.

The value of the fracture toughness parameters $K_I$ are derived from observed fracture load

$$K_I = Y\sigma\sqrt{\pi a}$$

$Y$ is the finite width correction factor which in isotropic material is a function of the ratio of the notch depth to the specimen’s width. For orthotropic materials, however $Y$ depends on the specimen’s geometry and also orthotropic material properties. For instance, for orthotropic drawn polymer $Y$ factors have been evaluated theoretically (Sweeney and Ward, 1988) Stresses near to a crack tip have been analysed by Sih (Sih and Irwin, 1965) in an orthotropic linear elastic solid. They show that the dependence of stress on distance from the crack tip is of the same inverse square root form as in an isotropic material so that the quantity $K_I$, can be carried over into orthotropic theory. $K_I$ and $Y$ are calculated by evaluating strain energy release rate $G$ for a notched body of the relevant geometry and mechanical properties.
6.2.2 Creating the ABAQUS Model

One quarter of the fracture specimen was modelled as shown in Figure 6.23. Two dimensional solid elements were implemented as the problem was simplified to 2D. Also, as we were assuming plane stress conditions, four node, and bilinear, plane stress quadrilateral CPS4 elements were used in the analysis. The ligaments modelled were 2.5, 3.0, and 4.5mm. Notch lengths either side were therefore 1.5, 2.0 and 2.5mm.

Figure 6-23: Diagram of fracture specimen boundary conditions
Figure 6-24: Finite element mesh for determination of Y factors
A typical mesh as shown in Figure 6.24 AB is the notch and B is the notch tip. AB and AF are free boundaries. In both cases DE is displacement restrained in the X direction and DB displacement restrained in Y direction directions. Tension is applied normal to EF by prescribing displacements in Y direction.

In this investigation, two separate set of models were created to study the effect of mesh on accuracy of fracture force. Fine and coarse meshes are applied as shown in Figure 6.25.

**Model 1**  
a coarse mesh with 25 elements in the x direction

**Model 2**  
a refined mesh with 50 elements in the x direction

Figure 6.26 shows meshes in which nodes are moved to increase crack length and change strain energy. In this way $G$ is a calculated using equation in the next section.

A displacement of 2mm was then applied to the top surface during the running of the ABAQUS program. This applied displacement as the model run accurately for all short and long ligament lengths were used.
Figure 6-25: Coarse and fine mesh fracture model
Figure 6-26: Notch depth node position a for 1.5mm, 2.0mm, and 2.5mm
Figure 6-27: Notch depth node position a for 1.45mm, 1.50mm, and 155mm
The .dat file was viewed once the ABAQUS analysis was complete. The total reaction force for the ligament nodes on the bottom surface was displayed near the end of the file. Total reaction forces for different notch depths for both coarse and fine mesh are the same to four significant figures; effectively, there are no changes in the values of force when doubling the mesh density. Reaction forces are listed in Table 6-7.

Model specimens with contours of von Mises stress for different ligament lengths for fine and coarse meshes can be seen from Figures 6.28 and 6.29.
Figure 6-28: Notch depth node position a for coarse mesh
Figure 6-29: Notch depth node position a for coarse mesh
Table 6-7: Calculated finite element reaction force for 0.11 Poison ratio

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<td>2.5</td>
<td>1.5</td>
<td>2</td>
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<tr>
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<td>125</td>
<td>121.9</td>
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<td>332</td>
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<td>1.5</td>
<td>2</td>
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<td>2.5</td>
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<td>2</td>
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<td>2.5</td>
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<td>2</td>
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<td>2</td>
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<td>1016.3</td>
<td>991.8</td>
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</table>
The equations below are used to calculate variables that are then used to determine finite element correction factor $Y$. Mechanical tensile test data are used from the input file from the finite element models to calculate reaction force for every node notch condition notch depth and draw ratio specimens. The actual input files can be found in the Appendix C.

Compliance matrix 

$$
\begin{bmatrix}
\varepsilon_{11} \\
\varepsilon_{22} \\
\varepsilon_{12}
\end{bmatrix} =
\begin{bmatrix}
S_{11} & S_{12} & S_{16} \\
S_{12} & S_{22} & S_{26} \\
S_{16} & S_{26} & S_{66}
\end{bmatrix}
\begin{bmatrix}
\sigma_{11} \\
\sigma_{22} \\
\sigma_{12}
\end{bmatrix}
$$

(6.1)

$K_i - G$ Relationship 

$K = \sqrt{G\over E}$

(6-2)

$$E = \frac{1}{S}
$$

(6-3)

$$K_i^2 = \frac{G}{\left( \frac{S_{11}S_{22}}{2} \right)^{1/2} \left( \frac{S_{22}}{S_{11}} \right)^{1/2} + \frac{2S_{12}S_{66}}{2S_{11}} \right)^{1/2}}
$$

(6-4)

Orthotropic compliance 

$$S = \left( \frac{S_{11}S_{22}}{2} \right)^{1/2} \left( \frac{S_{22}}{S_{11}} \right)^{1/2} + \frac{2S_{12}S_{66}}{2S_{11}} \right)^{1/2}
$$

(6-5)

$$G_{12} = \frac{1}{S_{66}}
$$

(6.7)

$$S_{11} = \frac{1}{E_1}
$$

(6.8)
\[ S_{22} = \frac{1}{E_2} \]  \hfill (6.8)

\[ S_{12} = -\nu_{12} S_{11} \]  \hfill (6.10)

\[ S_{66} = S_{11} + S_{22} - 2S_{12} \]  \hfill (6.11)

Total energy \[ U = \frac{1}{2} F \delta \]  \hfill (6.12)

By calculating reaction force in the model for the different positions of notch tip nodes, which are moved by 0.05 mm and 0.1 mm to give notch depths of 2.0 mm, 2.05 mm and 2.1 mm.

\[ U \text{ Total} = U = 4 \ast \frac{1}{2} F \delta \]  \hfill (6.13)

\[ G = \frac{dU}{da} \]  \hfill (6.14)

Strain release energy for every specimen draw ratio and notch depth can be calculated as:
\[ G = \Delta U_{Total} = \frac{2F_0\delta - 2F\delta}{2\delta a} = \frac{\Delta F}{\Delta a} \] (6.15)

\[ K_o \text{ for isolated crack} \quad K_o = \frac{F}{A} \sqrt{\pi a} \] (6.16)

\[ K_I = \sqrt{EG} \] (6.17)

\[ E = \text{orthotropic modulus} \quad E = \frac{1}{S} \] (6.17)

\[ Y = \frac{K_I}{K_o} \] (6.19)
The correction factor \( Y \) for the anisotropic material is used to calculate actual stress intensity factor for the double notch fractured specimens. The values of \( E_{11}, E_{22} \) were taken from material mechanical tests. We assumed \( E_{11} \) was the same value as for isotropic material, and \( E_{22} \) was that measured in the draw direction for each draw ratio. All these values were measured as described in Chapter Five. To derive the values of \( S_{12} \), the value of Poisson's ratio \( \nu_{12} \) for this material was assumed to be 0.11 from previous work on oriented polyethylene (Sweeney and Ward, 1988). \( S_{12} \) values were then derived from the definition of Poisson's ratio:

\[
\nu_{12} = -\frac{S_{12}}{S_{11}}.
\]

There is only a small increase in reaction force with increasing Poisson's ratio up to the value of 0.49. Comparison of Tables 6.7 and 6.8 shows that the reaction forces increased by less than 3% when Poisson's ratio values varied from 0.11 to 0.39. Similarly, comparison of Tables 6.7 and 6.9 shows that the increase is less than 4% when increasing Poisson's ratio values up to 0.49. This applies for all draw ratios and fibre levels.

The \( S_{66}, G, \) and \( E \) variables were calculated using equations (6.2)-(6.19). All variables are listed in Tables 6.8, 6.9 and 6.10.
Table 6-8: Calculated finite element reaction force for 0.39 Poisson's ratio.

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<td>1.5 2 2.5</td>
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### Table 6-9: Calculated finite element reaction force for 0.49 Poisson's ratio.

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<td></td>
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<td>2</td>
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</tr>
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Table 6-10: Isotropic and anisotropic material mechanical properties

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6.2.3 Correction factor determination

The correction factor $Y$ for anisotropic material was calculated using the simulation results. The actual stress intensity $K_I$ was calculated using $Y$ and the elementary stress intensity factor $K_0$.

Table 6.11 compares correction factor results obtained using the procedures described above. In general, the correction factor decreases with increasing draw ratio, and the effect of filler loading is small.

Deformed shape and stress concentration contour are shown in figures 6.30-6.49.
Table 6-11: Correction factor for isotropic and anisotropic material

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Figure 6-30: Stress concentration contour for 7% wt coarse mesh
Figure 6-31: Stress concentration contour for 7% wt fine mesh
Figure 6-32: Stress concentration contour for 13% wt coarse mesh
Figure 6-33: Stress concentration contour for 13% wt fine mesh
Figure 6-34: Stress concentration contour for 27% wt coarse mesh
Figure 6-35: Stress concentration contour for 27\%_w wt fine mesh
Figure 6.36: Stress concentration contour for 55% wt coarse mesh
Figure 6-37: Stress concentration contour for 55\% wt fine mesh
Figure 6-38: Stress concentration contour for 0% wt coarse mesh.
Figure 6-39: Stress concentration contour for 0% wt fine mesh
Figures 6.40-6.49 display the correction factors and reaction forces versus notch depth divided by specimen half-width for the simulation results. In all cases correction factors increased consistently with increasing a/b ratio.
Figure 6-40: Correction factor for 7% wt with different draw ratio

Figure 6-41: Reaction force for 7% wt with different draw ratio

Figure 6-42: Correction factor for 13% wt with different draw ratio

Figure 6-43: Reaction force for 13% wt with different draw ratio
Fracture behaviour

Figure 6-44 Correction factor for 27% wt with different draw ratio

Figure 6-45: Reaction force for 27% wt with different draw ratio

Figure 6-46 Correction factor for 55% wt with different draw ratio

Figure 6-47: Reaction force for 55% wt with different draw ratio
Figure 6-48: Correction factor for different draw ratio 0%wt

Figure 6-49: Reaction force for different draw ratio 0%wt
6.2.4 Fracture remote stress strain curves

The drawn and undrawn filled and unfilled polypropylene, fracture properties are investigated via fracture tensile testing of double edge notch specimens. It has been seen that these specimens exhibit improvements in fracture toughness with increasing short glass fibre content up to 13% with increasing draw ratio. Despite fracture toughness improvements, the inclusion of fibre causes the composite to become more brittle.

Critical stress intensity or fracture toughness represents the condition of crack propagation when the load overcomes the material resistance and the crack initiates, while the stress intensity factor is related to the elastic stress field around the crack tip whenever load is applied to the material. Thus, fracture toughness is a material property and can be assumed to be independent of notch length.

Typical stress versus strain curves for polypropylene +7% wt short glass fibre filled drawing at draw ratios of $\lambda=2.4$, $\lambda=2.6$, $\lambda=2.7$, and $\lambda=3.2$, obtained by double edge notch specimens with various notch depth, 1.5mm, 2.00mm, and 2.5mm are reported in Figure 6.1-6.4. The shape of the curves are similar for all the samples considered, and the area under the curves increases as the crack notch length decreases. The strain increases with increasing draw ratio.

Typical stress strain curves of double edge notch specimens of different crack notch length for drawn polypropylene with 13% wt short glass fibre are shown in Figure 6.5-6.8. It is noted that geometric similarity is approximately satisfied in these double edge notch specimens. The fracture propagation was stable and all notches were not yielded prior to fracture initiation.
Stress versus extension curves for 27%wt short glass fibre filled polypropylene drawn at draw ratios of \( \lambda = 1.71 \), \( \lambda = 1.73 \), and \( \lambda = 1.83 \), \( \lambda = 3.2 \), obtained by double edge notch specimens with various notch depth, 1.5mm, 2.00mm, and 2.5mm are reported in Figures 6.9-6.1. It is shown the drawn specimens becomes more brittle the (strain decrease) with increasing draw ratio.

Figures 6.12-6.13 shows remote stress extension curves of double edge notch specimens of different notch length for drawn polypropylene 55% wt short glass fibre. In these specimens it is apparent the addition of more fibres results in the material becoming stiffer, and brittle fracture propagates with no yield.

Figures.6.14-6.17.shows typical stress strain curves of double edge notch specimens of different notch length for drawn unfilled polypropylene. It is noted the fracture stress increased with increasing draw ratio and with decreasing notch length. Necking and whitening were observed to have propagated across the width of the specimen.

Stress versus strain curves for undrawn polypropylene 0%wt, 7%wt, 13%wt, 27%wt, and 55%wt short glass fibre filled, obtained by double edge notch specimens with various notch depth, 1.5mm, 2.00mm, and 2.5mm are shown in Figure.6.18-6.22. The addition of 7%wt, 13%wt, 27%wt, and 55%wt of short glass fibres promotes necking around the fractured crack. It was also noted that whitening had developed into the neighbouring gauge regions. On increasing fibre contents to 27%wt, and 55%wt the undrawn specimens becomes more brittle with a reduced in extension.

By observing the fracture tests, it is possible to establish that the onset of crack growth always occurs very close to the maximum load as shown in the figures. The
crack propagates at constant rate up to the very small yield, after which faster crack propagation is observed until fracture.

Calculations of fracture toughness were made using the Y correction factors discussed above and the observed fracture loads. The fracture toughness of 0% wt, 7% wt, and 13% wt short glass fibre filled polypropylene, for draw ratio are summarised in Table 6.12.
### Table 6-12: Values of critical actual stress intensity

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Plots of critical stress intensity factor or fracture toughness $K_{ic}$ versus the normalised notch depth $a/b$ are reported in Figures 6.50-6.55. For unfilled material, Figure 6.50 shows that fracture toughness generally increases with draw ratio. For undrawn material, Figure 6.55 shows that the fracture toughness increases as filler loading rises to 27wt%, and falls slightly as the loading reaches 55% wt. For drawn and filled material, the situation is more complex. For loadings of 7 and 13% wt, Figures 6.51 and 6.52 shows that fracture toughness continues to rise with draw ratio. However, for a loading of 27%wt, Figure 6.53 shows that toughness is increased as the draw ratio is increased to 1.71, but falls at higher draw ratios. At the highest filler loading of 55%wt, Figure 6.54 shows that toughness consistently falls with draw ratio. The highest toughness occurs at a filler loading of 13% wt and draw ratio of 2.6.
Table 6-13: Values of critical stress intensity factor for drawn polypropylene 27%wt and 55%wt short glass fibre filled

<table>
<thead>
<tr>
<th>fibre %</th>
<th>draw ratio</th>
<th>a/b</th>
<th>Y</th>
<th>K_0C</th>
<th>K_IC</th>
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<tbody>
<tr>
<td>27%</td>
<td>(\lambda = 1.71)</td>
<td>0.5</td>
<td>1.145</td>
<td>2.73</td>
<td>3.12</td>
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<tr>
<td></td>
<td></td>
<td>0.4</td>
<td>1.125</td>
<td>2.83</td>
<td>3.19</td>
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<tr>
<td></td>
<td></td>
<td>0.3</td>
<td>1.076</td>
<td>2.96</td>
<td>3.19</td>
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<tr>
<td></td>
<td>(\lambda = 1.73)</td>
<td>0.5</td>
<td>1.109</td>
<td>2.53</td>
<td>2.81</td>
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<tr>
<td></td>
<td></td>
<td>0.4</td>
<td>1.059</td>
<td>2.63</td>
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<tr>
<td></td>
<td></td>
<td>0.3</td>
<td>1.047</td>
<td>2.72</td>
<td>2.85</td>
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<tr>
<td></td>
<td>(\lambda = 1.83)</td>
<td>0.5</td>
<td>1.101</td>
<td>2.15</td>
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<tr>
<td></td>
<td></td>
<td>0.4</td>
<td>1.055</td>
<td>2.26</td>
<td>2.38</td>
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<tr>
<td></td>
<td></td>
<td>0.3</td>
<td>1.051</td>
<td>2.38</td>
<td>2.49</td>
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</table>

<table>
<thead>
<tr>
<th>fibre %</th>
<th>draw ratio</th>
<th>a/b</th>
<th>Y</th>
<th>K_0C</th>
<th>K_IC</th>
</tr>
</thead>
<tbody>
<tr>
<td>55%</td>
<td>(\lambda = 1.41)</td>
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<td>1.150</td>
<td>1.82</td>
<td>2.10</td>
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<td></td>
<td></td>
<td>0.4</td>
<td>1.104</td>
<td>1.91</td>
<td>2.10</td>
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<tr>
<td></td>
<td></td>
<td>0.3</td>
<td>1.090</td>
<td>1.94</td>
<td>2.11</td>
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<td></td>
<td>(\lambda = 1.42)</td>
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<td>1.109</td>
<td>1.51</td>
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<td></td>
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<td>0.4</td>
<td>1.045</td>
<td>1.59</td>
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<td></td>
<td></td>
<td>0.3</td>
<td>1.032</td>
<td>1.65</td>
<td>1.70</td>
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Dramatic improvements in material fracture toughness $K_{IC}$ are achieved by increasing draw ratio and fibre contents to 7% wt, 13% wt, in general enhancement of critical stress intensity factor, are attained when draw ratio are increased from 1.0 to 5.6 for unfilled, from 1.0 to 3.2 for 7% wt, from 1.0 to 2.6 for 13% wt, are also obtained simply by polymer orientation and fibre orientation. While there is no improvement when increasing fibre contents to 27% wt and 55% wt fracture toughness decrease to its lowest values.
Figure 6-50: Fracture toughness of 0% wt for different depth notch

Figure 6-51: Fracture toughness of 7% wt for different depth notch

Figure 6-52: Fracture toughness of 13% wt for different depth notch

Figure 6-53: Fracture toughness of 27% wt for different depth notch
Figure 6-54: Fracture toughness of 55% wt for different depth notch

Figure 6-55: Fracture toughness of undrawn 0% 7% 13% 27% 55% wt
Table 6-14: Values of critical stress intensity factor for undrawn polypropylene unfilled and short glass fibre filled

<table>
<thead>
<tr>
<th>fibre contents</th>
<th>Unfilled</th>
<th>7%</th>
<th>13%</th>
<th>27%</th>
<th>55%</th>
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<tr>
<td>a/b</td>
<td>0.5</td>
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<td>0.3</td>
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<tr>
<td>Y</td>
<td>1.21</td>
<td>1.17</td>
<td>1.15</td>
<td>1.21</td>
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<td>$K_{IC}$</td>
<td>1.01</td>
<td>1.11</td>
<td>1.12</td>
<td>1.33</td>
<td>1.44</td>
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<tr>
<td>$K_{IC}$</td>
<td>1.22</td>
<td>1.30</td>
<td>1.28</td>
<td>1.62</td>
<td>1.69</td>
</tr>
</tbody>
</table>
6.3 Summary

To analyze the fracture behaviour of drawn and undrawn polypropylene, both unfilled and short glass fibre filled, experimental testing and finite element simulation were employed. Fracture stress strain behaviour of polypropylene at 0%wt, 7%wt, 13% wt, 27% wt, and 55% wt short glass fibre loading with different draw ratios was measured using tensile testing of double edge notch specimens.

The specimens exhibit a highly brittle behaviour, with the maximum fracture stress being followed by a marked load drop. With unfilled material, toughness increased from the undrawn value of 1.2-1.3 MNm$^{-3/2}$ to ~3.6 MNm$^{-3/2}$ at draw ratio 5.6. For undrawn material, toughness increased up to a filler loading of 27wt%, with a slight drop at 55wt%. For filled and drawn material, drawing increases toughness at a filler loading of 13wt% to the maximum draw ratio obtainable of 2.5, giving the highest observed toughness of 3.9MNm$^{-3/2}$. At higher filler loadings, drawing beyond a certain level causes a drop in toughness. Thus, at a filler loading of 27wt%, drawing beyond 1.71 gives a drop in toughness; and at 55wt%, a drop in toughness is observed at the lowest draw ratio obtained of 1.41.
7 Summary Conclusion Recommendation and Future work

7.1 Summary and conclusion

The main goals of this research was to improve and enhance mechanical properties and investigate fracture behaviour of unfilled and short glass filled polypropylene by orienting fibres and polymer molecules using the small rig die drawing process. Combining fibres and polymer chain orientation with the die drawing process can produce materials with significant tensile modulus increases. There is found to be significant enhancement of mechanical properties with increasing draw ratio and fibre filler. The uniaxial drawing of fibre in the composite samples showed optimum enhancement of modulus and fracture toughness for fibre content 13% wt drawn to draw ratio of \( \lambda = 2.5 \).

A summary of the conclusions drawn in this study is given below. From previous chapters, experimental work, and results, the following conclusion can be derived.

7.1.1 Previous work

In preceding Chapter 2 we showed that molecular orientation and fibre orientation can improve polymer mechanical properties. From previous work (Cansfield and Ward, 1976), and (Coates and Ward, 1979) molecular orientation can be achieved by drawing specimens using the die drawing process. Unfilled polypropylene can draw at different draw ratio, deformation of unfilled material increases with increasing drawing speed from 10 mm/min to 20 mm/min, the actual draw ratio RA increases to 20 and modulus increases from 1.1 GPa to 20 GPa.
Tensile modulus achieved was 20GPa. Hope and Ward (1982) have shown that die drawn fibre reinforce polymer showed no significant increase in material stiffness and toughness (Hope. and I.M. Ward., 1982). This is the same result as for unfilled polypropylene behaviour (Taraiya and Ward, 1987). In their work the draw ratio increases with drawing speed, the maximum draw speed being limited by fracture of the specimens at machine maximum speeds 500mm/min. Fracture occurred beyond the die exit.

Specimens draw up draw ratios of $\lambda=23.2$ were obtained giving tensile modulus up to 20GPa in the draw direction, which represents a substantial enhancement over the isotropic value of 1.5GPa.

Filled specimens drew at draw ratios less than unfilled material. Highly filled specimens fracture with increasing draw ratio, with the tensile modulus of highly filled specimens being no higher than unfilled specimens. In composites the fibre consequently no longer behaves as an effective reinforcing phase, thus conforming the result obtained by Richardson and Ward (1982).
7.1.2 Die drawing process

Chapter 4 presented a demonstration of the die drawing process for unfilled and filled polypropylene with five different contents of short glass fibre, fabricated by injection moulding technique. The effects of drawing speed and fibre content on the drawing process was investigated and it was found that drawing load increased with increasing draw speeds, for both filled and unfilled specimens.

i. **Unfilled polypropylene.** Drawing mean load increases with increasing drawing speed, in a nonlinear way. Draw ratio increases linearly with increasing drawing speed. Maximum value of draw ratio $\lambda = 5.6$ is gained by drawing specimens at 50 mm/min.

ii. **Unfilled polypropylene:** Based on the finding of published data it should be possible to increases in draw speed but speeds greater than 50mm/min have not investigated in this work.

iii. **Filled polypropylene.** The lower ratio of fibre 7%wt and 13% wt could be drawn to the maximum draw speed of 50 mm/min with drawing load increasing with increasing fibre contents.

iv. **Filled polypropylene.** Specimens with high fibre contents of 27%wt, and 55%wt fail to draw at high speeds. Specimens of 27%wt fibre could only be drawn up to a speed of 20mm/min. Increasing speed over 20 mm/min caused fracture in the specimen at the die exit. The 55%wt specimens fail to draw after 10 mm/min. Again these specimens fracture inside the die exit.
7.1.3 Tensile test of drawn and undrawn both filled and unfilled

Chapter 5 show that material mechanical behaviour is affected by draw ratio and fibre content. Measurement of tensile properties for drawn and undrawn specimens both filled and unfilled indicated that the drawing process enhances properties in the draw direction. There is a strong influence of drawing in the properties of short glass fibres filled polypropylene that can lead to enhancement of the mechanical properties. The effect of draw ratio and the effect of fibre contents are clearly seen in test specimens.

i. **Undrawn filled specimens.** Increasing fibre contents make specimens significantly stiffer compared with the pure undrawn polypropylene. With increasing fibre content modulus increased to a maximum value of 8.5 GPa for 55% wt glass fibre content specimens.

ii. **Drawn unfilled:** Increasing draw ratio was found to increase the tensile strength, and modulus of drawn specimen compared with undrawn unfilled specimens. Improvements up to 450% were noted for the specimens with highest draw ratio of $\lambda = 5.6$. The specimens produced with draw ratios of $\lambda = 4.6$, $\lambda = 4.7$, and $\lambda = 5$ show improvements in tensile modulus of 250%, 270%, 320% respectively.

iii. **Drawn filled polypropylene:** Modulus and tensile stress were found to increase with increasing draw ratio for only 7%, and 13%wt fibre content. When fibre contents increased above 13%wt modulus and tensile stress decrease to minimum values.

**Tensile modulus:** of polypropylene +7%wt glass fibre shows significant improvement at a draw ratio of $\lambda = 3.2$. The modulus was enhanced by
130% compared with the undrawn composites, and showed a
230% improvement compared to undrawn, unfilled, polypropylene.

iv. The tensile modulus of the 13% wt glass fibre drawn specimens show
the greatest improvement among all drawn specimens. When drawn at
a draw ratio of \( \lambda = 2.3 \) the most optimum mechanical properties were
obtained. An increase of more than 100% for modulus was obtained,
compared to the undrawn filled polypropylene, and 392% compare
with undrawn polypropylene.

v. Die drawing of both the 27%wt and 55%wt specimens results
in a considerable drop in modulus and tensile strength. Die drawing
is shown to be detrimental for these highly loaded composites. There
is a reduction in modulus by about 25% and 110% for 27%wt and
55wt % respectively compared to undrawn specimens.

7.1.4 Double edge notch fracture test

Fracture toughness behaviour of polypropylene drawn and undrawn both
filled and unfilled was investigated and studied using three different notch depth
specimens. The effect of fibre contents and fibre draw ratio on critical stress
intensity factor was studied. Fracture test results can be summarize:

i. **Unfilled drawn specimens**: Remarkable improvement in critical stress
   intensity for specimens drawn at the highest draw ratio of \( \lambda = 5.6 \) of about
   150% compared to undrawn unfilled specimens.

ii. **Filled drawn specimens**: Greater enhancement in critical stress intensity
    was noted for 13%wt glass fibre composites. This represent an
improvement of about 120% for drawn specimen at a draw ratio of $\lambda=2.5$
compared with undrawn specimens, and 210% compared to unfilled undrawn material.

iii. Draw ratio of $\lambda=3.2$ for 7%wt shows good improvement about 48% from undrawn specimens, and 91% compared to unfilled undrawn material.

iv. By increasing fibre contents to 27%wt and 55%wt, stress intensity factor decreased with increasing draw ratio to a minimum value of 15% and 40% for 27%wt and 55%wt respectively.

v. Fracture test results of drawn and undrawn both fibre filled and unfilled composite, summarized in the result chapter show that 13%wt fibre composite has the highest toughness.

vi. Correction factors found for isotropic materials are found to be higher than anisotropic material. Correction factor increased with increasing $a/b$ ratio and decreased with increasing fibre content and draw ratio.

vii. Finite element model has been used to analyse to investigate the behaviour of anisotropic material and to calculate correction factors $Y$. Correction factors for anisotropic material decreased with increased draw ratio and fibre contents.
7.2 Recommendation and future work

Material

In the presented work a study of short glass fibre reinforced polypropylene resin has been concluded. The fibre contents ranged from 7% wt to the highest content of 55%wt. In terms of modulus and fracture toughness the optimum formulation was 13%wt at a draw ratio 2.5. It will be of interest to investigate intermediate short fibre levels of 10, 11, 12, 13, 14, 15, and 16%wt.

Die drawing rig

The small rig die used in this study with cross section 2 mm thickness by 5 mm width is too small to produce oriented specimens of a high draw ratio and of thickness and width meeting all the fracture test requirements. Possible strategies are to increase the die width and thickness dimension and try to explore the use of different die angles. Therefore work can be carried out towards a new design of die so as to maximise width and thickness. Further study should also include investigation of higher drawing speeds in the small die rig to produce highly oriented specimens, and increasing draw ratio for filled specimens. It would be beneficial to design a drawing rig that unable drawn product of thicker dimension to be made. This will allow testing of mechanical properties of thicker drawn specimens in the transverse direction.

The work shown here was based on single die geometry of 15° half angle. Alternative geometry dies could allow further drawing of the filled material.
**Fibre orientation study**

The injection moulding process could produce some degree of fibre orientation in moulded samples. The level of orientation was not investigated in this study, but could have a significant effect on the drawing behaviour. Therefore more comprehensive studies of moulding conditions-fibre orientation relationships will further enhance our understanding of the influence of fibre orientation in die drawing behaviour.

**Void analysis**

Microscopic analysis of undrawn and drawn specimens should be done to check the effect of die drawing process on void formation and growth. It could also provide further understanding as to why highly filled composites have poor drawing characteristics.
References


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Technology, 62, 1469-1476.
Series A 221, 163-198.
(New York).
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drawing thermoplastics illustrated with high density polyethylene. Polymer
Engineering and Science, 18 (11), 861-863.
Hashemi and Williams, J. G. (1984) size and loading mode effects in fracture
toughness testing of polymer. Journal of material science, 19, 3746-3759.
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Hill, .New York.
Hope, P. S., Richardson, A., and Ward, I. M. (1981a) Manufacture of ultrahigh-
modulus poly(oxy)methylenes by die drawing. Journal of Applied Polymer
Science, 26 (9), 2879-2896.
drawing of glass fibre reinforced poly(oxy)methylene. polymer Engineering
References


References


References


Williams, T. J. (1973) Material science, 8 (59).

Appendix A: Nomenclature

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<td>ASTM</td>
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<td>Initial circular cross-section area</td>
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<td>Final circular cross-section area</td>
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<td>Die exit circular cross-section area</td>
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Appendix B: Material Technical Data Sheets

Appendix B1: Polypropylene PP513MNK40

![SABIC® PP 513MNK40](image)

**Description:**
This very high flow grade shows a medium impact resistance, even at low temperatures, combined with high stiffness. SABIC® PP 513MNK40 is provided with an anti-static package. It is used for high speed processing of thin walled packaging articles like margarine tubs, ice cream containers and flowerpots. SABIC® PP 513MNK40 can also be applied for use in caps and closures, toys and housewares. This grade is also available without anti-static additives.

**Health, Safety and Food Contact regulations:**
Material Safety Data Sheets (MSDS) and Product Safety declarations are available on our Internet site http://www.sabic-europe.com

The product mentioned herein is in particular not tested and therefore not validated for use in pharmaceutical/medical applications.

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SABIC® PP 513MNK40
PP block copolymer for Injection moulding

Quality:
SABIC Europe is fully certified in accordance with the internationally accepted quality standard ISO9001.

Storage and handling:
Avoid prolonged storage in open sunlight, high temperatures (>50 °C) and/or high humidity as this could well speed up oxidation and consequently loss of quality of the material and/or its packaging. Keep material completely dry for good processing.

Disclaimer. The information contained herein may include typical properties of our products or their typical performances when used in certain typical applications. Actual properties of our products, in particular when used in conjunction with any third party material(s) or for any non-typical applications, may differ from typical properties.

It is the customer's responsibility to inspect and test our product(s) in order to satisfy itself as to the suitability of the product(s) for its and its customers particular purposes. The customer is responsible for the appropriate, safe and legal use, processing and handling of all product(s) purchased from us.

Nothing herein is intended to be nor shall it constitute a warranty whatsoever, in particular, warranty of merchantability or fitness for a particular purpose.

SABIC Europe as referred to herein means any legal entity belonging to the SABIC Europe group of companies.

internet www.sabic-europe.com
email pp.info@sabic-europe.com
# Appendix B2: Polypropylene compound G3155X

**Description:**
SABIC® PP compound G3155X is a 55% short glass fiber reinforced Polypropylene. This material has been designed for high stiffness, high impact, high heat resistance and chemical resistance. The glass fibres are chemically coupled to the PP matrix. Typical application of this material would include air intake manifolds. The material is available in standard black.

SABIC® PP compound G3155X is a designated automotive grade.

**IMDS ID:** 136528626

### Typical values

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1. All measurements on injection molded samples.
2. Stress of testing according to a temperature of 23 °C ± 1 °C.
3. Flexural testing.
4. All quoted loads: U.S. 1/16 in.

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*Internet: [www.sabic-europe.com](http://www.sabic-europe.com)
*Email: pp.info@sabic-europe.com

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Appendix Technical Data Sheets

SABIC® PPcompound G3155X Provisional
PP short glass fiber reinforced for Automotive injection moulding

Quality:
SABIC Europe is fully certified in accordance with the internationally accepted quality standard ISO9001.

Storage and handling:
Avoid prolonged storage in open sunlight, high temperatures (>50 °C) and/or high humidity as this could well speed up oxidation and consequently loss of quality of the material and/or its packaging. Keep material completely dry for good processing.

Disclaimer: The information contained herein may include typical properties of our products or their typical performances when used in certain typical applications. Actual properties of our products, in particular when used in conjunction with any third party material(s) or for any non-typical applications, may differ from typical properties.

It is the customer's responsibility to inspect and test our product(s) in order to satisfy itself as to the suitability of the product(s) for its and its customers particular purposes. The customer is responsible for the appropriate, safe and legal use, processing and handling of all product(s) purchased from us.

Nothing herein is intended to be nor shall it constitute a warranty whatsoever, in particular, warranty of merchantability or fitness for a particular purpose.

SABIC Europe as referred to herein means any legal entity belonging to the SABIC Europe group of companies.

Internet: www.sabic-europe.com
email: pp-info@sabic-europe.com
Appendix C: Drawn and undrawn specimens modulus

Appendix C1 Polypropylene 0%wt short glass fibre filled
Nominal Tensile Stress (MPa) vs. Engineering Strain

- λ = 4.7
- λ = 5
Appendix

Mechanical properties

![Nominal Tensile Stress (MPa) vs Engineering Strain for different λ values](image1)

![Nominal Tensile Stress (MPa) vs Engineering Strain](image2)
Appendix

Mechanical properties

Nominal Tensile Stress (MPa) vs. Engineering Strain

- 
  $y = 2600x$

- 
  $\lambda = 4.7$

Nominal Tensile Stress (MPa) vs. Engineering Strain

- 
  $y = 2951.3x$

- 
  $\lambda = 5$
y = 3609.9x
Appendix C2 Polypropylene 7%wt short glass fibre filled

![Graph 1: Nominal Stress vs Engineering Strain](image1)

![Graph 2: Nominal Stress vs Engineering Strain](image2)
Appendix

Mechanical properties

![Graphs showing mechanical properties with equations and engineering strain]

1. \( y = 2687.5x \)
2. \( y = 2787.9x \)
3. \( y = 3030.3x \)

Nominal Stress (MPa) vs. Engineering Strain

- \( \lambda = 2.6 \)
- \( \lambda = 2.7 \)
- \( \lambda = 3.2 \)
Appendix

Mechanical properties

![Graph of Tensile Modulus (GPa) vs. Draw ratio for 7% wt.](image1)

![Graph of Stress at break (MPa) vs. Draw ratio for 7% wt.](image2)

![Graph of Yield Stress (MPa) vs. Draw ratio for 7% wt.](image3)
Appendix C3 Polypropylene 13% wt short glass fibre filled

Stress (MPa) vs. Strain

λ1

Stress (MPa) vs. Strain

λ2.1
Appendix

Mechanical properties

\[ y = 2045.5x \]

\[ y = 4100x \]

[Graphs showing stress-strain curves with equations and axes labeled.]
Appendix

Mechanical properties

\[ y = 4260.9x \]

\[ y = 4375x \]
\[ y = 4682.5x \]
Appendix C4 Polypropylene 27% wt short glass fibre filled

![Graph of Tensile Stress vs. Tensile Strain for Polypropylene 27% wt short glass fibre filled]
Appendix

Mechanical properties

![Graph showing tensile stress vs. strain with the equation \( y = 3819.4x \)]

![Graph showing tensile modulus vs. draw ratio with the data points at \( \lambda = 1.71 \) and 27% wt.]
Appendix C5 Polypropylene 55% wt short glass fibre filled
Mechanical properties

- $y = 8333.3x$
- $y = 5000x$
- $y = 4000x$
Appendix D: Double edge fracture model

Appendix D1 Materials and methods

The ABAQUS program was used for the simulations double edge fracture notch. Elements used, modelling detail, and analysis techniques will described. The simulation models consist of the double edge notched specimens, 2D linear elastic behaviour and non linear plastic to model the structure, material behaviour values of Young's modulus, Poisson's ratio associated with the materials. Finite element models were used in this research to analytically study the behaviour of the test specimen’s, to verify how well the model predicts the deformation behaviour of the structure, to explore deformation shape and stress-strain response of the specimens. The resulting images were compared with photographs of actual test specimens.

A series of elements and nodes were used to represent the geometry of the double notch specimen. The material and cross-section definitions applicable to the fractured specimens sections were defined within the model. Constraints and boundary conditions were also applied to applicable nodes throughout the analysis. The FE models were considered plastic. A modulus of elasticity of 3.9 GPa and a Poisson’s Ratio of 0.49 were used. Plasticity data obtained from stress-strain curve of fracture test and utilize in the model.
Model Description

Element Types

The element used in the polymer billet 2D model is CPS4, a 4-node linear brick reduced integration. A 9720 element, 12408 nodes, was created to the model. For each node, there are six degrees of freedom: nodal translations in x, y, and z directions. The geometry of the 2-D Full modelled of the fracture specimen is shown in Figure 8.

Figure 8: Double notch fracture specimen
Boundary condition 2D

Figure 9: Double notch fracture specimen
boundary condition 3D
Boundary condition

Mesh

By subdividing the specimen, a regularly meshed could be obtained as shown in Figure 8. A fine mesh is used to capture the deformation, strain, and stress concentrations as accurately as possible.

Boundary Conditions

A full model of polymer billet was developed for solution in ABAQUS, 2D model of double edge fracture specimen. The boundary conditions specified for at the plane of symmetry were that translation in the x-direction, for the top surface and constrain translation, rotation in the y-direction, and the displacement of the top surface only in one x-direction. Specimen fixed at XY direction. From bottom, left side and right side restrained in X direction free to move to in Y direction and from the top surface loaded by motion in x-direction, as shown in Figure 9.
Fracture Model

Double edge notch model validation

Both 2D and 3D model completed run successfully the result showed good agreement in deformation between experimental and simulation work, deformation shape, stress concentration are shown in Figures 10 and 11.

![Figure 10: 2D Double edge notch model stress contours](image-url)
Figure 11: 3D Double edge notch stress contours
Appendix D2 Double edge Fracture input file

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*End Instance
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9.70,0.74,100
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19.31,1.38,100
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35.68,2.05,100
36.48,2.07,100
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68.96,2.68,100
75.80,2.77,100
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1., 1., 1e-05, 1.
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** BOUNDARY CONDITIONS
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*Boundary _PickedSet7, ENCASTRE
** Name: pull Type: Displacement/Rotation
*Boundary _PickedSet6, 2, 2, 0.5
**
** OUTPUT REQUESTS
**
*Restart, write, frequency=0
**
** FIELD OUTPUT: F-Output-1
**
*Output, field, variable=PRESELECT
**
** HISTORY OUTPUT: H-Output-1
**
*Output, history, variable=PRESELECT
*End Step
*Step, name=pull2
*Static  
1., 1., 1e-05, 1.
**
** BOUNDARY CONDITIONS
**
** Name: fixed Type: Symmetry/Antisymmetry/Encastre
*Boundary _PickedSet7, ENCASTRE
** Name: pull Type: Displacement/Rotation
*Boundary _PickedSet6, 2, 2, 1.5
**
** OUTPUT REQUESTS
**
*Restart, write, frequency=0
** FIELD OUTPUT: F-Output-1

*Output, field, variable=PRESELECT

** HISTORY OUTPUT: H-Output-1

*Output, history, variable=PRESELECT
*End Step
*Step, name=pull50
*Static
1., 1., 1e-05, 1.

** BOUNDARY CONDITIONS

** Name: fixed Type: Symmetry/Antisymmetry/Encastre
*Boundary
_PickedSet7, ENCASTRE

** Name: pull Type: Displacement/Rotation
*Boundary
_PickedSet6, 2, 2, 520

** OUTPUT REQUESTS

*Restart, write, frequency=0

** FIELD OUTPUT: F-Output-1

*Output, field, variable=PRESELECT

** HISTORY OUTPUT: H-Output-1

*Output, history, variable=PRESELECT
*End Step
Appendix D2 Coarse mesh double notch input file

2.5mm notch depth specimens input file

*HEADING
fracture specimen 2.5notch depth
*NODE
1,0.0,0.
13,2.5,0.0
26,5.0,0.0
2601,0.0,35.0
2613,2.5,35.0
2626,5,35.0
*NGEN,NSET=x1
1,13
*NGEN,NSET=x3
13,26
*NGEN,NSET=x2
2601,2613
*NGEN,NSET=x4
2613,2626
*NGEN,NSET=Y1
1,2601,26
*NGEN,NSET=Y2
26,2626,26
*NGEN,NSET=Y3
13,2613,26
*NFILL,BIAS=1.1
y1,y3,12
*NFILL,BIAS=0.85
y3,y2,13
*NFILL, BIAS=0.98
X1,X2,100,26
*NFILL, BIAS=0.98
X3,X4,100,26
*ELEMENT,TYPE=CPS4
1,1,2,28,27
*ELGEN,ELSET=all
1,25,1,1,100,26,25
*NSET,NSET=LIG,generate
1,13,1
*NSET, NSET=XTOP
x2,x4
*ORIENTATION, NAME=GLOB
1., 0., 0., 0., 1., 0.
*SOLID
SECTION, ELSET=ALL, MATERIAL=TWOPRO, ORIENTATION=GLOB
1.0
*MATERIAL, NAME=TWOPRO
*ELASTIC, TYPE=LAMINA
0.9500E3, 2.024E3, 0.11, 5.6e3
*RESTART, WRITE, FREQUENCY=1
*BOUNDARY
LIG, 2,,
Y1, 1,,
XTOP, 1,,
**step 1
*STEP, NLGEOM, INC=1000
*STATIC
0.1, 1.0, 0.0000000001, 0.1
*BOUNDARY
XTOP, 2, 2, 1.
*NODE PRINT, FREQUENCY=1, NSET=XTOP, TOTALS=YES
RF2
*NODE PRINT, FREQUENCY=1, NSET=XTOP
U2
*NODE PRINT, FREQUENCY=1, NSET=LIG
U1
*END STEP
Double notch input file 2.5mm plus 0.05

*HEADING
fracture specimen 2.5notch depth

*NODE
1,0.0,0.
13,2.45,0.0
26,5.0,0.0
2601,0.0,35.0
2613,2.5,35.0
2626,5,35.0

*NGEN,NSET=x1
1,13
*NGEN,NSET=x3
13,26
*NGEN,NSET=x2
2601,2613
*NGEN,NSET=x4
2613,2626
*NGEN,NSET=Y1
1,2601,26
*NGEN,NSET=Y2
26,2626,26
*NGEN,NSET=Y3
13,2613,26

*NFILL,BIAS=1.1
y1,y3,12
*NFILL,BIAS=0.85
y3,y2,13
*NFILL, BIAS=0.98
X1,X2,100,26
*NFILL, BIAS=0.98
X3,X4,100,26

*ELEMENT,TYPE=CPS4
1,1,2,28,27
*ELGEN,ELSET=all
1,25,1,1,100,26,25
*NSET,NSET=LIG,generate
1,13,1
*NSET, NSET=XTOP
x2,x4

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*SOLID
SECTION,ELSET=ALL,MATERIAL=TWOPRO,ORIENTATION=GLOB
1.0
*MATERIAL,NAME=TWOPRO
*ELASTIC,TYPE=LAMINA
0.9500E3,2.024E3,0.11,5.6e3
*RESTART,WRITE,FREQUENCY=1
*BOUNDARY
LIG,2,,
Y1,1,,
XTOP,1,,
**step 1
*STEP,NLGEOM,INC=1000
*STATIC
0.1,1.0,0.0000000001,0.1
*BOUNDARY
xTOP,2,2,1.
*NODE PRINT,FREQUENCY=1,NSET=xTOP,TOTALS=YES
RF2
*NODE PRINT,FREQUENCY=1,NSET=xTop
U2
*NODE PRINT,FREQUENCY=1,NSET=LIG
U1
*END STEP
Double notch input file 2.5mm plus 0.1

*HEADING
fracture specimen 2.5notch depth
*NODE
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  13,2.4,0,0
  26,5.0,0,0
  2601,0,0,35.0
  2613,2.5,35.0
  2626,5,35.0
*NGEN,NSET=x1
  1,13
*NGEN,NSET=x3
  13,26
*NGEN,NSET=x2
  2601,2613
*NGEN,NSET=x4
  2613,2626
*NGEN,NSET=Y1
  1,2601,26
*NGEN,NSET=Y2
  26,2626,26
*NGEN,NSET=Y3
  13,2613,26
*NFILL, BIAS=1.1
  y1,y3,12
*NFILL, BIAS=0.85
  y3,y2,13
*NFILL, BIAS=0.98
  X1,X2,100,26
*NFILL, BIAS=0.98
  X3,X4,100,26
*ELEMENT,TYPE=CPS4
  1,1,2,28,27
*ELGEN,ELSET=all
  1.25,1,1,100,26,25
*NSET,NSET=LiG.generate
  1,13,1
*NSET, NSET=XTOP
  x2,x4
*ORIENTATION,NAME=GLOB
  1.,0.,0.,0.,1.,0.
*SOLID
SECTION,ELSET=ALL,MATERIAL=TWOPRO,ORIENTATION=GLOB
1.0
*MATERIAL,NAME=TWOPRO
*ELASTIC,TYPE=LAMINA
0.9500E3,2.024E3,0.11,5.6e3
*RESTART,WRITE,FREQUENCY=1
*BOUNDARY
LIG,2,,
Y1,1,,
XTOP,1,,
**step 1
*STEP,NLGEOM,INC=1000
*STATIC
0.1,1.0,0.0000000001,0.1
*BOUNDARY
XTOP,2,2,1.
*NODE PRINT,FREQUENCY=1,NSET=XTOP,TOTALS=YES
RF2
*NODE PRINT,FREQUENCY=1,NSET=XTop
U2
*NODE PRINT,FREQUENCY=1,NSET=LIG
U1
*END STEP


**Appendix D3 Correction factor determination**

In order to investigate the point at which there was notch crack start for the drawn anisotropic specimens for the experimental results. Correction factor, for anisotropic $Y$ was calculated using the simulated results. The actual stress intensity $K_I$ was calculated using $Y$ and stress intensity factor $K_0$.

Table 1 compares reaction force and correction factor results from the .dat file. When comparing the reaction force experienced by DEN 7%wt short glass fibre filled specimens drawing $g$ at draw ratio of $\lambda=2.4$ and with draw ratio of $\lambda=2.6$, $\lambda=2.7$, and $\lambda=3.2$ simulated in ABAQUS, we found that the reaction, refined and increased with increasing draw ratio the higher draw ratio of $\lambda=3.2$ gave reaction force results of approximately 422 N, 432N, and 438N for $a/b$ 0.5, 0.4 and 0.3 respectively. The correction factor decreased with increasing draw ratio.

Fractured DEN specimens with 13%wt short glass fibre filled, notch depth of 1.50mm, 2.0mm, 2.5mm drawn at different draw ratio of $\lambda=2.1$, $\lambda=2.2$, $\lambda=2.3$, and $\lambda=2.5$, the reaction forces for the draw ratio of $\lambda=2.2$ were approximately 608 N, 594 N, and 576 N the higher draw ratio shows the lowest reaction force, correction factor decrease with increasing draw ratio.

Double edge notch Specimens 27%wt and 55%wt reaction force are 753N, 785N, and 801N for 27%wt and, 1274N, 1308N, and 1333N for 55%wt.

It can be seen from the finite element results for 0%wt and 7%wt, DEN specimens with different notch depth that the reaction forces are increased with
increasing draw ratio. But for 13\%wt, 27\%wt, and 55\%wt increased only for specific draw ratio when draw ratio increased the reaction force decreased.

Undrawn DEN isotropic specimens, the reaction forces and correction factor are listed in Table 2. It is can be seen that with increasing filler weight correction factor increased and with increasing fibre contents for all different notch depth reaction force increased. Deformed shape and stress concentration contour are shown in figures 19, and 20.
Figure 18: Stress contours 2.49mm notch length
Figure 19: Stress contours 2.50mm notch length
Figure 20: Stress contours 2.55mm notch length
Figures 22-25 display correction factor versus notch depth half specimen width for simulated results. The simulated results were acquired using an ABAQUS model, which was calculated using strain energy release. Figure 22 displays results specifically for drawn specimens with 7% wt with different draw ratio and notch depth, correction factor increased gradually with a/b ratio increasing.

Figure 24 relates the same results for 13% wt with different draw ratio and notch depth node was at position 0.05 mm and 0.1 mm, correction factor increased gradually with a/b ratio increasing and increased with fibre contents increased.
Table 1: correction factor for isotropic and anisotropic material

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<th>55 %</th>
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<td>a/b</td>
<td>Y</td>
<td>Draw ratio</td>
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<td>0.4</td>
<td>1.1316</td>
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<td>0.5</td>
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<tr>
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<td>0.3</td>
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<td>0.3</td>
<td>1.0387</td>
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</table>
Figure 21: correction factor for 7% wt with different draw ratio

Figure 22: reaction force for 7% wt with different draw ratio

Figure 23: correction factor for 13% wt with different draw ratio

Figure 24: reaction force for 13% wt with different draw ratio
The following Figures 26-29 an isotropic correction factor results for the 27%wt and 55%wt short glass fibre DEN Specimens drawn at different draw ratios which notch depth node were 1.5mm, 2.0mm, and 2.5mm. The notch depth position moved 0.05mm, and 0.1mm for every notch. It is apparent that correction factor decreased with increasing fibre contents more than 13%wt short glass fibre.
Figure 25: correction factor for 27% wt with different draw ratio
Figure 26: reaction force for 27% wt with different draw ratio

Figure 27: correction factor for 55% wt with different draw ratio
Figure 28: reaction force for 55% wt with different draw ratio
Figure 30 plots correction factor versus a/b for the 0%wt unfilled DENT Specimens drawn at draw ratio of $\lambda=4.6$, $\lambda=4.7$, $\lambda=5.0$, and $\lambda=5.6$. Anisotropic specimens’ correction factor decreased with increasing draw ratio.

Comparing the figures 22-32, it can be seen that the results for the higher fibre filled have a lowest correction factor value due to the increasing in reaction force.
Figure 29: Correction factor for different draw ratio 0% wt

Figure 30: Reaction force for different draw ratio 0% wt