### EFFECTS OF INJECTION MOLDING CONDITIONS ON THE MECHANICAL PROPERTIES OF POLYAMIDE / GLASS FIBER COMPOSITES

### A THESIS SUBMITTED TO THE GRADUATE SCHOOL OF NATURAL AND APPLIED SCIENCES OF MIDDLE EAST TECHNICAL UNIVERSITY

BY

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IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF MASTER OF SCIENCE IN POLYMER SCIENCE AND TECHNOLOGY

JUNE 2007

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#### ABSTRACT

### EFFECTS OF INJECTION MOLDING CONDITIONS ON THE MECHANICAL PROPERTIES OF POLYAMIDE / GLASS FIBER COMPOSITES

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June 2007, 140 pages

In this study, effect of injection molding process parameters on fiber length and on mechanical properties of Polyamide-6 / glass fiber composite were investigated to produce higher performance composites. Polyamide-6 was first compounded with an E-grade glass fiber in a co-rotating intermeshing twin screw extruder. Then, by using this composite, twenty-five types of experiments were performed by injection molding by changing the barrel temperature, injection pressure, hold pressure, mold temperature, cooling time and screw speed. Izod notched impact, tensile, viscosity, heat deflection temperature, differential scanning calorimetry tests were performed on injection molded samples. By performing these tests, the effects of process parameters on mechanical properties and on fiber length were observed. In order to understand the variation in mechanical properties, thermal tests were also conducted. Also, fiber length distributions of the samples were measured. Experimental data show that fiber breakage decreases with increasing screw speed, injection pressure, however, fiber length increases with increasing barrel temperature, mold temperature and cooling time. Fiber length is almost not affected with the hold pressure. It is assumed in this study that crystallinity is not affected with injection pressure, hold pressure and screw speed. As barrel temperature and cooling time increase, crystallinity increases, however, as mold temperature increases, crystallinity decreases. Impact strength, tensile modulus and tensile strength increase, whereas elongation at break decreases with the average fiber length. Crystallinity affects the tensile strength and modulus positively. The tensile strength and modulus increase with increasing crystallinity.

Key Words: Composite, Injection Molding, Polyamide-6, Glass fiber, Mechanical Properties

### ÖΖ

# ENJEKSİYON MAKİNESİ ÇALIŞMA ŞARTLARININ CAM ELYAF TAKVİYELİ- POLİAMİD KARMA MALZEMELERİNİN MEKANİK ÖZELLİKLERİNE OLAN ETKİSİ

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Yüksek Lisans, Polimer Bilimi ve Teknolojisi Bölümü Tez Yöneticisi: Prof. Dr. Ülkü Yılmazer Haziran 2007, 140 sayfa

Bu çalışmada, enjeksiyon makinesi proses parametrelerinin elyaf boyutlarına ve cam elyaf takviyeli Poliamid-6 karma malzemesinin mekanik özelliklerine etkisi incelenmiştir. İlk olarak Poliamid-6 ve E-tipi cam elyaf ekstrüsyonda harmanlanmıştır. Daha sonra bu malzeme ile birlikte, enjeksiyon makinesinin kovan sıcaklığı enjeksiyon basıncı, ütüleme basıncı, kalıp sıcaklığı, soğutma zamanı ve vida hızı değiştirilerek, 25 tip deney yapılmıştır. Enjeksiyonla kalıplanmış örnekleri kullanarak, darbe, çekme, viskosite, ısı eğilme testi, DSC diferansiyel ısı ölçümü tarama testi yapılmıştır. Bu testler yapılarak, proses parametrelerinin mekanik özellikleri ve elyaf boyu üzerindeki etkileri incelenmiştir. Mekanik özelliklerdeki değişimi anlamak amacı ile termal testler de yapılmıştır. Ayrıca, örneklerin elyaf boyutu dağılımı da ölçülmüştür. Deneysel veriler ve test sonuçlarına göre; enjeksiyon basıncı ve vida hızı arttırıldığında, elyaf kırılmasının azaldığı; kovan sıcaklığı, kalıp sıcaklığı ve soğutma zamanı arttırıldığında ise elyaf kırılmasının azaldığını göstermiştir. Elyaf boyu; ütüleme basıncından neredeyse hiç etkilenmemiştir. Bu çalışmada, kristal yüzdesinin, enjeksiyon basıncı, ütüleme basıncı ve vida hızından etkilenmediği farz edilmektedir. Kovan sıcaklığı ve soğutma zamanı artırıldığında, kristal yüzdesi artarken, kalıp sıcaklığı arttırıldığında kristal yüzdesi azalmıştır. Ortalama elyaf boyutu arttığında, darbe, çekme ve modulus artarken, kopmadaki uzama azalmıştır. Kristal yüzdesi arttığında ise çekme ve modulus olumlu olarak etkilenmiştir.

Anahtar Kelimeler: Karma Malzeme, Enjeksiyon Makinesi, Poliamid-6, Cam Elyaf, Mekanik Özellikler

### ACKNOWLEDGEMENTS

I would like to express my deep and sincere gratitude to Prof. Dr. Ülkü Yılmazer for his invaluable encouragement, help and guidance through this study.

I express my deepest thanks to Prof. Dr. Duygu Kısakürek for her endless help and encouragement since I am in this university and throughout this study.

Very special thanks to Murat Cansever for his endless support, continuous encouragement, guidance and help in completing this thesis. It was a pleasure to share his experiences in polymers.

I would like to express my appreciation to Murat Topsakaloğlu, technical manager, Hasan Camadan and Mustafa Çalışkan, laboratory staff of Eurotec Company. I am also very thankful to the company staff for their helpful and friendly attitude throughout my experiments.

I offer my great thanks to Dr. Güralp Özkoç from Kocaeli University, for his invaluable encouragement, endless help and advice.

I would like to express my great pleasure to Osman Bilgin for his endless support, continuous encouragement and advices since I know him.

Many thanks to my friends, especially, İsmail Doğan Günbaş, Arda Ünsal, Onur Bütüner, Utku Uslu, Nihal Demirkol, Serdar Hasipek and many others for their help, support and friendship during the hard days of my study.

Finally, my deepest thanks to my family, meaning of my life, for their patience, support and faith in me.

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### LIST OF SYMBOLS

- $a_{iN}$  : Izod impact strength of the notched specimens, kJ/ m<sup>2</sup>
- D : Diameter of the fiber,  $\mu$
- E : Modulus, MPa
- $E_{f}$  : Modulus of fibers (bending), MPa
- GF : Glass fiber
- $\Delta H_{\rm f}$  : Change in heat of fusion

 $\Delta H_{f(pure)}$ :Heat of fusion of pure nylon

- J : The orientation function
- L : Length of the fiber, mm
- L/D : Aspect ratio
- $(L/D)_c$ : Critical aspect ratio
- L<sub>o</sub> : Initial fiber length, mm
- $L_c$  : Critical fiber length, mm
- $L_i \qquad : \text{Length of the fiber, } \mu$
- $L_n$  : Number average fiber length,  $\mu$
- $L_w$ : Weight average fiber length,  $\mu$
- $l_e$  : fiber embedded in matrix of this length ,  $\mu$
- $l_{ce}$  : critical fiber length ,  $\mu$
- $N_i \qquad : \text{Number of fibers of length } L_i$
- $\eta$  Viscosity
- $q(\theta)$ : The distribution of fiber orientation angles
- 2R : Inter fiber spacing
- R : Functionality of the silane coupling agent
- \*R : Functionality of the the polymer
- PP : Polypropylene

- r : Radius of the fiber,  $\mu$
- V : Volume fraction
- V<sub>f</sub> : Volume fraction of fibers
- V<sub>j</sub> : Volume fraction of fibers above critical length
- V<sub>m</sub> : Volume fraction of matrix
- W : Weight fraction
- W<sub>f</sub> : Weight fraction of glass fiber
- W<sub>m</sub> : Weight fraction of matrix
- X<sub>c</sub> : Percent crystallinity
- $\beta$  : The ratio of the area under the stress distribution curve over the length

 $l_c/2$  to the area of  $\sigma_{fu}l_c/2$ 

- $\epsilon_{b}$ : Elongation at break
- δ : Density, g/cm<sup>3</sup>
- $\sigma$  : Tensile strength, MPa
- $\sigma_c$  : Tensile strength, MPa
- $\sigma_{fu}$  : Tensile strength of the glass fibers, MPa
- $\sigma_{\rm f}$  : The average stress of fiber, MPa
- $\sigma_{f}^{*}$  : The fracture strength of the fiber, MPa
- $\sigma_{f,av}$  : Average fiber strength, Mpa
- $\gamma$  : Shear stress
- $\tau$  : Interfacial bond strength, MPa
- $\tau_{crit}$  : Critical shear stress, MPa
- $\tau_{I}$  : Interfacial bond strength, MPa
- $\sigma_m$  : Maximum stress applied to the fiber, MPa
- $\sigma_{m'}$  : Stress carried by the matrix at the fiber failure strain, Mpa
- $\pi$  : Angle of  $180^{\circ}$
- $\theta$  : Angle

### CHAPTER I

### **INTRODUCTION**

Plastics for replacement of metals and for new products began essentially in the late 1930s, and their development and use of products has proliferated ever since. Plastic materials display properties that are unique when compared to other materials and have contributed greatly to quality of our everyday life. Plastics, properly applied, will perform functions at a cost that other materials cannot match. Plastics are used in our clothing, housing, automobiles, aircraft, packaging, electronics, signs, recreation items, and medical implants to name but a few of their many applications.

Plastics are changed into useful shapes by using many different processes. The processes that are used to mold or shape thermoplastics basically soften the plastic material so it can be injected into a mold, flow through a die, formed in or over a mold. The processes usually allow any scrap parts or material to be ground up and reused. Some of the more common processes are injection molding, extrusion, blow molding, rotational molding, calendering, thermoforming (which includes vacuum forming), and casting.

Glass fiber reinforced plastics have a large area in industry nowadays because of their reduced weight, enhanced strength and stiffness, flexibility in design, good chemical, corrosion and electrical resistance.

Injection molding is very widely used in automotive industry to produce plastic articles. A major advantage of this manufacturing technique is forming fairly complex shapes at a high production rate in view of the cyclic nature of the process. For effective processing of the glass fiber reinforced composites, adhesion of matrix resin and glass fibers, volume fraction, fiber length distribution, fiber diameter, fiber and molecular orientation must be characterized.

Fiber length has a great effect on mechanical properties of composites. Firstly, with extrusion compounding, then injection molding; fiber length decreases to only a small portion of its original value so this length reduction affects the mechanical properties of the composite negatively. The reinforcing effects of fiber reinforcement increase with aspect ratio. Processing conditions of injection molding causes fiber attrition such that molded products have low aspect ratio values so; by determining the optimum conditions, this situation can be controlled. Fibers display flow orientation during injection molding. This orientation also depends on aspect ratio and affects the mechanical properties of molded articles

In this study, 30% glass fiber reinforced Polyamide-6 was used, and by altering the process parameters of injection molding, test specimens were prepared to observe the effects of these parameters on mechanical properties, fiber length and the effect of the latter on the former one.

### **CHAPTER II**

### LITERATURE SURVEY

#### 2.1 Theory

Composite materials are engineering materials made from two or more constituent materials that remain separate and distinct on a macroscopic level while forming a single component. The reason why composites are produced is obtaining better properties by combining the advantageous properties of constituents instead using them alone. There are two separate phases in composite materials which are the matrix and reinforcement. The matrix material surrounds and supports the reinforcements by maintaining their relative positions. The reinforcements impart their special mechanical and physical properties to enhance the matrix properties. Most of the composites use fibers as reinforcement.

The importance of fiber reinforced composites appears widely from the fact that such materials can have exceptionally high strength and stiffness for a given weight of material so as a result of this, fiber reinforced composites are taking place of metal parts in industrial applications such as in automotive industry. Short glass fiber reinforced Polyamide-6 composite which has high mechanical performance, corrosion resistance, good design property and easy processability are an example of this.

Polyamides were the first engineering plastics and still represent by far the biggest and most important class of these types of material. The combination of mechanical and thermal properties allows them to be employed for highly specified end uses and often for metal replacement applications. Polyamides, often also referred to as nylons, are high polymers which contain the amide repeat linkage in the polymer

backbone. They are also characterized as tough, translucent, semicrystalline polymers that are moderately low cost and easily manipulated commercially by melt processing.

#### 2.1.1 Polyamide-6

Polyamide-6, a semicrystalline polymer, occupies a prominent place in the engineering thermoplastics family because of its broad processing range and the relative ease with which the base polymer can be modified to achieve a wide spectrum properties. Polyamide-6 is not a condensation polymer, but instead is formed by ring-opening polymerization. Polyamide-6 begins as a pure caprolactam. As caprolactam has 6 carbon atoms, it got the name Polyamide-6. When caprolactam is heated at about 260  $^{0}$  C in an inert atmosphere of nitrogen for about 4-5 hours, the ring breaks and undergoes polymerization.



Figure 2.1 Polymerization of Polyamide-6

There are two polymerization techniques of Polyamide-6 which are batch process and continuous process. Batch processing of Polyamide-6 is generally used only for the production of specialty. In a typical modern batch process, the caprolactam is mixed in a holding tank with the desired additives and then charged to an autoclave with small amount (2-4%) of water. During the two-stage polymerization cycle, the temperature is raised from 80 to 260 <sup>o</sup>C. In the first stage water is held in the reactor, the pressure increases, then the hydrolysis and addition steps occur. After a predetermined time, the pressure is released and the final condensation reaction step occurs. The molecular weight of the polymer can be increased by means of a vacuum finishing step, if desired.

The entire process can take three to five hours. The final polymer is than drained, often with a forcing pressure of inert gas, through a die to form ribbons of polymer, which are then cooled in water and cut into pellets. Because Polyamide-6 has such a high monomer and oligomer content, 10-12% by weight, in the cast pellets, which would significantly reduce the quality of the final fiber or resin products, it must be extracted. This is usually done in hot water under pressure at 105-120 °C for 8-20 hours. Most of the caprolactam and higher oligomers that are released with steam from an autoclave or extracted from the pellets in hot water are then recycled. The pellets must be carefully dried because excess water decreases the molecular weight of the polymer during subsequent melt processing. The final polymer processed through water extraction and drying can have an oligomer level of <0.2% and a moisture level of <0.05%. A low level of total oligomers is necessary because on remelting and further processing, the oligomers' content will increase owing to the reestablishment of the equilibrium distribution of molecular species that occurs for all condensation polymers. Because of the approach to equilibrium progresses at a moderate rate, it is possible to utilize extracted Polyamide-6 in a remelt process without increasing the oligomer concentration above 2-3% and thus avoiding any significant drop in the final properties.



Figure 2.2 Flow chart for batch preparation of Polyamide-6 (Kohan, 1971)

Commercial production of Polyamide-6 is by a continuous process. In the continuous polymerization process for Polyamide-6, the three steps of polymerization can be made to take place in a series of connected vessels or in a single long, vertical, tubular reactor. There are many variations and proprietary reactor designs for the continuous process. However, the purpose of the various configurations is the same as in the batch process; first, to provide water-rich reaction media to accelerate hydrolysis and the initial coupling of the monomers; and then to provide a low water environment for the polycondensation reaction to approach equilibrium. The polymer can be cast and cut into pellets in a continuous pelletizing and drying operation similar to the batch process. However, a continuous, vacuum-stripping step can be applied to remove much of the caprolactam while the Polyamide-6 is still in the melt; the polymer can then be spun directly into fiber or cast into resin. The oligomer content in this case is 2-3%; and, when this level of oligomers is acceptable, the advantage of the lower cost for vacuum stripping can be attained by eliminating the water quench, extraction, drying, and remelting steps. In order to attain higher molecular weight polymer, Polyamide-6 can also be polymerized in the solid. The same advantages and disadvantages arise in the case of Polyamide-6, except that one additional difficulty occurs for Polyamide-6 from the presence of residual caprolactam. (Joseph N.W., 1996)



Figure 2.3 Continuous manufacturing process for Polyamide-6 chips (Kohan M.I., 1971)

The most significant case in nylons is the relatively high concentration of caprolactam in Polyamide-6. Although caprolactam can be an eye, skin and respiratory irritant, this is rarely a problem in the final product where the concentrations are kept low (<2-3%) and lactam is well below its melting point. Mechanical and thermal processing can generate higher levels of caprolactam in the air from Polyamide-6 or its copolymers and create dust from most polyamides, which can act as irritants and which are usually monitored and corrected in the workplace. (Joseph N.W., 1996)

#### 2.1.2 E-glass

Glass fibers are the most common of all reinforcing fibers for polymeric matrix composites. The principal advantages of glass fibers are low cost, high tensile strength, high chemical resistance, and excellent insulating properties. The disadvantages are low tensile modulus, relatively high specific gravity (among the commercial fibers, sensitivity to abrasion with handling which decreases its tensile strength), relatively low fatigue resistance, and high hardness (which causes excessive wear on molding dies and cutting tools).

The basic commercial form of a continuous glass fiber is a strand. Chopped strands are used in injection molding which are produced by cutting continuous strands into short lengths. (Mallick, P.K, 1993)

Many different compositions of mineral glasses have been used to produce fibers. The most common ones are based on silica (SiO<sub>2</sub>) with additions of oxides of calcium, boron, sodium, iron and aluminium. E-glass is the most commonly used glass because it draws well and has good strength, stiffness, electrical and weathering properties and also the lowest cost of all commercially available reinforcing fibers. C-glass has a higher resistance to chemical corrosion than Eglass but has lower strength properties. S-glass has a higher Young's modulus and more temperature resistant than E-glass. The composition and properties of various glasses are shown in Tables 2.1 and 2.2 respectively. (Hull D., 1987)

Composition	E-glass	C-glass	S-glass
SiO <sub>2</sub>	52.4	64.4	64.4
$Al_2O_3$ , $Fe_2O_3$	14.4	4.1	25.0
Ca0	17.2	13.4	
MgO	4.6	3.3	10.3
$Na_2O, K_2O$	0.8	9.6	0.3
Ba <sub>2</sub> O <sub>3</sub>	10.6	4.7	
BaO		0.9	

Table 2.1 Composition of glass used for fiber manufacture (Hull D., 1987)

Table 2.2 Properties of Glass Fibers (Seymour R.B, 1991)

Properties	Ε	С	S
Softening Point, °C	841	749	-
Tensile Strength, MPa	3448	3033	4585
% Elongation	4.8	4.8	5.7
Specific gravity	2.55	2.5	2.5
Index of Refraction	1.547	-	1.523

The addition of E-glass to Polyamide-6 affects the properties dramatically. These are shown in Table 2.3.

Table 2.3 Effects of glass fiber reinforcement on the properties of Polyamide-6

Stiffness	Increases
Tensile Strength	Increases
Heat Deflection Temperature	Increases
Creep resistance	Increases
Fatigue strength	Increases
Thermal expansion coefficient	Decreases
Mold shrinkage	Decreases
Moisture pickup	Decreases
Ductility	Decreases
Impact strength	Increases
Anisotropy	Increases
Viscosity	Increases
Processability	Decreases

#### 2.1.3 Silane Coupling Agents

In order to transfer the stress load to the reinforcement fiber, the way is to treat the fiber with a reactive chemical that will form a stable bond between the glass surface and the surrounding matrix resin. The chemisty is what is referred to as the 'sizing' chemistry of the reinforcement. Coupling agents play a very important role for this purpose in composites. They promote wetting of the fibers and ensure good stress transfer between the weak matrix polymer and the stronger fibers by acting as a bridge between the two. If the coupling fails under stress, the fibers no longer reinforce the matrix. The bond between fiber and matrix is partly physical and chemical by way of the coupling agent. Coupling agents need to be applied at very low levels as an extremely thin coating or interface. A thick layer of coupling agent may fail in the coupling agent layer, since it is not intended to be a load-bearing member itself. Silane coupling agent is used in nylons. The silicone containing inorganic portion of the molecule provides strong bonding to fibers and primary amine containing organic portion reacts with matrix. It attains, higher mechanical strength, good processability, and excellent weathering resistance. Figure 2.4 shows the reactions of organosilanes. The reactions of silane coupling agent promoting the interfacial adhesion are represented in Figure 2.4 in which trialkoxysilane hydrolyzes in aqueous media to form a silanol compound, then, silanol reacts with the hydroxyl group of the glass surface. The coupling reaction occurs during processing between glass fibers functionalized by organo-functional silane and polymer, if it is chemically favorable. 'R' is the organic functional group to interact with the functionality of polymer '\*R'. (Ozkoc, et al., 2004)

The interfacial bond created by silanes or other coupling agents allows a better shear stress transfer between fibers and matrix, which in turn improves the tensile strength as well as the interlaminar shear strength of the composite. However, the extent of improvement depends on the compatibility of coupling agent with the matrix resin. (Mallick P.K., 1993)



**Figure 2.4** Reactions of organosilanes (R and \*R are the functionalities of the silane coupling agent and polymer, respectively) (Ozkoc, et al., 2004)



Figure 2.5 Schematic Diagram of Injection Molding Machine (Osswald, et al., 2002)

#### 2.1.4 Injection Molding

Injection molding machine shown in Figure 2.5 is singularly the most popular of all the plastics processes. Unlike extrusion or blow molding, it allows producing a plastic part with three-dimensional characteristics. This permits very intricate designs and high production rates. (Muccio E.A, 1994)

The injection molding machine consists of an injection unit and a clamp unit. The injection unit is the part where the plastic pellets are melted and the plastic melt is forced into the mold. The injection unit is very similar to an extruder in design and construction, particularly in that it has an alloy barrel and a flighted screw. However, unlike an extruder, the injection screw is capable of moving back and forth in a reciprocating motion. This has led to the name reciprocating injection molding machine. The clamp unit opens, closes and holds the mold closed against the pressure of injection. The size of an injection molding machine is described by the capacity of its clamping unit, ranging from 50 to 1000 tons. A machine with a given clamp unit can be supplied with a variety of injection units. Injection unit capacity is described by the shot size, which is the maximum volume of melt that can be injected in a single cycle. Shot size is determined by the diameter of the screw and the distance over which it is designed to reciprocate. Shot size is usually expressed as weight or as volume. (Xanthos M. and Todd D.B., 2003)

An injection molding machine is operated by hydraulic power and equipped with an electric motor. A toggle mechanism of clamping unit opens and closes the mold and holds the mold closed during injection. A hydraulic cylinder forces the screw forward, thereby injecting the melt into the mold. A separate hydraulic motor turns the screw to plasticate, homogenize and pressurize the melt. Control of these systems is a combined function of hydraulic, electrical and toggle mechanism.

In the injection molding machine, the clamp unit is on the left and the injection unit is on the right. A mold is in position between the platens of the
clamp unit with one-half of the mold fastened to the fixed platen and the other to the movable platen. When the mold is opened, the movable platen moves away from the fixed platen and the molded part can be removed. After part ejection, the mold is closed in preparation for the next injection cycle. In contrast to extrusion, the screw in the injection unit rotates only during part of molding cycle. When the screw turns, it pumps melt forward. The rearward movement of the screw is controlled by the placement of a limit switch, which stops the hydraulic motor. The maximum length of reciprocation is approximately three screw diameters. The shot size is directly proportional to the amount of screw reciprocation. The front of the screw is usually equipped with a check valve. While the screw rotates, the melt can move freely forward through the valve. However, the valve closes to prevent any reverse flow. The position of the screw is adjusted in such a way that there is always some melt in front of the screw when the mold is full. This pad or cushion of melt transfer pressure from the screw to the plastic in the mold. After initial filling, some additional melt flows into the mold; this is called packing. (Xanthos M. and Todd D.B., 2003)

### 2.1.4.1 The Injection Unit

#### Screw

The injection screw must perform several functions during the molding cycle. In addition to conveying and melting the plastic, the screw must mete out the correct amount of plastic in front of the screw and it must inject this plastic melt into the mold.

#### **Check Valve**

It is attached to the discharge end of the thermoplastic injection molding screws. To understand its function, it is necessary to understand the flow of plastic melt in front of the screw. When the material in front of the screw reaches sufficient pressure, it forces the still-turning screw rearward. The screw continues to turn, but it is forced rearward until it reaches a predetermined set point, called the shot size, which determines how much plastic melt will be allowed to advance in front of the screw. At this set point, the screw stops turning. The next step in the process is for the screw to move forward at a controlled rate of speed and pressure. As the screw moves forward it does not turn, and its plunger-like action forces the plastic melt into the mold. During this forward plunger action, it is critical that the plastic melt in front of the screw not be allowed to flow rearward, back over the screw. To prevent this from happening, a check valve seals off, preventing the plastic melt from moving forward and rearward. (Muccio E.A, 1994)

## **Screw Diameter**

One of the most overlooked aspects of the injection screw is the area reduction associated with the diameter of the screw and the tip of the screw. Regardless of whether a check valve is used, the diameter of the screw and screw tip is significantly less than the area of the rear hydraulic cylinder where pressure is applied. Depending on the screw diameter and tip design, most screws have approximately a 10-to-1 reduction in area between the hydraulic cylinder and the screw diameter. This area reduction increases the effective injection pressure to a level 10 times that of the hydraulic pressure applied to the rear of the screw. (Muccio E.A., 1994)

# **Screw Rotation**

On most injection molding machines, the screw rotational speed is capable of being varied so as to suit a particular material/machine combination.

#### **Screw Decompression**

After the screw has been forced back by the melt which it has produced, there will be some residual pressure remaining in the melt. By drawing the screw back a controlled distance, this residual pressure can be relieved and the need for complex shut-off nozzles may be eliminated. The ability to decompress the melt is extremely useful and is now considered by many molders to be an essential feature. (Whelan A., 1982)

## Hopper

Hopper is the part where the granules are fed. It is connected to the injection unit from barrel. All of the feeding in injection molding is made from the hopper.

# **Barrel Capacity**

The capacity of injection molding machine is the maximum volume of the material that can be injected each time the screw or ram moves forward during a cycle of operations. Capacity of injection molding machine is usually rated with ounces before and nowadays with grams. In the plastic industry it is customary to rate injection molding machines in terms of the weight of polystyrene that the machine can inject with one stroke of the screw or ram. It is unlikely that 100% of the injection unit capacity would be used. 70 to 90% of the capacity is suggested to be used for the shot size of a particular mold. Less than 70% will allow the plastic to reside too long in the injection unit which may result in thermal degradation of the plastic. Using over 90% of the capacity may leave insufficient material for process adjustments and for cushion. (Muccio E.A., 1994)

#### **Residence** Time

Residence time is the time it takes a plastic pellet to journey from the hopper, where it enters the barrel of the injection unit, then to the nozzle, where it exits the barrel. Residence time is so important that if the plastic spends too much time in the heated barrel, it may degrade, resulting in a change of appearance, a reduction in properties, or both.

#### **The Heating System**

The number of zones, into which the barrel has been divided for heating purposes, is usually given on machine specifications. As each zone is associated with a temperature controller, it is important to check, when comparing different machine specifications, that each machine has the same number of zones as temperature control systems can be expensive. The temperature of the barrel is raised by means of heater bands and as different types are available, it is again worthwhile checking that one is comparing like with like. Ceramic heater bands will probably be the most expensive, but with any heater band, the cost also depends on the heating capacity of that particular band. (Whelan A., 1982)

# The Nozzle

The nozzle is the extension on the discharge end of the barrel that allows the plastic melt to exit the barrel and enter the mold through the sprue bushing. It may be one piece in design, or it may have a removable tip to facilitate cleaning and material changeovers. The injection unit is held again the sprue bushing by the action of the hydraulic cylinder that maintains pressure on the sled that supports the injection unit. The alignment of the nozzle is controlled by the alignment of the injection unit and the sled on which it rides.

The nozzle must be properly matched and aligned to the sprue bushing. Otherwise, plastic will leak from between the nozzle and sprue, and the process will deteriorate. The radius of the nozzle tip and the hole through which the plastic melt is injected must conform to the radius and hole of the sprue bushing.

A reverse tapered nozzle shown in Figure 2.6 provides a slightly widening orifice to facilitate removal of solidified plastic material from the tip. This configuration is suggested for some semicrystalline plastic materials such as nylon that have a tendency to freeze off. (Muccio, 1994)



Figure 2.6 Nozzle tip configurations a) Straight taper b) Reverse taper (Muccio, 1994)

When pressure is applied to the plastic material, to force it from the barrel into the mold, then some of the pressure works in such a way as to force the nozzle away from the sprue bush. To combat this separating force, a counter-force must be applied. This is the nozzle contact force and it is usually expressed in tonnes, tons or kilonewtons. (Muccio, 1994)

# **Sprue Break**

Sprue break is measured in inches or millimetres and specifies how far the injection unit can be withdrawn or moved away from the mold. There are two sprue breaks; an operating sprue break and a maintenance sprue break. The operating sprue break is used during machine operation and is normally set to a minimum value so that time is not lost by making the injection carriage move more than absolutely necessary. The setting of this small sprue break may be over-ridden so that, for example, the injection carriage may be withdrawn further away from the mold so as to assist in nozzle cleaning or a heater band change. A large sprue break facility is always useful as it can ease maintenance and simplify the installation of extended nozzles. (Whelan A., 1982)

#### 2.1.4.2 The Clamping Unit

The clamping unit of an injection molding machine shown in Figure 2.7 has one main purpose; to keep the mold closed under sufficient pressure during the injection of the plastic melt to prevent any plastic from escaping.

# **Clamping Pressure**

The clamp tonnage required to keep the mold closed during the injection stage is determined by the type of the mold, the mold size and the projected area of the mold (the total surface area of the mold that will be exposed to plastic, as seen through the plane of the parting line of the mold). (Muccio E.A., 1994)

# The Toggle Clamping Mechanism

It clamps the mold using a mechanical advantage developed through a series of linkages. As the linkages are forced into a straight or closed position by the action of a hydraulic cylinder on a crosshead, the tie bars strain or stretch and clamping forces are developed. Some of the advantages of toggle mechanism are their fast motion, low oil flow requirements and positive clamping action with no bleed off or pressure loss. In addition, the toggle mechanism only transmits its maximum closing force when the system is fully extended.



Figure 2.7 Clamping unit with a toggle mechanism (Osswald, et al., 2002)

#### The Clamp Stroke

The clamp stroke is also known as the opening stroke and it is given in either inches or millimeters. It is the maximum distance over which the moving platen can be made to move and although a large opening stroke is desirable, it must not be forgotten that this stroke must be capable of being easily reduced if a shallow component is being molded. (Whelan A., 1982)

# **Clamp Speeds**

The mold opening and closing speeds should be capable of independent adjustments so that ideally any speed at any point within the stroke can be obtained. Such an ideal flexibility of setting is not often obtained because of practical difficulties. However, the final mould movements should be slow or cushioned so that mold or component damage is avoided. (Whelan A., 1982)

## **Tie Bar Clearance**

The clearance between the tie bars determines whether or not a mold can be accommodated in that particular machine.

# **The Platens**

Platens are the massive cast steel plates that support the clamping system and the mold. They are machined with a specific pattern of holes that allow the molds to be easily located and mounted. There are two platens; the stationary platen is used to align the center of the mold with the center of the platen and ultimately, the injection unit. The moving platen has a number of strategically located through holes. These are designed to allow knockout bars to pass from the rear of the platen, where they are actuated by a hydraulic cylinder. The knockout bars enter the mold base and bump or push the mold's ejector system forward to eject the plastic parts. (Muccio E.A., 1994)

#### Daylight

It is the amount of space between the platens.Maximum daylight is the maximum distance between the platen surfaces when the clamp system is fully opened. Minimum daylight is the minimum distance between the platen surfaces when the movable platen is fully forward without a mold mounted.

#### 2.1.4.3 Mold Cavity

The central point in injection molding machine is the mold. The mold distributes polymer melt into and throughout the cavities, shapes the part, cools the melt, and ejects the finished product. During mold filling, the melt flows through the sprue and is distributed into the cavities by the runners. If the runner system is symmetric then all the cavities fill at the same time and cause the polymer to fill all cavities in the same way. The disadvantage of this balanced runner system is that the flow paths are long, leading to high material and pressure consumption. On the other hand, the asymmetric runner system leads to parts of different quality. Equal filling of the mold cavities can also be achieved by varying runner diameters. There are two types of runner systems- cold and hot. Cold runners are ejected with the part, and are trimmed after mold removal. The advantage of cold runner is lower mold cost. The hot runner keeps the polymer at or above its melt temperature. The material stays in the runners system after ejection and is injected into the cavity in the following cycle. Although a hot runner system considerably increases mold cost, its advantages include elimination of trim and lower pressures for injection. A pin-type gate is a small orifice that connects the sprue or the runners to the mold cavity. The part is easily broken off from such a gate, leaving only a small mark that usually does not require finishing. Other types of gates are film gates, which are used to eliminate orientation and disk or diaphragm gates, which are used for symmetric parts such as compact discs. (Osswald, et al., 2002)

#### 2.1.4.4 The Injection Molding Process

#### **Barrel Temperature**

Depending on the size and design of the injection unit, there may be three to five distinct zones to control. If there are five zones, the middle zone may have a temperature setting 10 <sup>0</sup>C higher than that of the feed zone and the temperature of the front zone will be set approximately equal to the desired melt temperature of the plastic being processed. The nozzle's temperature is highest because of keeping the plastic melted. (Muccio E.A., 1994)

Barrel temperature influences the orientation, degradation and viscosity of the melt.

#### **Injection Pressure**

It is also called pack pressure, high pressure, boost pressure and first stage pressure. Basically stated, it is the pressure generated by the screw tip on the plastic melt (the pressure used to pack the mold cavity once it has been filled). There is a hydraulic pressure continuum from the screw through the plastic in the mold. Until this pressure is generated, the only pressure on the plastic melt is associated with its resistance as it fills the mold (Muccio E.A., 1994).

Injection pressure influences the surface quality, orientation and mechanical stressing of the melt, therefore, excessive pressure should be avoided.

#### **Holding Pressure**

It is also called hold pressure or second stage pressure. As its name implies, holding pressure is used to maintain the cavity pressure after the cavity has been packed with plastic. During the time the holding pressure is in effect, the gate cools sufficiently to prevent any plastic from exiting the cavity. Because the plastic material shrinks as it cools, the pressure in the cavity begins to decrease, so the holding pressure can be lower than the injection pressure. (Muccio E.A., 1994)

Holding pressure should be set just enough in order to prevent voids, sink marks and control shrinkage.

#### **Mold Temperature**

Cavity surface temperatures are the temperatures which often would be essentially the same as the temperature of the circulating water or other fluid used to control the mold temperature. Higher mold temperatures delay freezing to facilitate filling long, thin sections. They also encourage greater crystallization of the semicrystalline resins, which affects both mechanical properties and shrinkage or dimensions. Accurate temperature control of the mold cavity walls is important and has a direction influence on the production of quality molded parts

#### **Cooling Time**

Cooling time is the major portion of the total molding cycle. The cooling requirements are dependent on the part thickness and the level of filler in a composite. Glass fiber reinforced composites will cool faster than unfilled compounds due to the higher thermal diffusivity of these materials.

# **Screw Speed**

The screw speed is usually controlled by a hydraulic motor, and most general purpose screws can be operated satisfactorily up to about 100 rpm but with common low melt viscosity nylons, higher screw speeds may produce nonuniform melt temperatures or even unmelted particles. In general, it is beneficial to rotate the screw only as fast as necessary to fit within the available cooling time in the molding cycle.

#### 2.1.4.5 The Injection Molding Cycle

The cycle shown in Figure 2.8 begins when the mold closes, followed by the injection of the polymer into the mold cavity. Once the cavity is filled, a holding pressure is maintained to compensate for material shrinkage. In the next step, the screw turns, feeding the next shot to the front of the screw. This causes the screw to retract as the next shot is prepared. Once the part is sufficiently cool, the mold opens and the part is ejected. The total cycle time can be calculated using

$$t_{\text{cycle}} = t_{\text{closing}} + t_{\text{cooling}} + t_{\text{ejection}}$$
(1)



Figure 2.8 Injection Molding Cycle (Osswald, et al., 2002)

Glass fiber reinforced nylons are used where the components must have a higher heat distortion temperature, greater rigidity and dimensional stability than that offered by the unreinforced material. Glass fiber reinforced nylons need higher injection pressures, barrel temperatures and mold temperatures than the unfilled grades. Cycles may be shorter as the parts can be ejected at higher temperatures.

#### 2.1.5 General Effect of Orientation and Crystallinity on Properties

# 2.1.5.1 Effect of Molecular Orientation

Polymer molecules in their normal or unstressed state exist as coiled, intertwined chains; as pressure and therefore stress is applied to the polymer melt (the material is at its processing temperature), the long chain macromolecules are stretched in the flow direction. This stretching or distortion is referred to as orientation and it is important for polymers simply because polymer molecules are so incredibly long. (Whelan A., 1982)

In injection molding, the molecules are not given sufficient time and so complex relaxation cannot occur. The residual orientation is sometimes called 'frozen-in-strain' or a 'frozen-in-stress'.

There are three mechanisms that lead to high degrees of orientation in injection molded parts which are fountain flow effect, radial flow and holding pressure induced flow.

The fountain flow effect is caused by the no-slip condition on the mold walls, which forces material from center of the part to flow outward to the mold surfaces. As figure 2.9 shows, the melt that flow inside the cavity freezes upon contact with the cooler mold walls. The melt that subsequently enters the cavity flows between the frozen layers, forcing the melt skin at the front to stretch and unroll onto the cool wall where it freezes instantly. The molecules that move past the free flow front are oriented in the flow direction and laid on the cooled mold surface, which freezes them into place, yet allows some relaxation of the molecules after solidification. (Osswald, et al., 2002)



Figure 2.9 Flow and Solidification mechanisms through the thickness during injection molding (Osswald, et al., 2002)

Radial flow is the second mechanism that often leads to orientation perpendicular to the flow direction in the central layer of an injection molded part.

As figure 2.10 suggests, the material that enters through the gate is transversely stretched while it radially expands as it flows from the gate.



Figure 2.10 Deformation of the polymer melt during injection molding (Osswald, et al., 2002)

The flow induced by the holding pressure as the part cools leads to additional orientation in the final part. This flow is responsible for the spikes in the curves shown in figure 2.11.



**Figure 2.11** Shrinkage distribution of injection molded polystyrene plates (Osswald, et al., 2002)

As the polymer molecules are aligned more in one direction than they are in another, it would seem reasonable to assume that the strength properties are different in different directions. If tensile strength samples were cut in two directions at right angles to each other from an anisotropic plastic moldings, the strength parallel to the flow direction would be much higher than the strength measured perpendicular to the flow direction. In the parallel direction, the applied load would be sustained by main-chain bonds and a high tensile strength would result. (Whelan A., 1982)

When the samples cut from the other direction are tested then the applied load would be supported or resisted by much weaker bonds and the strength measured will be correspondingly lower.Whelan A., 1982)

If izod-charpy impact strength samples were cut from the same anisotropic plastics molding then the impact strength measured would also have been

different. Parallel to the flow direction, the impact strength would be very high. Perpendicular to the flow direction, the impact strength would be very low. (Whelan A., 1982)

# 2.1.5.2 Effect of Crystallization

As the molecules are packed closer together, crystallinity increases and this increases the rigidity and tensile strength. Transparency is obtained by keeping the size of crystal structures small. High levels of crystallinity in moldings lower the permeability to gases and liquids.

### 2.1.6 Fibers as Reinforcement

It is common to strengthen a matrix material with discontinuous fibers. Chopped fibers are the example for discontinuous fibers. The effectiveness of strengthening by discontinuous fibers depends upon the length of the fibers

#### 2.1.6.1 Fiber-Stress Theory

It is known that for a certain fiber content and fiber diameter, the strength of the composite increases as the fibers are made longer. This is due to the fact that the average tensile stress in a discontinuous fiber is always less than that in a continuous fiber. This average stress increases toward that of a continuous fiber when the fiber length increases. To better understand the relationship between fiber average tensile strength and fiber length, it is necessary to examine the load-transference mechanism in the composite. As a result of the difference of the strain in the fibers and the strain in matrix, shear stresses are induced around the fibers in the direction of the fiber axes. Plastic deformation may occur in the matrix or through the shearing of the fiber in tension. It is through this transferring of stress that the applied load can be distributed among the fibers and the matrix. (Vinson and Chou, 1975)

Figure 2.12 shows the variation of tensile stress in a fiber with its length. The maximum stress attainable in the fiber is the fiber tensile strength  $\sigma_{fu}$ . The minimum fiber length necessary for the tensile stress to build up to  $\sigma_{fu}$  is denoted as  $l_c$ , the critical fiber length. The critical fiber length can be found easily by considering the tensile and shear stresses;

$$L_{c}/D = \sigma_{fu}/2\tau$$
<sup>(2)</sup>

where D is the diameter of fiber,  $\sigma_{fu}$  is the tensile strength of fiber,  $\tau$  is the shear strength of either the matrix or the interface.

The length  $l_c/2$  is often referred to as the load transfer length. Z is the ratio of the area under the stress distribution curve over the length  $l_c/2$  to the area of  $\sigma_{fu}l_c/2$ . Then the average stress in fiber  $\sigma_f$  can be expressed as

$$\sigma_{\rm f=}\sigma_{\rm fu}(1-l_{\rm c}/2l) \tag{3}$$

The most important parameters affecting the mechanical properties of composite material are fiber content and fiber length. The fiber content is determined depending on the selected matrix material, while the fiber length is determined depending on the part of geometry to be produced. Fibers that are shorter than the critical fiber length will pull out from the matrix under tensile load. This causes poor mechanical properties and because of this pull out, full load transference is not realized. At the critical length both the fiber and the matrix will fracture along the same failure plane. Additional increase in fiber length will not increase the strength of the composite, since the failure will be the same as that experienced as shown in Figure 2.12. (Bigg, 1985)



Figure 2.12 Variations of fiber tensile stress with fiber length (Vinson and Chou, 1975)

For matrix materials with constant yield stress, Z=1/2, for matrix materials that show strain hardening behaviour, Z>1/2.

In Figure 2.13, it is shown that the tensile stress is zero at the fiber ends (x=0, x=1) and is a maximum in the centre of the fiber. The shear stress is a maximum at the fiber ends and fall almost zero in the center. These results show that there are regions at the ends of the fiber which don't carry the full load so that the average stress in a fiber of length is less than in a continuous fiber subjected to the same external loading conditions. The reinforcing efficiency decreases as the average fiber length decreases because a greater proportion of the total fiber length is not fully loaded.



Figure 2.13 Variation along the fiber of tensile stress in the fiber and shear stress at the interface according to Cox (Hull, 1987)

Z: 2 Cox showed that for an applied stress on the resin parallel to the fiber tensile stress along the fiber is given by

$$\sigma_{\rm f} = E_{\rm f} \, \epsilon_{\rm m} \left\{ \frac{1 - \cosh \beta(\frac{1}{2}l - x)}{\cosh \frac{1}{2}\beta l} \right\} \tag{4}$$

where

$$\beta = \left\{ \frac{2G_{\rm m}}{E_{\rm f} r^2 \ln (R/r)} \right\}^{\frac{1}{2}}$$
(5)

and 2R is the inter fiber spacing. Cox showed the shear stress at the interface by

$$\tau = E_{\rm f} \,\epsilon_{\rm m} \left\{ \frac{G_{\rm m}}{2E_{\rm f} \ln\left(R/r\right)} \right\}^{\frac{1}{2}} \frac{\sinh\beta(\frac{1}{2}l-x)}{\cosh\frac{1}{2}\beta l} \tag{6}$$

# **Fiber Length**

Fiber length is normally expressed as number average and weight average fiber length.

$$L_{n} = \frac{\sum N_{i} L_{i}}{\sum N_{i}}$$
(7)

$$L_{w} = \frac{\sum N_{i} L_{i}^{2}}{\sum N_{i} L_{i}}$$
(8)

where  $N_i$  is the number of fibers of length  $L_i$ .

## **Fiber Content**

The glass fiber content is normally expressed as volume or weight fraction.

$$V_{f} = \frac{W_{f} / \delta_{f}}{(W_{m} / \delta_{m}) + (W_{f} / \delta_{f})}$$
(9)

$$\mathbf{W}_{\rm f} = \frac{\delta_{\rm f} \, \mathbf{V}_{\rm f}}{\left(\delta_{\rm m} \, \mathbf{V}_{\rm m}\right) + \left(\delta_{\rm f} \, \mathbf{V}_{\rm f}\right)} \tag{10}$$

where V and W are the volume and weight fraction respectively,  $\delta$  is the density, f denotes the fiber and m denotes the matrix.



Figure 2.14 Average fiber length vs. fiber weight content (○, A L<sub>n</sub>; Δ, B L<sub>n</sub>; ●, A L<sub>w</sub>▲, B L<sub>w</sub>).(A: Containing 123D-10C glass fiber, B: Containing 173X-10C glass fiber) (Thomason, 2006)

Figure 2.14 shows that  $L_w$  and  $L_n$  decrease with glass fiber content and  $L_w$  is higher than  $L_n$ .

In the case of low fiber content in short fiber reinforced composites, the orientation distribution obtained from simulation is consistence that by the image processing method, however, the distribution cannot be predicted for high fiber content due to the effects of fiber interaction.

#### 2.1.6.2 Fiber Pull-Out

The two surfaces are held together by fibers which bridge the fracture plane. Kelly et., al. (1970) and Outwater and Murphy (1969), show that the work done in separating the surfaces makes a major contribution to the total energy of fracture. The basic principles can be understood by reference to the single fiber experiment in Figure 2.15. The fiber is embedded in the matrix over the length  $l_e$  If the shear strength of the interface is  $\tau$ , the tensile stress on the fiber required to produce bond breakage is determined to a first approximation by balancing the tensile and shear stresses, thus

$$\sigma \Pi r^2 = 2 \Pi r l_e \tau \tag{11}$$



Figure 2.15 Pull-out test a) Fiber embedded in resin, b) Typical variation of pullout stress with embedded length(Hull D., 1987)

When the tensile stress required for bond breakage is plotted against the embedded length  $l_e$ , there is a sharp cut-off due to fiber fracture before debonding as shown in Figure 2.15b. The critical fiber length depends on the strength of the bond. This technique can be used to measure  $\tau$  since  $l_{ce}=\sigma_f^*r/2\tau$  where  $\sigma_f^*$  is the fracture strength of the fiber. (Hull D., 1987)

#### 2.1.6.3 Fiber Fracture

During compounding of granule composites, fiber reinforced materials fracture. The first fracture increase with increasing fiber content. Extruder and injection screw speed, shear stress and pressure also contribute to fiber fracture. The second fracture takes place with melting and injection molding of granules. Due to the fiber content, which has an influence on the fracture mechanism, mechanical strength of the composites does not increase linearly with increasing fiber content. (Güllü, 2004)

For short fibers already parallel to the matrix flow, fracture will depend on the presence or absence of adhesion. Fiber ends play an important role in the fracture of short fiber composites and also in continuous fiber composites since the long fibers may break down into discrete lengths.

In tensile experiments, the fracture mechanism can take place in three steps; crack initiates at fiber ends, cracks propagate in the matrix along the interface, thus leaving a thin layer of matrix material adhered to the fiber (only in systems with poor fiber-matrix bonding does the interface itself all), matrix cracks grow from the interfacial cracks, possibly after generation of the matrix plastic deformation. (Horst and Spoormaker, 1996)



**Figure 2.16** Failure mechanism in a tensile experiment. Left: initiation of crack, Right: growth of crack. (Horst and Spoormaker, 1996)

#### 2.1.6.4 Fiber Orientation

In industry, short fibers are often preferable to long, continuous fibers. Theoretically, they don't provide the same mechanical properties as continuous fiber, but this difference may be minimized by careful control. In contrast to continuous fiber reinforced composites, the properties of short fiber reinforced composites greatly depend on the variable orientation distribution of fibers in plastic matrix, which provide an improvement in physical properties relative to those of the unfilled material. The properties of short fiber composite parts are highly dependent on the way the part is manufactured. As the resin or molding compound flows and deforms to achieve the desired shape, the orientation of the fibers is changing. Fiber orientation changes stop when the matrix solidifies and the orientation pattern become part of the microstructure of the finished article.

One of the ways of aligning an initially random array of fibers is convergent flow as shown in Figure 2.17 and 2.18. It is useful to calculate the minimum change of velocity or change of shape necessary to produce a given degree of orientation and it is convenient to think of the flow as extrusion. The additional shear to convergent flow causes misalignment rather than improved alignment. (Parratt, 1972)



Figure 2.17 Orientation by extrusion (convergent flow) (Parratt, 1972)



Figure 2.18 Observed effect of convergent flow, followed by shear flow (Parratt, 1972)

## **Fiber Orientation Factor**

The orientation of fiber is considered as two-dimensional (Yamada, 1984). Fiber orientation is in the range of  $0 \le \Theta < \Pi$ . The function J which expresses the distribution  $q(\Theta)$  of fiber orientation angles as it follows:

$$q(\theta) = \pi^{-1} \left[ \frac{(1-J)\cos^2 \theta}{1+J} + \frac{(1+J)\sin^2 \theta}{1-J} \right]^{-1}$$
(12)

where J is the orientation function

$$J = 2 \int_{-\pi/2}^{\pi/2} \cos^2 \theta \, q(\theta) \, \mathrm{d}(\theta) - 1 \tag{13}$$

If J=0, it means random orientation. If J=1 or -1, it means unidirectional orientation for the x- or y-direction, respectively.

Figure 2.19 shows fiber orientation state for an injection molded product. Fiber orientation angle  $\Theta$  is measured in a clockwise sense on the basis of flow direction, being called the ratio of fiber total length having some angle  $\Theta$  and the total length of the measurement region is the relative fiber length for  $\Theta$ .



Figure 2.19 Fiber orientation state of a rectangular-shaped part after injection molding (fiber content %50 weight) (Kim et al., 2001)

## **Fiber Orientation Distribution**

Flow of a fiber suspension during injection molding results in a preferential orientation of short fibers which is frozen into the matrix as the composites solidified. As shown in Figure 2.20, during injection molding, shear dominated flow near the surface tends to align the fibers along the flow (shell region), whereas if the flow is extensional in the plane of the part, the fibers near the mid-plane of the cavity tend to align transverse to the flow (core region). (Gupta and Wang, 1993)



Figure 2.20 Gupta and Wang carried out simulation and experimental verification on the fiber orientation of short fiber reinforced composites (1993)

# **Rule of Mixtures**

A rule of mixtures has been formulated to express the dependence of the modulus on the fraction of the constituent phases. This rule is given as two equations that bound the modulus. They are given as:

a) Upper bound (longitudinal loading for aligned fibers)

$$E_{c}(u) = E_{m}V_{m} + E_{f}V_{f}$$
(14)

b) Lower bound ( transverse loading for aligned fibers)

$$E_{c}(l) = E_{m}E_{f} / (V_{m}E_{f} + V_{f}E_{m})$$

$$(15)$$

where; E= modulus, V= volume fraction, m= matrix phase, f = fiber phase and c= composite phase.

The effect of orientation is shown in Figure 2.21



Figure 2.21 The design method and applications of short fiber reinforced rubber composites. (Lee, 1996)

# **Prediction of Composite Strength**

Kelly-Tyson model which has been adapted by Lunt and Shortall(1979) through addition of a fiber orientation factor K for the prediction of the strength of the composite reinforced with misaligned short fibers is well known as

$$\boldsymbol{\sigma}_{c} = K \left( \sum_{L_{f}=0}^{L_{i}=L_{c}} \left( \frac{V_{i} \tau_{I} L_{i}}{d} \right) + \sum_{L_{f}=L_{c}}^{L_{f}=\infty} \boldsymbol{\sigma}_{f} V_{j} \left( 1 - \frac{L_{c}}{2 L_{j}} \right) \right) + \left( 1 - V_{f} \right) \boldsymbol{\sigma}'_{m}$$
(16)

where  $\sigma_c$  is the theoretical composite strength, K is the fiber orientation factor, V<sub>i</sub> is the volume fraction of fibers below critical length,  $\tau_I$  is the interfacial bond strength, d is the diameter, L<sub>c</sub> is the critical fiber length,  $\sigma_f$  is the tensile strength of the glass fibers, V<sub>j</sub> is the volume fraction of fibers above critical length, V<sub>f</sub> is the volume fraction of fibers  $\sigma'_m$  is the stress carried by the matrix at the fiber failure strain. The first term in the curly brackets is the contribution of the subcritical fibers and the second term that of the super-critical fibers. The final term is the matrix contribution. (Eriksson, et al., 1996)

#### 2.1.6.5 Fiber Damage in Injection Molding

Fiber damage or fiber attrition during injection molding is present where normally high shear stresses are present. As the polymer is melted and pumped inside the screw section of the injection molding machine and as it is forced through the narrow gate, most fibers shorten in length, reducing the properties like stiffness and strength of the final part.



Figure 2.22 Fiber in compression and tension as it rotates during simple shear flow (Osswald, et al., 2002)

Figure 2.22 helps explaining the mechanism responsible for fiber breakage. The figure shows two fibers rotating in a simple shear flow fiber 'a', which is moving out of its 0-degree position, has a compressive loading and fiber 'b', which is moving into its 0-degree position, has a tensile loading. It is clear that the tensile loading is not large enough to cause any fiber damage, but the compressive loading is potentially large enough to buckle and break the fiber. A common equation exists that relates a critical shear stress,  $\tau_{crit}$ , to elastic modulus  $E_{f}$ , and to the L/D ratio of the fibers

$$\tau_{\rm erit} = \frac{\ln(2L/D) - 1.75}{2(L/D)^4} E_f$$
(17)

where  $\tau_{\text{crit}}$  is the stress required to buckle the fiber. When the stresses are greater than  $\tau_{\text{crit}}$ , the fiber L/D ratio is reduced. Figure 2.23 shows a dimensionless plot of critical vs. L/D ratio of a fiber computed using equation 17.

It is worth pointing that although equation 17 predicts L/D ratios for certain stress levels, it doesn't include the uncertainty that leads to fiber L/D ratio distributions that is very common in fiber-filled systems.



Figure 2.23 Critical stress,  $\tau_{crit}$ , versus L/D ratio (Osswald, et al., 2002)

Figure 2.24 shows that, most of the fiber damage occurs in the transition section of plasticating screw during injection molding. Lesser effects of fiber damage were measured in the metering section of the screw (Thieltges, 1992) and in the throttle valve of the plasticating machine The damage observed in the mold cavity was marginal. The small damage observed inside the mold cavity, however, is great of importance because the fibers flowing inside the cavity underwent the highest stresses, further reducing their L/D ratios.



**Figure 2.24** Fiber damage measured in the plasticating screw, throttle valve, and mold during injection molding of a polypropylene plate with 40% fiber content by weight (Thieltges, 1992)

Another mechanism responsible for fiber damage is explained in Figure 2.25 where the fibers that stick out of partially molten pellets are bent, buckled and sheared-off during melting.



Figure 2.25 Fiber damage mechanism of the interface between solid and melt (Thieltges, 1992)

#### **2.2 Experimental Studies**

Rosato (1996), studied the injection molding of high performance reinforced plastic composites.

It was concluded that, with proper adhesion or bond between fibers and resin matrix, maximum performance was achieved. However, commercially the higher performance was overwhelmingly achieved with long or continuous fibers as shown in Figure 2.26.



Figure 2.26 Effect of fiber length on reinforced plastic strength (Rosato, 1996)

Using different injection molding machines with different modifications such as using free flowing nozzle valve, large runner size and shape, nonrestrictive/larger gates and proper location of gates, reduced viscosity of the melt entering the mold, thus reduces the shear, which in turn reduces the fiber damage. This free-flow action from the hopper to the mold cavity results in 30% higher overall mechanical properties with up to 30-50% more fiber lengths when compared to standard restrictive type screw.

Dave and Chundury (1997) studied the effect of injection molding conditions on the properties of filled and reinforced polypropylene.

The design of experimental approach was used to identify key injection molding process parameters, which improved the 'performance-property'

characteristics for polyolefin-based filled and reinforced products. A commercial design and analysis software was used for this study.

The products selected for their study were homopolymer polypropylene compounded with the following reinforcing agents: a) glass fiber, b) calcium carbonate, c) talc, based compounds.

The results showed that the most significant effect on the tensile and flexural strength properties of these materials were barrel temperature, mold temperature, injection speed and screw speed. A higher mold temperatures resulted in better flow of the polymer melt (of the outer layer) in the mold cavity. This change in mold temperature and flow behavior had been shown to have a significant influence on tensile strength as shown in Figure 2.27. The effect was most likely due to a change in the degree of fiber orientation or base polymer crystallinity. Increases in injection speed and screw speed are likely to result in a greater breakage of the glassfiber in the extruder section of the machine and resulted in the loss in physical properties like shown in Figure 2.28.



**Figure 2.27** Optimized tensile strength for barrel and mold temperature (<sup>0</sup>F) of glass fiber reinforced PP. (Dave and Chundury, 1997)



Figure 2.28 Effect of injection speed and screw speed on the tensile strength of glass fiber reinforced PP (Dave and Chundury, 1997)

Kim, et al. (2001) studied the distribution of fiber orientation by the image processing method for injection molded products in which fiber content was measured and numerical analysis for orientation distribution was conducted, the orientation distribution by numerical simulation was compared with the results obtained from image processing.



Figure 2.29 Fiber orientation distribution for a fiber content of 30 weight%, a) soft X-ray photograph; b) fiber orientation by image processing, c) fiber orientation by mold flow (Kim, et al., 2001)



Figure 2.30 Fiber orientation distribution for a fiber content of 70 weight%, a) soft X-ray photograph; b) fiber orientation by image processing, c) fiber orientation by mold flow (Kim, et al., 2001)

In this study, the result of fiber orientation distribution obtained by the numerical simulation was consistent with that obtained from the image intensity method for low fiber content as shown in Figure 2.29. However it was not consistent that when increasing the fiber content, due to the effects of fiber interaction as shown in Figure 2.30

Zainudin, et al. (2002) studied fiber orientation of short fiber reinforced injection molded thermoplastic composites. In this study it was shown that fiber orientation distribution was played an important role, which affected the properties of short fiber reinforced composite parts.

As a result of this study, it was found that orientation in short fiber reinforced composites was affected in a complex manner by various parameters of processing condition and material properties. Advanced improvements in property could be accomplished if methods could be developed to ensure that the fibers were placed in the most appropriate way. Mallick, et al. (2002) studied the effects of temperature and strain rate on the tensile behavior of short fiber reinforced Polyamide-6. Tensile behavior of extruded short E-glass fiber reinforced Polyamide-6 composite sheet was determined at different temperatures and different strain rates. The results are given in Tables 2.4 and 2.5

The material used in this study was a short E-glass fiber reinforced Polyamide-6. The fiber content in this composite was 33% by weight.

Strain Rate (min <sup>-1</sup> )	Temp. (°C)	Elastic Modulus E (GPa)	Tensile Strength v <sub>e</sub> (MPs)	Failure Strain E <sub>6</sub> (%)	Stress Exponent n	Stress Coefficient o* (MPa)
0.05	21.5	14.68	111.8	2.330	1.022	118.8
0.5		15.79	122.3	2.222	1.056	132.0
5		16.99	132.0	2.116	1.057	138.6
0.05	50	5.067	83.68	4.664	1.094	87.11
0.5		5.226	89.65	5.717	1.049	94.31
5		5.472	98.35	6.073	1.058	101.6
0.05	75	4.175	71.92	5.526	1.067	70.60
0.5		4.340	76.38	5.977	1.068	77.20
5		4.651	78.78	6.129	1.074	79.60
0.05	100	3.441	63.44	4.675	1.065	58.71
0.5		3.631	65.97	4.758	1.025	62.90
5		3.711	71.71	6.103	1.024	64.81

**Table 2.4** Experimental results on tensile properties of short fiber reinforcedPolyamide-6 in extrusion direction (Mallick, et al., 2002)

Strain Rate (min <sup>-1</sup> )	Temp. (°C)	Eleatic Modulus E (GPa)	Tensile Strength ՄԵ (MPa)	Failure Strain e <sub>b</sub> (%)	Stress Exponent	Stress Coefficient o* (MPa)
0.05	21.5	4.625	56.84	6.711	0.9658	53.01
0.5		6.191	70.90	4.804	0.9226	71.81
5		7.028	73.06	5.737	0.9531	75.38
0.05	50	1.074	40.97	18.25	0.9388	41.46
0.5		1.243	42.59	19.45	0.9341	43.66
5		1.370	44.61	18.81	0.9480	45.35
0.05	75	0.6891	35.81	15.57	0.9577	33.20
0.5		0.7501	34.73	18.23	0.9502	35.44
5		0.8279	35.43	23.63	0.9157	36.69
0.05	100	0.5912	25.79	16.21	0.9749	23.61
0.5		0.6086	28.24	19.14	0.9639	27.98
5		0.6556	30.30	22.08	0.9629	30.43

**Table 2.5** Experimental results on tensile properties of short fiber reinforcedPolyamide-6 normal to the extrusion direction (Mallick, et al., 2002)

Experimental results showed that this composite was a strain rate and temperature dependent material. Both elastic modulus and tensile strength of the composite increased with strain rate and decreased with temperature. Güllü, et al. (2004) studied the influence of silane coated glass fibers added to polypropylene and polyamide-6 plastics. To determine the mechanical properties and effects of glass fibers, polyamide-6 materials were reinforced with 15 and 30 weight% glass fibers.

In this study, the most important parameters having influence on tensile strength and impact energy were found to be average fiber length and fiber length distribution. Glass fiber reinforcement increased the tensile strength value. It was observed that fiber reinforcement had different mechanisms on impact energy. Depending on the fiber length in the composite, increasing fiber length improved the tensile strength and increasing fiber fracture improved the impact energy value. With increasing injection speed, fiber fracture increased and the fibers were oriented perpendicularly to the flow direction. Tensile strength decreased and impact energy increased with increasing injection speed and injection unit screw speed.

Thomason (2004) studied the mechanical performance of injection molded long fiber reinforced polypropylene with a glass fiber content in the range 0-73 weight %. The level of fiber matrix interaction was increased by adding coupling agent. In this study of the mechanical performance of injection molded long glass fiber reinforced polypropylene, it was found that composite modulus increased linearly with fiber volume fraction over the whole range of the study. However, both strength and impact performance exhibit nonlinear dependence on the fiber content. Both the strength and notched impact performance showed a maximum performance in the 40-50 weight % fiber content range. At higher fiber content, these properties decreased significantly and approached the unreinforced polypropylene performance at the highest fiber content of 73 weight %. The residual fiber length in these injection molded composites decreased linearly with increasing fiber content.

Thomason (2006) studied the performance of the injection molded glass fiber reinforced polyamide-66 with glass content between 0 and 40% and based on two chopped glass products both sized with polyamide compatible sizing. This study of the 'dry as molded' performance of injection molded glass fiber reinforced polyamide-66 had revealed that the modulus of these moldings increased linearly with fiber content between 0 and 40 weight %. Excellent agreement between the experimental data and the theoretical data over the range of concentrations was obtained.

In terms of tensile and flexural strength, a linear relationship was obtained at lower glass contents. However, at higher glass contents, deviations from linearity appeared. Both notched and unnotched izod impact resistance increased with glass content in 10-40 weight %. Using values for the interfacial strength and fiber average orientation in the Kelly-Tyson equation, it was possible to obtain an excellent fit between calculated composite strength and the experimental data.

# **CHAPTER III**

# **EXPERIMENTAL**

The effects of injection molding processing conditions on mechanical properties and on the average fiber length of Polyamide / glass fiber composites were determined by twenty-five experimental runs. 30% glass fiber reinforced Nylon-6 was used in this study.

Fiber length measurements were carried out for all experimental runs.

These experimental runs were based on injection molding parameters of barrel temperature, injection pressure, hold pressure, mold temperature, cooling time and screw speed.

This study has a basis of industrial relevance. The machinery, and the materials are used in industry. For compounding; twin screw extruder was used, then for mechanical tests, test specimens were prepared by injection molding. Glass fiber reinforced Nylon-6 was used for this study because of its potential in automotive and electrical applications.

# **3.1 Materials**

The material used in this study is 30% glass fiber reinforced Polyamide-6.

Polyamide-6 ( with a trade name of Akulon K125, obtained from DSM, Holland) and chopped glass fiber strands (with a trade name of PA1, obtained from Cam Elyaf, Turkey) were compounded by an extruder.
The properties of Polyamide-6 and glass fiber can be seen in Tables 3.1 and 3.2.

Properties	Unit	Test	Value
		Method	
Density	g/cm <sup>3</sup>	ISO 1183	1.13
Relative Viscosity	-	ISO 307	2.8
Melting Temperature	°C	DSC	220
Tensile Strength	MPa	ISO 527	67
Tensile Modulus	MPa	ISO 527	2778
Elongation at Break	%	ISO 527	70
Notched Izod Impact Strength	kJ/m <sup>2</sup>	ISO 180 A	5.8

 Table 3.1 Properties of Polyamide-6, Akulon K125

Table 3.2 Properties of Glass Fiber, PA1

Properties	Unit	Value
Glass Type	-	E
Fiber Diameter	μ	13.5
Moisture Content	%	Max. 0.07
Fiber Length	mm	4.5
Coupling Type	-	Silane
Coupling Amount	%	0.65±0.15

#### **3.2 Experimental Apparatus**

#### 3.2.1 Compounding Apparatus (Compounding Line)

Compounding of Polyamide-6/Glass Fiber composite consists of an extruder and seven auxiliary equipments.

These are respectively; extruder, feeders, extrusion control unit, feeder control unit, heat exchanger, cooling bath, pelletizer, storage silo and bagging unit as shown in Figure 3.1. The extruder used for compounding is CoperionW&P 70 Mcc (900 rpm). (Figure 3.2)



Figure 3.1 Schematic diagram of extruder machine



Figure 3.2 Image of the extruder machine in Eurotec Company

## **3.2.2 Sample Preparation Apparatus**

## **Injection Molding**

Injection molding machine used for preparing specimens is Arburg 320 K 700-100. In engineering plastics industry, injection molding is used for obtaining the ISO standards for impact and tensile tests. Technical properties of the injection molding machine used in this study are shown in Table 3.3.

**Table 3.3** Technical Properties of Injection Molding Machine used in this study

Property	Unit	Value
Hopper Capacity (PS)	kg	5
Screw Diameter	mm	25
Injection Pressure	bar	2000
Motor Power	kW	18
Motor Speed (max)	rpm	1800
Screw Speed (max)	m/min	44
Clamping Force (max)	tons	70
Mould Dimensions (max)	mm	125 x 280 x 174
Mould Dimensions (min)	mm	63 x 63 x 76



Figure 3.3 Schematic diagram of the injection molding machine



Figure 3.4 Image of the injection molding machine used in this study

Injection molding machine in this study is reciprocating screw type machine. It has a screw that rotates forward and fills the mold with molten plastic and holds the molten plastic under high pressure. The screw forces more molten plastic into the mold as required. The mold eventually becomes full and the plastic cools in the mold. This separates the cold plastic in the mold from the liquid plastic in the screw. The screw stops while the heater around the cylinder and the screw inside the cylinder melt more pellets. The mold then opens, typically in half, and the cooled solid plastic part is ejected as mold is closed again and prepared for the next shot of melted plastic.

## The Plasticating and Injection Unit

A plasticating and injection unit is shown in Figure 3.5. The major tasks of the plasticating unit are to melt the polymer, to accumulate the melt in screw chamber, to inject the melt into the cavity, and to maintain holding pressure during cooling. The main elements of the plasticating unit are; hopper, screw, heating bands, check valve and nozzle. The hopper, heating bands, and the screw are similar to a plasticating single screw extruder, except that the screw in an injection molding machine can slide back and forth to allow for melt accumulation and injection.

The hopper is the part of injection molding machine where the material was fed.

Heating bands are thought as a control valve that heats or cools the barrel, depending on the process requirements.

The check valve, or nonreturn valve, is at the end of the screw and enables it to work as a plunger type screw during injection and packing without allowing polymer melt back flow in to the screw channel.

The nozzle is the extension on the discharge end of the barrel that allows the plastic melt to exit the barrel and enter the mold through the sprue bushing.



Figure 3.5 Schematic of the plasticating unit and injection unit

### The Clamping Unit

The job of a clamping unit in an injection molding machine is to open and to close the mold tightly during filling and holding. The mechanism in this injection molding machine is toggle mechanism (Figure 3.6). which has an advantage that it only transmits its maximum closing force when the system is fully extended.



Figure 3.6 Schematic of the clamping unit with a toggle mechanism

#### The Mold

The central point in an injection molding machine is the mold. The mold distributes the polymer melt into and through out the cavities, shaping the part, cooling the melt, and ejecting the finished product.

Injection molding machine is fully computer controlled. The barrel temperature, injection pressure, hold pressure, cooling time, screw speed, material volume in the mold, continuous cycle or manual cycle are controlled by computer.

## Furnace

The furnace used in this study is NUVE MF120. It is used to obtain glass fiber content and samples for observing the fiber length by burning the polymer matrix at 750  $^{0}$ C.



Figure 3.7 Image of the Furnace used in this study

### 3.3 Sample Testing and Measurement



Figure 3.8 Image of the Impact Test machine used in this study

## **Impact Test**

Pendulum type testing machine, Ceast Resil Impactor is used to measure impact values of samples. Izod notched impact type experiment is applied to test specimens. It measures the energy consumed by the pendulum to break the sample. Specimen dimensions are 80 mm long, 10 mm wide and 4 mm thick. The notch depth is 2 mm. The sample is clamped vertically into position with the notch end facing the direction of the pendulum. The pendulum is released, allowed to strike the sample and swung through. The sample has to break completely in order for the data to be useful. An energy value is taken from the pendulum swung and divided by the sample thickness. Results are reported in kJ/m<sup>2</sup>.



Figure 3.9 Test Specimen Dimensions



Figure 3.10 Image of the Tensile Test machine used in this study

#### **Tensile Test**

Tensile values are measured by Tinius Olsen 25 KS testing machine (Figure 3.10). Sample dimensions are 154 mm long, 20 mm wide and 33 mm thick (Figure 3.9). The shape of this sample is dog-bone shape. The rationale for this shape is that it localizes the sample displacement in the gauge region for rigid samples. The tensile properties are generally measured at a constant strain rate of 0.5 min<sup>-1</sup>. For measuring tensile strength, the sample is placed in the grips of the testing machine. The grips are tightened strongly to prevent any slippage. The gauge length is 50 mm. An extension indicator is mounted on the machine to determine the distance between two designated points within the gauge length of the test specimen as it is stretched as a function of load or elapsed time form the start of the test or both. By this information, the elongation and modulus are found. The speed of the testing is set at the proper rate and machine is started. The load extension curve is recorded. The elongation of sample is continued until the sample breaks. The results for tensile strength, tensile modulus and elongation at break are obtained by the test program on the computer of this machine.



Figure 3.11 Image of the HDT test machine used in this study

## Heat Deflection Test, HDT

Heat deflection values are measured by Ceast -HDT 3 P/N 6911.000 test machine shown in Figure 3.11. This test measures the temperature at which a given sample will deform a specified amount under a prescribed load. The sample is the same type which is used in impact test. The sample is placed in a three-point bending fixture with supports 101.6 mm apart. The force is applied to the thickness side of the sample. The assembly is placed in an oil bath. The sample is then preloaded with the prescribed load. The oil medium is heated at a rate of 2 <sup>0</sup>C/min. While heating the sample, it begins to soften and deflect. The specified deflection is 0.33 mm. The temperature is recorded and reported as the sample's heat distortion temperature.



Figure 3.12 Image of the DSC test machine used in this study

## **Differential Scanning Calorimetry, DSC**

DSC values are measured by Perkinelmer -Pyris 6 DSC test machine shown in Figure 3.12. DSC measures heat flow of a sample. The measured heat flow shows a peak in the curve. 5 to 10 milligrams is sealed in a conductive span. The pan is placed inside a well-insulated oven. The temperature in the oven is programmed to heat or cool. After that, at transition points, more or less energy is required depending whether the transition is endothermic or exothermic. The melting point is endothermic where energy is absorbed. The crystallization point is exothermic where heat is given off. From  $\Delta H_f$  values which are displayed on the DSC graphs, the crystallinity (X<sub>c</sub>) is determined.



Figure 3.13 Image of the Viscosity test machine used in this study

## **Solution Viscosity Test**

Viscosity values were measured by Lauda Proline Pv24 test machine shown in Figure 3.13. Viscosity property determines whether a material can be used in a given manufacturing process; it establishes processing conditions; it classifies materials and aids in material development.

Before viscosity measurements, because of our material's containing glass fibers, firstly in a test tube, the material is dissolved by adding  $H_2SO_4$  in a test tube and mixed for 4 hours for homogeneous dispersion, then, in a centrifuge, glass fibers are precipitated and this solution then is filtered by the help of vacuum pump. After that, this filtered solution is put in viscometer by an injector, and the tube is put in test machine. The pipes from where the solution flows into Ubbelohde capillary are fixed. The water in the test machine is 25  $^{\circ}C$ . By the help of computer program, the test is started. At the end of the test, relative viscosity values are seen on the screen.

### **Fiber Length Measurement**

Prior B3000 laboratory microscope is used for fiber length measurement. It has a SLR camera connected to a computer for image analysis by the help of Image Pro-Plus program.

## **Determination of Fiber Length**

Firstly, a piece of injection molded test specimen is burned at 750 <sup>o</sup>C for 30 minutes. Small parts of ash samples from the recovered fibers of injection molded test specimens are transferred to a glass slide and dispersed in water. The slide is then placed on the microscope for measurement. For every sample, approximately 250 fibers are evaluated. A typical photograph is shown in Figure 3.14



Figure 3.14 Dispersed fibers removed from the matrix.

#### **3.4 Experimental Parameters**

The aim for this study is to study the effects of injection molding process parameters on the mechanical properties of Polyamide-6/glass fiber composites. Experiments are performed by changing one parameter while the other variables are kept constant. The process parameters used in this study are: Barrel temperature, injection pressure, hold pressure, mold temperature, cooling time, and screw speed. Totally 25 measurements are done for 30% glass fiber reinforced Polyamide-6. Then, to observe the effect of changes in injection molding process parameters on fiber length, and ashes are obtained from all measurements and fiber lengths are analyzed.

Totally 25 experimental runs are made investigating six process parameters. These are given in Table 3.4

The reference mid point for the experiments has the following values:

Barrel Temperature (<sup>0</sup>C): 240/245/250/255/260 Injection Pressure (bar): 1000/900 Hold Pressure (bar): 700/600/500 Mold Temperature (<sup>0</sup>C): 80

Cooling time (sec): 15

Screw Speed (rpm): 25

 Table 3.4 Experimental Runs for Injection Molding Process Parameters

Parameter	Code	Run #	Data
	3.a.1	-20	220/225/230/235/240
Barrel	3.a.2	-10	230/235/240/245/250
Temperature	3ref	T (ref)	240/245/250/255/260
( <sup>0</sup> C)	3.a.3	+10	250/255/260/265/270
	3.a.4	+20	260/265/270/275/280
	3.b.1	-400	600/500
Injection	3.b.2	-200	800/700
Pressure	3ref	P (ref)	1000/900
(bar)	3.b.3	+200	1200/1100
	3.b.4	+400	1400/1300
	3.c.1	-300	400/300/200
Hold	3.c.2	-150	550/450/350
Pressure	3ref	P (ref)	700/600/500
(bar)	3.c.3	+150	850/750/650
	3.c.4	+300	1000/900/800
	3.d.1	-40	40
Mold	3.d.2	-20	60
Temperature	3ref	T (ref)	80
( <sup>0</sup> C)	3.d.3	+20	100
	3.d.4	+40	120
	3.e.1	-10	5
Cooling	3.e.2	-5	10
Time	3ref	t (ref)	15
(sec)	3.e.3	+5	20
	3.e.4	+10	25
	3.f.1	-8	17
Screw	3.f.2	-4	21
Speed	3ref	V (ref)	25
(rpm)	3.f.3	+4	29
	3.f.4	+8	33

## **CHAPTER IV**

## **RESULTS AND DISCUSSION**

Injection molding is one of the most common manufacturing methods for shaping plastics. In order to determine the performance of a polymeric composite, the processing conditions of the injection molding process has to be based on the results of mechanical and thermal tests. In this study, interactions between the injection molding processing conditions, fiber length distribution, crystallinity and mechanical properties of the glass fiber reinforced Polyamide-6 were studied. Fiber length distribution and crystallinity data are used to understand the variation of mechanical properties of the products obtained after several experimental runs. Thus the number and weight average fiber length and crystallinity values were determined and reported. It is known that barrel temperature, mold temperature and cooling time have an important effect on crystallinity. Therefore, differential scanning calorimetric method was used to determine the crystallinity obtained under various processing conditions. Relative viscosity from molded parts were also determined, however no significant results were obtained so they were not emphasized during the study.

Accurate results for fiber length measurements were obtained by taking into account the fibers which have lengths greater than 30  $\mu$ . Fiber length distributions are shown in terms of histograms, where first range is set as 100  $\mu$ , and the other ranges are arranged set as 50  $\mu$ . For each experimental run the distributions and related property data are given in Appendix A1, Tables A1.1 to A1.25 and Figures A1.1 to A1.50. Fiber length histograms for each operating condition are also drawn as smooth curves in order to provide better visualization of the effect of operating conditions on fiber length distribution. These curves are given in Appendix A2.

Number average fiber length,  $L_n$ , and weight average fiber lengths,  $L_w$ , were calculated according to the following equations.

$$L_n = \frac{\sum N_i L_i}{\sum N_i}$$
(1)

$$L_{w} = \frac{\sum N_{i} L_{i}^{2}}{\sum N_{i} L_{i}}$$
(2)

 $L_n$  is an indicator of the occurrence of short fibers and  $L_w$  is an indicator of the occurrence of long fibers. Therefore, the value of  $L_w$  is always higher than the value of  $L_n$ . As the number of fibers measured in the sample increases, the probability of finding short fibers also increases and this causes  $L_n$  to attain a lower value.  $L_n$  and  $L_w$  would be equal if all fibers measured have the same length which is normally not possible. As  $L_w$  represents the intensity of long fibers in the examined sample, it is used to evaluate the results to have a better understanding on the properties of the composites.

 $L_n$  and  $L_w$  values for reference data after extrusion is 198  $\mu$  and 406  $\mu$  respectively.  $L_w$  value is approximately 10% of its initial value. Then, after injection molding,  $L_w$  value for reference data is about 179  $\mu$ . This is approximately 4% of its initial value. This means that fiber degradation continues by injection molding after extrusion.

Structurally, polymers in the solid state may be amorphous or crystalline. When polymers are cooled from the molten state, molecules are often attracted to each other and tend to come together as close as possible. In Polyamide 6, during some of the solidification, molecular chains are packed regularly in an orderly manner. The resulting solid is a semicrystalline polymer with three dimensional and ordered arrangement.

Crystalline structure of a polymer composite affects the mechanical properties. In this study, in order to understand the behavior that is mostly linked to temperature, DSC analysis were made and crystallinity results were calculated based on the given formulation.

$$\% \mathbf{X}_{c} = \frac{\Delta H_{f}}{\Delta H_{f(pure)} \times (1 - \frac{W_{f}}{100})} \times 100$$
(3)

# 4.1 Effects of Injection Molding Process Parameters on Fiber Length and Mechanical Properties

Injection molding is a manufacturing method in which the composite material is mixed and melted by a reciprocating screw with the help of heating bands and forced to flow through a narrow channel to fill out the mold to obtain the required shape. During this process, localized high shear stress and temperature variances occur. Polymers are non-Newtonian materials whose viscosity depends on both shear rate and temperature. A shear stress applied on the polymer melt not only causes a chain scission in the polymer molecule but also may lead to an increase in glass fiber degradation. On the other hand, when temperature increases melt viscosity decreases, which creates lower force acting between the glass fiber and the polymer matrix at the interface, therefore glass fiber degradation decreases. However care must be taken during the adjustment of temperature profiles to optimize the crystallization behavior of the final product. (Gupta, et al., 1989)

The major variables that are important for fiber length distribution and crystallinity can be given as cycle time, cooling time, barrel temperature, mold temperature, screw speed, injection pressure, hold pressure, back pressure, shot size, mold design, part design, glass fiber concentration and screw configuration.

High moisture content in Polyamide-6 leads to poor surface appearance and loss in mechanical properties. In order to overcome this problem, pellets were dried at 80 °C for 2 hours prior injection molding.

In this study 30% glass fiber reinforced Polyamide-6 was injection molded in a 70 ton machine with a screw diameter of 25 mm. These injection molded samples were kept in safekeeping containers. During experiments, barrel temperature, injection pressure, hold pressure, mold temperature, cooling time and screw speed were changed by keeping the other variables constant. The operating conditions of all experimental runs are given in Table 3.4. Reference data settings were adjusted according to the specifications of the composite provided by the producer. Minimum and maximum process data for each experiment is obtained in order not to have sink marks, short shots and excessive flashing on the molded parts.

### 4.1.1 Effect of Barrel Temperature

Final fiber length values are given in Table 4.1 for each barrel temperature setting. The detailed data are in Tables A1.2 to A1.5 and Figures A1.1 to A1.10.

Injection Molding Parameter		Exp. Code	L <sub>w</sub> μ	L <sub>n</sub> μ
	-20	3.a.1	174	140
Barrel	-10	3.a.2	183	140
Temp.	Ref	Ref	179	149
("C)	+10	3.a.3	182	147
	+20	3.a.4	188	153

**Table 4.1** Final fiber length values for barrel temperature setting



Figure 4.1 Effect of Barrel Temperature on Fiber Length

It is clearly observed from Figure 4.1, which shows the effect of barrel temperature on fiber degradation that average fiber length increases when barrel temperature is higher.

As the barrel temperature is increased, temperature of the polymer melt inside the barrel increases, thus the melt viscosity of the polymer matrix flowing inside the injection molding machine decreases. Lower viscosity results in lower force acting between the glass fiber and the polymer matrix at the interface, therefore glass fiber degradation decreases.

When  $L_n$  and  $L_w$  parameters are compared, it is observed that, they almost show the same trend where weight average gives a higher value with in comparison to number average.

As already mentioned, temperature has an effect on crystallinity of a polymer, thus it affects the mechanical properties. Dependence of crystallinity on barrel temperature is given in Figure 4.2.



Figure 4.2 Effect of Barrel Temperature on Crystallinity

It is observed from the Figure 4.2 that the reference temperature setting has the highest crystallization rate. Crystallization often has an activation time and can be a strong function of the cooling rate. The balanced difference between the temperature of the polymer melt and the constant mold temperature and cooling time to obtain highest crystallization is thought to be realized at the reference data. Below reference temperature, T(ref)-10 and T(ref)-20, polymer melt temperature was not high enough, however at T(ref)+10 and T(ref)+20 cooling time was not enough to have the right crystallization.

The average values of mechanical properties for various barrel temperature settings are summarized in Table 4.2. In this table,  $W_f$  shows the actual weight fraction of glass fibers after injection molding.

Dependence of mechanical properties on barrel temperature can be examined from Figures 4.3 to 4.8. It is obvious from Figure 4.3 that the impact strength value is highly dependent and directly proportional with the fiber length. Fiber ends are the points of stress concentration locations, which weaken the composite, so it is obvious that longer fibers produce stronger composite.

Long fibers are observed to affect the elongation at break,  $\varepsilon_b$ , negatively when Figure 4.4 is examined. It is known that fiber content and fiber length are inversely proportional with elongation at break.

Average fiber length values with tensile strength and tensile modulus of the glass fiber reinforced Polyamide-6 composite are presented in Figures 4.5 and 4.6 respectively. Results show that both strength and modulus is proportional to the fiber length in the sample. In order to understand the maximum level of value at reference point for both properties, equivalent graphs are prepared with crystallization ratios that are shown in Figures 4.7 and 4.8. It is clear that the maximum level of crystallization observed for the reference point resulted in higher tensile strength and modulus. As a result, it can be said that both fiber length and crystallization ratio have significant effect on tensile strength and tensile modulus.

Inje	ction						
Mol	ding	Exp.	a <sub>iN</sub>	σc	Eb	Ε	$\mathbf{W}_{\mathbf{f}}$
Para	neter	Code	kJ/m <sup>2</sup>	MPa	%	MPa	%
	-20	3.a.1	13.00	147.4	3.73	8934	29.45
Barrel	-10	3.a.2	13.21	148.9	3.69	8941	29.55
Temp.	Ref	Ref	13.31	153.6	3.53	9221	29.52
( <sup>0</sup> C)	+10	3.a.3	13.60	150.5	3.58	8985	29.67
	+20	3.a.4	14.01	151.7	3.56	9007	29.58

 Table 4.2 Final mechanical properties for barrel temperature setting



Figure 4.3 Dependence of Impact Strength and Fiber Length on Barrel Temperature



Figure 4.4 Dependence of Elongation at Break and Fiber Length on Barrel Temperature



Figure 4.5 Dependence of Tensile Strength and Fiber Length on Barrel Temperature



Figure 4.6 Dependence of Tensile Modulus and Fiber length on Barrel Temperature



Figure 4.7 Dependence of Tensile Strength on Crystallinity and Barrel Temperature



Figure 4.8 Dependence of Tensile Modulus on Crystallinity and Barrel Temperature

### 4.1.2 Effect of Injection Pressure

For each injection pressure setting, fiber length values are shown in Table 4.3. The detailed data are in Tables A1.6 to A1.9 and Figures A1.11 to A1.18

Table 4.3 Final fiber length values for injection pressure setting

Injection Molding Parameter		Exp. Code	$L_{ m w}$ $\mu$	L <sub>n</sub> μ
	-400	3.b.1	185	150
Injection Pressure (bar)	-200	3.b.2	182	145
	Ref	Ref	179	149
	+200	3.b.3	181	146
	+400	3.b.4	175	141



Figure 4.9 Effect of Injection Pressure on Fiber Length

During injection molding, molten material is forced to flow from the barrel through the nozzle, where excessive shear occurs. When injection pressure is increased the shear stress also increases and as already observed from Figure 4.9 average fiber length decreases.  $L_n$  and  $L_w$  values have similar decreasing trend when injection pressure is increased.

It is assumed in this study that injection pressure would have no significant effect on crystallinity so in this part of the study, the effect of fiber length effect was investigated on the mechanical properties. The average values of mechanical properties for various injection pressure settings are summarized in Table 4.4.

Dependence of mechanical properties on injection pressure can be seen from Figures 4.10 to 4.13. It is obvious from Figures 4.10 to 4.12 that the impact strength, tensile strength and tensile modulus are directly proportional to the fiber length. As fiber fracture occurs, mechanical properties are affected negatively. When Figure 4.13 is examined it can be concluded once again that in the presence of shorter fibers in composite, elongation at break increases.

<b>Table 4.4</b> Final mechanical properties for injection pressure setting	

Injection Paran	Molding neter	Exp. Code	a <sub>iN</sub> kJ/m <sup>2</sup>	σ <sub>c</sub> Mpa	Е <sub>b</sub> %	E MPa	W <sub>f</sub> %
	-400	3.b.1	14.32	155.1	3.66	9292	29.45
Injection	-200	3.b.2	14.06	154.8	3.68	9270	29.48
Pressure	Ref	Ref	13.31	153.6	3.53	9221	29.52
(bar)	+200	3.b.3	13.95	150.2	3.74	9027	29.44
	+400	3.b.4	13.72	148.3	3.77	9001	29.50



Figure 4.10 Dependence of Impact Strength and Fiber Length on Injection pressure



Figure 4.11 Dependence of Tensile Strength and Fiber Length on Injection Pressure



Figure 4.12 Dependence of Tensile Modulus and Fiber Length on Injection Pressure



Figure 4.13 Dependence of Elongation at Break and Fiber Length on Injection Pressure

### 4.1.3 Effect of Hold Pressure

Final fiber length values are given in Table 4.5 for each hold pressure setting. The detailed data are in Tables A1.10 to A1.13 and Figures A1.19 to A1.26.

Injection Molding Parameter		Exp. Code	L <sub>w</sub> μ	L <sub>n</sub> μ
	-300	3.c.1	178	147
Hold	-150	3.c.2	180	140
Pressure	Ref	Ref	179	149
(bar)	+150	3.c.3	180	143
	+300	3.c.4	177	150

Table 4.5 Final fiber length values for hold pressure setting



Figure 4.14 Effect of Hold Pressure on Fiber Length

The hold pressure is refers to the set pressure used to compress and hold the molten material in the mold directly after filling and before cooling. It is necessary from the time the mold fills until the gate of the mold freezes. Higher hold pressures mean that more material being pushed into mold during the hold phase, thus it will give better aesthetics. (Dave and Chundury, 1997) Other studies show that, hold pressure also has an effect on part quality eliminating voids, sink marks and shrinkage. Hold pressure helps to pack the polymer better and compensates for the shrinkage effects. As hold pressure increases, mechanical properties improve.

It is assumed in this study that holding pressure has no significant effect on crystallinity as an injection molding parameter so the effect of fiber length was observed in this part of the study. However, as it is clearly observed from Figure 4.14 that hold pressure has almost no effect on fiber length.

The average values of mechanical properties for various hold pressure settings are summarized in Table 4.6.

Dependence of mechanical properties on hold pressure can be examined from Figures 4.15 to 4.18. When hold pressure is increased, orientation is preserved in the direction of the flow. It is obvious from the Figures 4.15 to 4.17 that impact strength, tensile strength and tensile modulus is dependent and in general directly proportional to the increase in hold pressure except the tensile properties for P(ref)+300, this test resulted in high fiber content, W<sub>f</sub> of 29.89%, but the mechanical properties are low which is most probably due to an experimental error.

An increase in hold pressure affects the elongation at break negatively and it is obvious from the Figure 4.18 that as hold pressure increases, elongation at break decreases. This is also due to the higher orientation in the direction of flow at high hold pressure.

Injec Molc Paran	tion ling neter	Exp. Code	a <sub>iN</sub> kJ/m <sup>2</sup>	σ <sub>c</sub> MPa	8 %	E MPa	W <sub>f</sub> %
	-300	3.c.1	13.42	151.2	3.60	9047	29.45
Hold	-150	3.c.2	13.50	150.4	3.53	9067	29.50
Pressure	Ref	Ref	13.31	153.6	3.53	9221	29.52
(bar)	+150	3.c.3	13.57	155.0	3.55	9227	29.55
	+300	3.c.4	13.79	153.2	3.43	9054	29.89

Table 4.6 Final mechanical properties for hold pressure setting



Figure 4.15 Dependence of Impact Strength and Fiber Length on Hold Pressure



Figure 4.16 Dependence of Tensile Strength and Fiber Length on Hold Pressure



Figure 4.17 Dependence of Tensile Modulus and Fiber Length on Hold Pressure



Figure 4.18 Dependence of Elongation at Break and Fiber Length on Hold Pressure

### 4.1.4 Effect of Mold Temperature

Considering each mold temperature adjustment, average fiber length values are given in Table 4.7. The detailed data are in Tables A1.14 to A1.17 and Figures A1.27 to A1.34.

Injection Molding Parameter		Exp. Code	$egin{array}{c} \mathbf{L}_{\mathrm{w}} \ \mu \end{array}$	L <sub>n</sub> μ
	-40	<b>3.d.1</b>	177	139
Mold	-20	3.d.2	177	138
Temp.	Ref	Ref	179	149
( <sup>u</sup> C)	+20	3.d.3	180	140
	+40	<b>3.d.4</b>	182	142

**Table 4.7** Final fiber length values for mold temperature setting



Figure 4.19 Effect of Mold Temperature on Fiber Length

It is observed from Figure 4.19, which shows the effect of mold temperature on fiber degradation that average fiber degradation decreases slightly when mold temperature is increased. This slight decrease is due to the lower melt viscosity that results in lower shear between the glass fiber and the polymer matrix at high mold temperatures in mold cavity. When  $L_n$  and  $L_w$  parameters are compared, it observed that, they almost show the same trend where  $L_w$  gives a higher value with respect to  $L_n$ .

As mentioned before, temperature has a significant effect on crystallinity of a polymer. Therefore mechanical properties are dependent on mold temperature. To understand the effect precisely, dependency of crystallinity on mold temperature is given in Figure 4.20.



Figure 4.20 Effect of Mold Temperature on Crystallinity

In normal injection molding conditions, when mold temperature is increased, at the same time, cooling time should be increased to have more crystalline structures. However, in this study, all other parameters including cooling time were kept constant, therefore there was not enough time for the material to cool inside the mold with an increase in the temperature. Therefore, hot molded part that left the mold was immediately in touch with room temperature (faster cooling) resulting in lower crystallinity which can be seen from Figure 4.20.

The average values of mechanical properties for various mold temperature settings are summarized in Table 4.8. Dependence of mechanical properties on the mold temperature can be examined from Figures 4.21 to 4.26. As mentioned above, it is obvious from Figure 4.21 that the impact strength value is highly dependent and directly proportional to fiber length. At the same time, it is obvious from Figure 4.24 that elongation at break is highly dependent, but, inversely proportional to fiber length.

Average fiber length values and tensile strength and tensile modulus of the glass fiber reinforced Polyamide-6 composite are presented in Figures 4.22 and 4.23 respectively. When fiber length increases, tensile strength and modulus should increase but it is obviously seen from the figures that both of them decrease as the mold temperature is increased. This is because of the crystallization effect on the specimens. As illustrated above, when mold temperature is increase thus tensile strength and modulus decrease as shown in Figures 4.25 and 4.26. It is clear that crystallinity has more effect than fiber length on tensile strength and modulus when mold temperature results are examined.

Injection Molding Parameter		Exp. Code	a <sub>iN</sub> kj/m <sup>2</sup>	σ <sub>c</sub> MPa	եր Ա	E MPa	W <sub>f</sub> %
Mold Temp. ( <sup>0</sup> C)	-40	3.d.1	13.28	155.1	3.62	9285	29.54
	-20	3.d.2	13.55	154.5	3.60	9280	29.50
	Ref	Ref	13.31	153.6	3.53	9221	29.52
	+20	3.d.3	13.86	151.5	3.40	9076	29.41
	+40	3.d.4	13.90	149.7	3.55	8940	29.58

**Table 4.8** Final mechanical properties for mold temperature setting



Figure 4.21 Dependence of Impact Strength and Fiber Length on Mold Temperature



Figure 4.22 Dependence of Tensile Strength and Fiber Length on Mold Temperature


Figure 4.23 Dependence of Tensile Modulus and Fiber Length on Mold Temperature



Figure 4.24 Dependence of Elongation at Break and Fiber Length on Mold Temperature



Figure 4.25 Dependence of Tensile Strength on Crystallinity and Mold Temperature



Figure 4.26 Dependence of Tensile Modulus on Crystallinity and Mold Temperature

### 4.1.5 Effect of Cooling Time

Final fiber length values are given in Table 4.9 for each cooling time setting. The detailed data are in Tables A1.18 to A1.21 and Figures A1.35 to A1.42.

Table 4.9	Final fiber	length	values	for co	ooling	time	setting
-----------	-------------	--------	--------	--------	--------	------	---------

Injection Para	Molding meter	Exp. Code	L <sub>w</sub> μ	L <sub>n</sub> µ
	-10	3.e.1	181	133
Cooling	-5	3.e.2	182	141
time	Ref	Ref	179	149
<b>(s)</b>	+5	3.e.3	185	144
	+10	3.e.4	187	153



Figure 4.27 Effect of Cooling time on Fiber Length

In Figure 4.27, the effect of cooling time on fiber degradation was shown. The average fiber length increases when cooling time is increased. When cooling time is increased, cycle time increases and the residence time of polymer melt inside barrel increases. As a result, at high cooling times, thermal degradation occurs, and melt viscosity of the polymer decreases Thus glass fiber degradation decreases, leading to longer fibers.



Cooling time has an effect on crystallinity shown in Figure 4.28

Figure 4.28 Effect of Cooling time on Crystallinity

It is observed from the Figure 4.28 that the reference time setting has the highest crystallinity. As examined in barrel temperature section, crystallization often has an activation time and can be a strong function of the cooling rate. The balanced difference between the temperature of the polymer melt and the constant mold temperature to obtain highest crystallization is thought to be obtained at the reference data.

The average values of mechanical properties for various cooling time settings are summarized in Table 4.10 Dependence of mechanical properties on cooling time can be examined from Figures 4.29 to 4.34.

It is clear from Figure 4.29 that as fiber length increases, impact strength increases. On the other hand, Figure 4.32 shows a decrease in elongation at break as fiber length increases.

Average fiber length values and tensile strength and tensile modulus of the glass fiber reinforced Polyamide-6 composite are presented in Figures 4.30 and 4.31 respectively.

Both strength and modulus increase as the fiber length increases. In order to understand the maximum level of tensile strength and modulus at the reference point, equivalent graphs are prepared with crystallization ratios that are shown in Figures 4.33 and 4.34. It is clear that the maximum level of crystallinity corresponds to maximum level in the tensile properties. As a result, it can be said that both fiber length and crystallinity have significant effect on tensile strength and tensile modulus.

Injeo Mol Parai	ction ding meter	Exp. Code	a <sub>iN</sub> kj/m <sup>2</sup>	σ <sub>c</sub> MPa	եր %	E MPa	W <sub>f</sub> %
	-10	3.e.1	13.61	150.8	3.62	9047	29.52
Cooling	-5	3.e.2	13.88	152.3	3.64	9117	29.45
time	Ref	Ref	13.31	153.6	3.53	9221	29.52
(s)	+5	3.e.3	13.96	152.5	3.53	9126	29.63
	+10	3.e.4	14.51	152.7	3.32	9130	29.31

**Table 4.10** Final mechanical properties for cooling time setting



Figure 4.29 Dependence of Impact Strength and Fiber Length on Cooling Time



Figure 4.30 Dependence of Tensile Strength and Fiber Length on Cooling Time



Figure 4.31 Dependence of Tensile Modulus and Fiber Length on Cooling Time



Figure 4.32 Dependence of Elongation at Break and Fiber Length on Cooling Time



Figure 4.33 Dependence of Tensile Strength on Crystallinity and Cooling Time



Figure 4.34 Dependence of Tensile Modulus on Crystallinity and Cooling Time

#### 4.1.6 Effect of Screw Speed

Table 4.11 shows fiber length values for each screw speed setting. The detailed data can be seen in Tables A1.22 to A1.25 and Figures A1.43 to A1.50.

Injection Para	Molding meter	Exp. Code	L <sub>w</sub> μ	L <sub>n</sub> μ
	-8	<b>3.f.1</b>	182	149
Screw	-4	3.f.2	182	144
Speed	Ref	Ref	179	149
(rpm)	+4	3.f.3	174	141
	+8	3.f.4	167	139

Table 4.11 Final fiber length values for screw speed setting



Figure 4.35 Effect of Screw Speed on Fiber Length

A shear stress imposed on the polymer melt inside the injection molding machine not only causes chain scission in a polymer molecule but also leads to a decrease in glass fiber length. As the screw speed is increased the shear rate increases and the melt viscosity of the polymer matrix flowing inside the barrel decreases. A complicating factor is that shear stress, $\tau$ , is the product of viscosity

and shear rate ( $\tau=\eta\gamma$ ). Since the decrease in viscosity is smaller than the increase in the shear rate, shear stress increases with the screw speed. An increase in screw speed also causes an increase in the melt temperature of the polymer and beyond a certain value higher temperature and lower viscosity result in lower force acting between the glass fiber and the polymer matrix at the interface, consequently extent of fiber degradation decreases. However, as it is clearly observed from Figure 4.35 that fiber attrition occurs with an increase in screw speed where the extent is much more after reference screw speed. Thus, in the range of screw speed studied, it is understood that the shear stress increases with the screw speed.

 $L_n$  and  $L_w$  values are in almost the same reducing trend when screw speed is increased.

It is assumed in this study that screw speed has no significant effect on crystallinity so in this part of the study, the effect of fiber length on mechanical properties was investigated. The average values of mechanical properties for various screw speed settings are summarized in Table 4.12.

Dependence of mechanical properties on screw speed can be seen in Figures 4.36 to 4.39. It is obvious from Figures 4.36 to 4.38 that the impact strength, tensile strength and tensile modulus are directly proportional with fiber length. As fiber fracture occurs, mechanical properties are affected negatively. When Figure 4.39 is examined it can be concluded again that in the presence of shorter fibers in composite, elongation at break increases, as expected.

Inje Mol Para	ction ding meter	Exp. Code	a <sub>iN</sub> kj/m <sup>2</sup>	σ <sub>c</sub> MPa	ե <sub>հ</sub> %	E MPa	W <sub>f</sub> %
	-8	<b>3.f.1</b>	14.45	153.7	3.51	9155	29.43
Screw	-4	3.f.2	14.30	151.2	3.57	9100	29.53
Speed	Ref	Ref	13.31	153.6	3.53	9221	29.52
(rpm)	+4	3.f.3	13.46	149.5	3.68	8940	29.58
	+8	<b>3.f.4</b>	13.04	149.1	3.71	8908	29.49

 Table 4.12 Final mechanical properties for screw speed setting



Figure 4.36 Dependence of Impact Strength and Fiber Length on Screw Speed



Figure 4.37 Dependence of Tensile Strength and Fiber Length on Screw Speed



Figure 4.38 Dependence of Tensile Modulus and Fiber Length on Screw Speed



Figure 4.39 Dependence of Elongation at Break and Fiber Length on Screw Speed

### **CHAPTER V**

#### CONCLUSIONS

In order to understand the effects of injection molding process parameters and fiber length-mechanical property interactions on glass fiber reinforced Nylon-6, twenty-five types of experiments were carried out. Mechanical and thermal tests were determined on injection molded samples, also fiber length and distributions were measured. The mechanical performance was characterized by impact and tensile tests, thermal properties were characterized by heat deflection temperature and differential scanning calorimetry tests. Also, solution viscosity tests were done to observe if there was any degradation in the samples.

For determining the effects of injection molding parameters, weight and number average fiber length distributions must be taken into account.  $L_w$  is correlated more with mechanical properties than  $L_n$  is. Impact and tensile strength, and tensile modulus increase as fiber length increases, whereas elongation at break decreases. As it is known that barrel and mold temperature, as well as cooling time have an important effect on crystallinity, therefore DSC tests were performed for these parameters.

As barrel temperature is increased, fiber degradation decreases, therefore impact and tensile strength and tensile modulus increase, whereas elongation at break decreases. An increase in barrel temperature also results in an increase in crystallinity, further increasing tensile strength and modulus.

As injection pressure is increased, shear stress increases, therefore average fiber length decreases. Thus, impact and tensile strength, and tensile modulus decrease, whereas elongation at break increases. As hold pressure is increased, fiber length is almost not affected. However, as hold pressure is increased, orientation is preserved in the direction of the flow, thus impact and tensile strength, and tensile modulus increase, whereas elongation at break decreases.

As mold temperature is increased, fiber degradation decreases slightly as a result of the lower shear between the glass fiber and the polymer matrix. Longer fiber length results in an increase in impact strength and decrease in elongation at break. Crystallinity decreases in this case, and it has more effect on tensile strength and modulus than fiber length, resulting in lower tensile strength and modulus.

As screw speed is increased, shear stress increases therefore fiber fracture occurs. As a result, mechanical properties are affected negatively. Impact and tensile strength, and tensile modulus decrease, whereas elongation at break increases.

As cooling time is increased, melt viscosity decreases due to degradation, therefore, glass fiber breakage decreases, thus impact and tensile strength, and tensile modulus increase, whereas elongation at break decreases. An increase in cooling time increases the crystallinity, resulting in an increase in tensile strength and modulus. Thus, it is concluded that both fiber length and crystallinity have significant effects on tensile strength and modulus.

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# **APPENDICES**

# Table A1.1 Experimental data for 3REF

Fiber Length						
Di	Distribution					
Range	% by	% by				
μ	Number	Weight				
0-100	26.7	11.6				
101-150	23.9	20.2				
151-200	25.6	29.5				
201-250	14.2	21.2				
251-300	9.7	17.5				
301-350						
351-400						

Material Physical Properties					
L <sub>n</sub>	L <sub>w</sub>	$L_{min}$	L <sub>max</sub>		
μ	μ	μ	μ		
149	179	30	284		

Material Mechanical Properties					
a <sub>iN</sub>	E	$\sigma_{c}$	ε <sub>b</sub>		
kJ / m <sup>2</sup>	MPa	MPa	%		
13.31	9221	153.6	3.53		

Material Thermal Properties			
DSC	HDT		
X <sub>c</sub> (%)	°C		
28.87	197.7		

Injection Molding Operating Conditions				
	Barrel T	emperati	ure, ⁰C	
240	245	250	255	260
Hold I	Pressure,	bar		
700	600	500		
Injection	ction P, bar Screw		V, rpm	
1000	900	2	25	
Mold	/lold T, <sup>0</sup> C Coolir		g t, sec	
80	)	1	5	



Figure A1.1 Number Average Fiber length Distribution



Figure A1.2 Weight Average Fiber Length Distribution

Table A1.2 Experimental data for 3A1

Fiber Length				
Di	stributio	า		
Range	% by	% by		
μ	Number	Weight		
0-100	29.0	13.1		
101-150	33.1	30.0		
151-200	17.7	21.9		
201-250	14.5	23.1		
251-300	5.6	9.7		
301-350				
351-400	0.8	2.2		

Material Physical Properties				
L <sub>n</sub>	L <sub>w</sub>	$L_{min}$	$L_{max}$	
μ	μ	μ	μ	
140	174	31	385	

Material Mechanical Properties					
a <sub>iN</sub> Ε σ <sub>c</sub> ε <sub>b</sub>					
$kJ / m^2$	MPa	MPa	%		
13.00 8934 147.4 3.73					

Material Thermal Properties		
DSC	HDT	
X <sub>c</sub> (%)	٥C	
24.11	196.9	

Injection Molding Operating Conditions					
	Barrel Temperature, <sup>0</sup> C				
220	225	230	235	240	
Hold Pressure, bar					
700	600	500			
Injection	Injection P, bar Screw V, rpm				
1000	900	25			
Mold	T, <sup>0</sup> C	Cooling t, sec			
80 15					



Figure A1.3 Number Average Fiber Length Distribution



Figure A1.4 Weight Average Fiber Length Distribution

 Table A1.3 Experimental data for 3A2

Fiber Length			
D	istribution		
Range	% by	% by	
μ	Number	Weight	
0-100	37.9	17.9	
101-150	22.0	19.6	
151-200	19.4	24.0	
201-250	11.0	17.6	
251-300	5.3	10.5	
301-350	3.1	7.1	
351-400	1.3	3.4	

Material Physical Properties				
L <sub>n</sub>	L <sub>w</sub>	L <sub>min</sub>	$L_{max}$	
μ	μ	μ	μ	
140	183	31	372	

Material Mechanical Properties				
a <sub>iN</sub> Ε σ <sub>c</sub> ε <sub>b</sub>				
$kJ / m^2$	MPa	MPa	%	
13.21 8941 148.9 3.69				

Material Thermal Properties		
DSC	HDT	
X <sub>c</sub> (%)	٥C	
26.28	197.1	

Injection Molding Operating Conditions				
	Barrel Temperature, <sup>0</sup> C			
230	235	240	245	250
Hold Pressure, bar				
700	600	500		_
Injection	Injection P, bar Screw V, rpm			
1000	900	25		
Mold T, <sup>0</sup> C Cooling t, sec				
80 15				



Figure A1.5 Number Average Fiber Length Distribution



Figure A1.6 Weight Average Fiber Length Distribution

Table A1.4	Experimental	data for	3A3
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Fiber Length				
Di	stribution			
Range	% by	% by		
μ	Number	Weight		
0-100	31.2	14.1		
101-150	18.8	15.7		
151-200	28.5	33.6		
201-250	11.3	17.1		
251-300	9.1	17.1		
301-350	0.5	1.1		
351-400	0.5	1.3		

Material Physical Properties				
L <sub>n</sub>	$L_{w}$	$L_{min}$	$L_{max}$	
μ	μ	μ	μ	
182	147	30	354	

Material Mechanical Properties					
a <sub>iN</sub> Ε σ <sub>c</sub> ε <sub>b</sub>					
$kJ / m^2$	MPa	MPa	%		
13.60 8985 150.5 3.58					

Material Thermal Properties			
DSC HDT			
X <sub>c</sub> (%)	٥C		
25.73 195.3			

Injection Molding Operating Conditions						
	Barrel T	emperati	ure, ⁰C			
250	250 255 260 265					
Hold I	Hold Pressure, bar					
700	700 600 500					
Injection P, bar Screw V, rpm						
1000 900 25						
Mold T, <sup>0</sup> C Cooling t, sec						
80 15						



Figure A1.7 Number Average Fiber Length Distribution



Figure A1.8 Weight Average Fiber Length Distribution

Table A1.5 Experimental data for 3A4

Fiber Length			
Di	stribution	Ì	
Range	% by	% by	
μ	Number	Weight	
0-100	23.4	9.9	
101-150	27.6	22.9	
151-200	27.1	31.3	
201-250	13.0	19.3	
251-300	6.8	11.9	
301-350	1.0	2.2	
351-400	1.0	2.5	

Material Physical Properties					
L <sub>n</sub>	L <sub>w</sub> L <sub>min</sub> L <sub>max</sub>				
μ	μ	μ	μ		
153	188	32	370		

Material Mechanical Properties					
a <sub>iN</sub> Ε σ <sub>c</sub> ε <sub>b</sub>					
kJ / m²	MPa	MPa	%		
14.01 9007 151.7 3.56					

Material Thermal Properties			
DSC HDT			
X <sub>c</sub> (%)	°C		
26.51 196.2			

Injection Molding Operating Conditions				
	Barrel Temperature, <sup>0</sup> C			
260	265	270	275	280
Hold I	Hold Pressure, bar			
700	600	500		_
Injection P, bar Screw V, rpm				
1000 900 25				
Mold T, <sup>0</sup> C Cooling t, sec				
80 15				



Figure A1.9 Number Average Fiber Length Distribution



Figure A1.10 Weight Average Fiber Length Distribution

 Table A1.6 Experimental data for 3B1

Fiber Length				
Di	stributio	า		
Range % by % by				
μ	Number	Weight		
0-100	26.2	10,4		
101-150	21.0	17,2		
151-200	27.9	31,5		
201-250	14.6	21,5		
251-300	9.9	18,2		
301-350				
351-400	0.4	1.1		

Material Physical Properties						
L <sub>n</sub>	L <sub>w</sub> L <sub>min</sub> L <sub>max</sub>					
μ	μ	μ	μ			
150	150 185 30 386					

Material Mechanical Properties				
a <sub>iN</sub> Ε σ <sub>c</sub> ε <sub>b</sub>				
kJ / m²	MPa	MPa	%	
14.32	9292	155.1	3.66	

Material Thermal Properties				
DSC HDT				
X <sub>c</sub> (%)	٥C			
-	198.1			

Injection Molding Operating Conditions						
	Barrel Temperature, <sup>0</sup> C					
240	240 245 250 255					
Hold I	Hold Pressure, bar					
700	700 600 500					
Injection P, bar Screw V, rpm						
600 500 25						
Mold T, <sup>0</sup> C Cooling t, sec						
80 15						



Figure A1.11 Number Average Fiber Length Distribution



Figure A1.12 Weight Average Fiber Length Distribution

Fiber Length			
Di	stribution	1	
Range	% by	% by	
μ	Number	Weight	
0-100	31.1	13.7	
101-150	22.8	19.7	
151-200	24.7	29.5	
201-250	12.8	19.5	
251-300	5.0	9.4	
301-350	3.2	7.1	
351-400	0.5	1.1	

Material Physical Properties			
L <sub>n</sub>	L <sub>w</sub>	$L_{min}$	$L_{max}$
μ	μ	μ	μ
145	182	32	356

Material Mechanical Properties					
a <sub>iN</sub>	Ε σ <sub>c</sub> ε <sub>b</sub>				
kJ / m²	MPa	MPa	%		
14.06	14.06 9270 154.8 3.68				

Material Thermal Properties		
DSC	HDT	
X <sub>c</sub> (%)	°C	
-	197.9	

Injection Molding Operating Conditions				
	Barrel T	emperati	ure, ⁰C	
240	245	250	255	260
Hold Pressure, bar				
700	600	500		
Injection P, bar Screw V, rpm				
800	700	2	25	
Mold	T, <sup>0</sup> C	Cooling t, sec		
80	)	1	5	



Figure A1.13 Number Average Fiber Length Distribution



Figure A1.14 Weight Average Fiber Length Distribution

# Table A1.8 Experimental Data for 3B3

Fiber Length			
Di	stribution	1	
Range	% by	% by	
μ	Number	Weight	
0-100	28.8	12.4	
101-150	23.4	19.7	
151-200	27.3	33.0	
201-250	12.7	19.2	
251-300	4.9	10.8	
301-350	2.4	5.2	
351-400	0.5	1.3	

Material Physical Properties			
L <sub>n</sub>	L <sub>w</sub>	$L_{min}$	L <sub>max</sub>
μ	μ	μ	μ
146	181	30	400

Material Mechanical Properties				
a <sub>iN</sub>	E	$\sigma_{c}$	ε <sub>b</sub>	
$kJ / m^2$	MPa	MPa	%	
13.95 9027 150.2 3.74				

Material Thermal Properties		
DSC	HDT	
X <sub>c</sub> (%)	°C	
-	196.9	

Injection Molding Operating Conditions				
	Barrel T	emperati	ure, ⁰C	
240	245	250	255	260
Hold Pressure, bar				
700	600	500		
Injection	ı P, bar	Screw	V, rpm	
1200	1100	2	25	
Mold	T, <sup>0</sup> C	Cooling t, sec		
80	)	1	5	



Figure A1.15 Number Average Fiber Length Distribution



Figure A1.16 Weight Average Fiber Length Distribution

Table A1.9 Experimer	ital data f	for 3B4
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Fiber Length			
Di	stributior	1	
Range	% by	% by	
μ	Number	Weight	
0-100	29.4	12.5	
101-150	25.1	21.8	
151-200	23.5	28.8	
201-250	16.6	26.5	
251-300	4.3	7.9	
301-350	1.1	2.4	
351-400			

Material Physical Properties					
L <sub>n</sub>	L <sub>w</sub> L <sub>min</sub> L <sub>max</sub>				
μ	μ	μ	μ		
141	175	31	319		

Material Mechanical Properties					
a <sub>iN</sub>	Ε σ <sub>c</sub> ε <sub>b</sub>				
kJ / m <sup>2</sup>	MPa	MPa	%		
13.72	9001	148.3	3.77		

Material Thermal Properties		
DSC	HDT	
X <sub>c</sub> (%)	٥C	
-	196.5	

Injection Molding Operating Conditions						
	Barrel T	emperati	ure, ⁰C			
240	240 245 250 255 260					
Hold Pressure, bar						
700	600	500				
Injection P, bar Screw V, rpm		V, rpm				
1400	1300	2	25			
Mold T, <sup>0</sup> C Cooling t, sec						
80 15						



Figure A1.17 Number Average Fiber Length Distribution



Figure A1.18 Weight Average Fiber Length Distribution

Table A1.10 Experimental data for 3	C1
-------------------------------------	----

Fiber Length			
Di	stribution	1	
Range	% by	% by	
μ	Number	Weight	
0-100	25.6	11.2	
101-150	26.8	23.2	
151-200	27.6	32.3	
201-250	11.8	17.7	
251-300	6.5	12.1	
301-350	1.6	3.5	
351-400			

Material Physical Properties					
L <sub>n</sub>	L <sub>w</sub> L <sub>min</sub> L <sub>max</sub>				
μ	μ	μ	μ		
147	178 30 318				

Material Mechanical Properties						
a <sub>iN</sub>	a <sub>iN</sub> Ε σ <sub>c</sub> ε <sub>b</sub>					
$kJ / m^2$	MPa	MPa	%			
13.42 9047 151.2 3.60						

Material Thermal Properties		
DSC	HDT	
X <sub>c</sub> (%)	٥C	
-	196.7	

Injection Molding Operating Conditions					
	Barrel Temperature, <sup>0</sup> C				
240	245	250	255	260	
Hold Pressure, bar					
400	300	200			
Injection P, bar Screw V, rpm					
1000	900	2	25		
Mold	T, <sup>0</sup> C	Coolin	g t, sec		
80	)	1	5		



Figure A1.19 Number Average Fiber Length Distribution





Fiber Length			
Di	stributior	n	
Range	% by	% by	
μ	Number	Weight	
0-100	35.4	15.7	
101-150	22.4	19.9	
151-200	20.6	26.2	
201-250	12.1	19.2	
251-300	6.7	12.9	
301-350	2.7	6.1	
351-400			

Material Physical Properties						
L <sub>n</sub>	L <sub>w</sub> L <sub>min</sub> L <sub>max</sub>					
μ	μ	μ	μ			
140	180	30	348			

Material Mechanical Properties						
a <sub>iN</sub>	a <sub>iN</sub> Ε σ <sub>c</sub> ε <sub>b</sub>					
kJ / m <sup>2</sup>	MPa	MPa	%			
13.50 9067 150.4 3.53						

Material Thermal Properties			
DSC HDT			
X <sub>c</sub> (%)	٥C		
-	196.5		

Injection Molding Operating Conditions				
	Barrel T	emperati	ure, ⁰C	
240	245	250	255	260
Hold Pressure, bar				
550	450	350		
Injection P, bar Screw V, rpm				
1000	900	2	25	
Mold T, <sup>0</sup> C Cooling t, s		g t, sec		
80	)	1	5	



Figure A1.21 Number Average Fiber Length Distribution



Figure A1.22 Weight Average Fiber Length Distribution

Table	A1.12	Experimental	data for	3C3
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Fiber Length			
Di	stributior	n	
Range	% by	% by	
μ	Number	Weight	
0-100	32.9	15.4	
101-150	23.3	20.2	
151-200	23.8	29.1	
201-250	11.4	17.6	
251-300	5.7	10.9	
301-350	1.9	4.3	
351-400	1.0	2.5	

Material Physical Properties						
L <sub>n</sub>	L <sub>w</sub> L <sub>min</sub> L <sub>max</sub>					
μ	μ	μ	μ			
143	180	30	392			

Material Mechanical Properties					
a <sub>iN</sub> Ε σ <sub>c</sub> ε <sub>b</sub>					
kJ / m²	MPa	MPa	%		
13.57 9227 155.0 3.55					

Material Thermal Properties		
DSC	HDT	
X <sub>c</sub> (%)	°C	
-	197.3	

Injection Molding Operating Conditions				
	Barrel Temperature, <sup>0</sup> C			
240	245	250	255	260
Hold Pressure, bar				
850	750	650		
Injection P, bar Screw V, rpm				
1000	900	2	25	
Mold T, <sup>0</sup> C Cooling t, sec				
80	)	1	5	



Figure A1.23 Number Average Fiber Length Distribution



Figure A1.24 Weight Average Fiber Length Distribution

Fiber Length			
Di	stributior	n	
Range	% by	% by	
μ	Number	Weight	
0-100	17.9	7.7	
101-150	25.0	20.3	
151-200	37.5	42.0	
201-250	14.9	21.5	
251-300	4.2	7.4	
301-350	0.6	1.2	
351-400			

Material Physical Properties					
L <sub>n</sub>	L <sub>w</sub>	L <sub>min</sub>	L <sub>max</sub>		
μ	μ	μ	μ		
150	150 177 30 307				

Material Mechanical Properties				
a <sub>iN</sub>	Ε σ <sub>c</sub> ε <sub>b</sub>			
kJ / m²	MPa	MPa	%	
13.79 9054 153.2 3.43				

Material Thermal Properties		
DSC	HDT	
X <sub>c</sub>	٥C	
-	196.2	

Injection Molding Operating Conditions				
	Barrel T	emperati	ure, ⁰C	
240	245	250	255	260
Hold Pressure, bar				
1000	900	800		
Injection	P, bar Screw		V, rpm	
1000	900	25		
Mold	T, <sup>0</sup> C	Cooling t, sec		
80 15				



Figure A1.25 Number Average Fiber Length Distribution



Figure A1.26 Weight Average Fiber Length Distribution

 Table A1.14 Experimental data for 3D1

Fiber Length			
Di	stributio	า	
Range	% by	% by	
μ	Number	Weight	
0-100	32.9	13.3	
101-150	20.0	18.3	
151-200	30.0	37.9	
201-250	13.3	22.1	
251-300	0.5	0.9	
301-350	1.9	4.5	
351-400	1.4	3.8	

Material Physical Properties				
L <sub>n</sub>	L <sub>w</sub>	$L_{min}$	L <sub>max</sub>	
μ	μ	μ	μ	
139	177 30 388			

Material Mechanical Properties				
a <sub>iN</sub>	Ε σ <sub>c</sub> ε <sub>b</sub>			
kJ / m²	MPa	MPa	%	
13.28 9285 155.1 3.62				

Material Thermal Properties		
DSC HDT		
X <sub>c</sub> (%)	٥C	
32.33 198.3		

Injection Molding Operating Conditions				
	Barrel T	emperati	ure, ⁰C	
240	245	250	255	260
Hold Pressure, bar				
700	600	500		
Injection	tion P, bar Screw		V, rpm	
1000	900	25		
Mold	T, <sup>0</sup> C	Coolin	g t, sec	
40 15				



Figure A1.27 Number Average Fiber Length Distribution



Figure A1.28 Weight Average Fiber Length Distribution

Fiber Length			
Di	stribution	ı	
Range	% by	% by	
μ	Number	Weight	
0-100	34.8	16.4	
101-150	28.5	26.0	
151-200	19.0	24.1	
201-250	8.7	14.5	
251-300	6.3	12.4	
301-350	2.4	5.6	
351-400	0.4	1.1	

Material Physical Properties				
L <sub>n</sub>	L <sub>w</sub> L <sub>min</sub> L <sub>max</sub>			
μ	μ	μ	μ	
138	177 31 380			

Material Mechanical Properties					
a <sub>iN</sub>	Ε σ <sub>c</sub> ε <sub>b</sub>				
$kJ / m^2$	MPa	MPa	%		
13.55	9280	154.5	3.60		

Material Thermal Properties		
DSC	HDT	
X <sub>c</sub> (%)	٥C	
30.56	197.9	

Injection Molding Operating Conditions				
	Barrel Temperature, <sup>0</sup> C			
240	245	250	255	260
Hold I	Hold Pressure, bar			
700	600	500		
Injection	Injection P, bar Screw V, rpm			
1000	900	2		
Mold	T, <sup>0</sup> C	Cooling t, sec		
60	)	1		



Figure A1.29 Number Average Fiber Length Distribution



Figure A1.30 Weight Average Fiber Length Distribution

# Table A1.16 Experimental data for 3D3

Fiber Length			
Di	stribution	Ì	
Range	% by	% by	
μ	Number	Weight	
0-100	33.5	13.5	
101-150	20.2	17.8	
151-200	26.1	32.8	
201-250	12.3	19.6	
251-300	4.9	9.3	
301-350	2.5	5.6	
351-400	0.5	1.3	

Material Physical Properties				
L <sub>n</sub>	L <sub>w</sub>	$L_{min}$	$L_{max}$	
μ	μ	μ	μ	
140	180	30	382	

Material Mechanical Properties					
a <sub>iN</sub>	a <sub>iN</sub> Ε σ <sub>c</sub> ε <sub>b</sub>				
kJ / m²	MPa	MPa	%		
13.86	3.40	151.5	9076		

Material Thermal Properties		
DSC	HDT	
X <sub>c</sub> (%)	٥C	
26.92	196.4	

Injection Molding Operating Conditions				
	Barrel Temperature, <sup>0</sup> C			
240	245	250	255	260
Hold	Hold Pressure, bar			
700	600	500		_
Injection P, bar Screw V		V, rpm		
1000	900	2		
Mold T, <sup>0</sup> C Cooling t, sec				
10	100 15			



Figure A1.31 Number Average Fiber Length Distribution



Figure A1.32 Weight Average Fiber Length Distribution

Table A1	.17 Exp	erimental	data f	or 3D4
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Fiber Length			
Di	stribution	1	
Range	% by	% by	
μ	Number	Weight	
0-100	34.0	14.5	
101-150	23.4	20.8	
151-200	19.6	24.3	
201-250	13.9	21.9	
251-300	7.2	13.9	
301-350	1.4	3.3	
351-400	0.5	1.2	

Material Physical Properties				
L <sub>n</sub>	L <sub>w</sub> L <sub>min</sub> L <sub>max</sub>			
μ	μ	μ	μ	
142	182	30	355	

Material Mechanical Properties					
a <sub>iN</sub>	Ε σ <sub>c</sub> ε <sub>b</sub>				
kJ / m²	MPa	MPa	%		
13.90	8940	149.7	3.55		

Material Thermal Properties		
DSC	HDT	
X <sub>c</sub> (%)	٥C	
25.56	195.8	

Injection Molding Operating Conditions					
	Barrel Temperature, <sup>0</sup> C				
240	245	250	255	260	
Hold Pressure, bar					
700	600	500			
Injection P, bar Screw		Screw	V, rpm		
1000	900	25			
Mold T, <sup>0</sup> C		Cooling t, sec			
12	120 15				



Figure A1.33 Number Average Fiber Length Distribution



Figure A1.34 Weight Average Fiber Length Distribution

Table A1.18	Experimental	data fo	r 3E1
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Fiber Length			
Di	stribution	ı	
Range	% by	% by	
μ	Number	Weight	
0-100	42.0	18.7	
101-150	21.0	20.2	
151-200	17.4	22.6	
201-250	9.6	16.5	
251-300	7.8	15.7	
301-350	0.9	2.2	
351-400	1.4	3.9	

Material Physical Properties					
L <sub>n</sub>	L <sub>w</sub> L <sub>min</sub> L <sub>ma</sub>				
μ	μ	μ	μ		
133	181	30	396		

Material Mechanical Properties					
a <sub>iN</sub>	Ε σ <sub>c</sub> ε <sub>b</sub>				
kJ / m <sup>2</sup>	MPa	MPa	%		
13.61	9047	150.8	3.62		

Material Thermal Properties		
DSC	HDT	
X <sub>c</sub> (%)	٥C	
25.54	196.7	

Injection Molding Operating Conditions					
	Barrel Temperature, <sup>0</sup> C				
240	245	250	255	260	
Hold Pressure, bar					
700	600	500			
Injection P, bar Screv		Screw	V, rpm		
1000	900	25			
Mold T, <sup>0</sup> C		Cooling t, sec			
80 5					



Figure A1.35 Number Average Fiber Length Distribution



Figure A1.36 Weight Average Fiber Length Distribution
Fiber Length				
Di	stribution	n		
Range	% by	% by		
μ	Number	Weight		
0-100	36.4	16.7		
101-150	20.9	17.9		
151-200	18.4	22.5		
201-250	14.6	23.5		
251-300	7.8	14.8		
301-350	1.9	4.4		
351-400				

Material Physical Properties			
L <sub>n</sub>	L <sub>w</sub>	$L_{min}$	L <sub>max</sub>
μ	μ	μ	μ
141	182	30	348

Material Mechanical Properties					
a <sub>iN</sub>	Ε σ <sub>c</sub> ε <sub>b</sub>				
$kJ / m^2$	MPa	MPa	%		
13.88	9117	152.3	3.64		

Material Thermal Properties		
DSC	HDT	
X <sub>c</sub> (%)	٥C	
25.66	197.5	

Injection Molding Operating Conditions				
	Barrel T	emperati	ure, ⁰C	
240	245	250	255	260
Hold Pressure, bar				
700	600	500		
Injection P, bar Screw		V, rpm		
1000	900	2	25	
Mold T, <sup>0</sup> C		Cooling t, sec		
80		1	0	



Figure A1.37 Number Average Fiber Length Distribution



Figure A1.38 Weight Average Fiber Length Distribution

Fiber Length				
Di	stribution	1		
Range	% by	% by		
μ	Number	Weight		
0-100	34.5	13.4		
101-150	14.0	12.2		
151-200	25.8	31.0		
201-250	16.6	25.8		
251-300	7.9	14.6		
301-350	1.3	2.9		
351-400				

Material Physical Properties				
L <sub>n</sub>	L <sub>w</sub>	$L_{min}$	L <sub>max</sub>	
μ	μ	μ	μ	
144	185	30	340	

Material Mechanical Properties					
a <sub>iN</sub>	Ε σ <sub>c</sub> ε <sub>b</sub>				
kJ / m²	MPa	MPa	%		
13.96	9126	152.5	3.53		

Material Thermal Properties			
DSC	HDT		
X <sub>c</sub>	٥C		
24.80	197.7		

Injection Molding Operating Conditions				
	Barrel T	emperati	ure, ⁰C	
240	245	250	255	260
Hold Pressure, bar				
700	600	500		
Injection P, bar Screw		V, rpm		
1000	900	2	25	
Mold T, <sup>0</sup> C		Coolin	g t, sec	
80		2	20	



Figure A1.39 Number Average Fiber Length Distribution



Figure A1.40 Weight Average Fiber Length Distribution

Table A1.	21 Expe	erimenta	l data	for	<b>3E4</b>
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Fiber Length			
Di	stributior	n	
Range	% by	% by	
μ	Number	Weight	
0-100	23.8	9.7	
101-150	28.7	23.8	
151-200	23.8	27.0	
201-250	11.2	16.5	
251-300	9.4	16.5	
301-350	2.7	21.2	
351-400	0.4	1.1	

Material Physical Properties			
L <sub>n</sub>	L <sub>w</sub>	L <sub>min</sub>	L <sub>max</sub>
μ	μ	μ	μ
153	187	31	383

Material Mechanical Properties			
a <sub>iN</sub> Ε σ <sub>c</sub> ε <sub>b</sub>			
kJ / m²	MPa	MPa	%
14.51	9130	152.7	3.32

Material Thermal Properties		
DSC	HDT	
X <sub>c</sub> (%)	°C	
25.92	197.9	

Injection Molding Operating Conditions				
	Barrel Temperature, <sup>0</sup> C			
240	245	250	255	260
Hold I	<sup>&gt;</sup> ressure,	bar		
700	600	500		
Injection P, bar Screw V, rpm				
1000	900	12	25	
Mold T, <sup>0</sup> C Cooling t, sec				
80	80 25			



Figure A1.41 Number Average Fiber Length Distribution



Figure A1.42 Weight Average Fiber Length Distribution

Table A1.2	2 Experim	ental data	for 3F1
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Fiber Length			
Di	stributior	1	
Range	% by	% by	
μ	Number	Weight	
0-100	32.1	17.0	
101-150	29.1	30.7	
151-200	21.5	30.1	
201-250	12.2	21.7	
251-300	3.8	7.9	
301-350	0.8	2.1	
351-400	0.4	1.2	

Material Physical Properties			
L <sub>n</sub>	L <sub>w</sub>	$L_{min}$	$L_{max}$
μ	μ	μ	μ
149	182	30	372

Material Mechanical Properties			
a <sub>iN</sub>	E	$\sigma_{c}$	ε <sub>b</sub>
kJ / m²	MPa	MPa	%
14.45	9155	153.7	3.51

Material Thermal Properties		
DSC	HDT	
X <sub>c</sub> (%)	٥C	
-	197.9	

Injection Molding Operating Conditions				
	Barrel Temperature, <sup>0</sup> C			
240	245	250	255	260
Hold Pressure, bar				
700	600	500		
Injection	P, bar	Screw V	√, m/min	
1000	900	1	7	
Mold T, <sup>0</sup> C Cooling t, sec				
80 15				



Figure A1.43 Number Average Fiber Length Distribution



Figure A1.44 Weight Average Fiber Length Distribution

Table A1.23 Experimental data for 3F2

Fiber Length			
Di	stribution	Ì	
Range	% by	% by	
μ	Number	Weight	
0-100	30.4	13.1	
101-150	23.8	20.5	
151-200	24.6	29.2	
201-250	10.8	16.4	
251-300	7.3	13.8	
301-350	2.3	4.9	
351-400	0.8	2.0	

Material Physical Properties				
L <sub>n</sub>	L <sub>w</sub>	L <sub>min</sub>	L <sub>max</sub>	
μ	μ	μ	μ	
144	182	30	377	

Material Mechanical Properties						
a <sub>iN</sub> Ε σ <sub>c</sub> ε <sub>b</sub>						
kJ / m²	MPa	MPa	%			
14.30 9100 151.2 3.57						

Material Thermal Properties		
DSC	HDT	
X <sub>c</sub> (%)	°C	
-	196.5	

Injection Molding Operating Conditions				itions
	Barrel To	emperatu	re, ⁰C	
240	245	250	255	260
Hold I	Pressure,	bar		
700	600	500		
Injection	Injection P, bar Screw V, m/min			
1000	900	21		
Mold	T, <sup>0</sup> C	Cooling t, sec		
80 15				



Figure A1.45 Number Average Fiber Length Distribution



Figure A1.46 Weight Average Fiber Length Distribution

Table A1.24 Experimental data for 3	F3
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Fiber Length			
Di	stribution	1	
Range	% by	% by	
μ	Number	Weight	
0-100	33.0	16.6	
101-150	30.6	27.9	
151-200	19.6	25.0	
201-250	11.0	17.9	
251-300	2.9	5.6	
301-350	2.4	5.5	
351-400	0.5	1.4	

Material Physical Properties			
L <sub>n</sub>	L <sub>w</sub>	$L_{min}$	L <sub>max</sub>
μ	μ	μ	μ
141	174	31	400

Material Mechanical Properties					
a <sub>iN</sub> Ε σ <sub>c</sub> ε <sub>b</sub>					
kJ / m²	MPa	MPa	%		
13.46	8940	149.5	3.68		

Material Thermal Properties		
DSC	HDT	
X <sub>c</sub> (%)	°C	
-	196.1	

Injection Molding Operating Cond				litions
	Barrel T	emperati	ure, ⁰C	
240	245	250	255	260
Hold I	Pressure,	bar		
700	600	500		
Injection	Injection P, bar Screw V, m/min			
1000	900	2	29	
Mold	T, <sup>0</sup> C	Cooling t, sec		
80 15				



Figure A1.47 Number Average Fiber Length Distribution



Figure A1.48 Weight Average Fiber Length Distribution

Table A1.25	Experimental	data	for	3F4
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Fiber Length							
Distribution							
Range	% by	% by					
μ	Number	Weight					
0-100	32.1	16.0					
101-150	30.7	29.0					
151-200	25.0	33.3					
201-250	9.9	16.5					
251-300	1.4	3.0					
301-350	0.9	2.2					
351-400							

Material Physical Properties							
L <sub>n</sub>	$L_{w}$	$L_{min}$	$L_{max}$				
μ	μ	μ	μ				
139	167	30	317				

Material Mechanical Properties							
a <sub>iN</sub>	Е	$\sigma_{c}$	ε <sub>b</sub>				
$kJ / m^2$	MPa	MPa	%				
13.04	8908	149.1	3.71				

Material Thermal Properties								
DSC	HDT							
X <sub>c</sub> (%)	°C							
-	195.8							

Injection Molding Operating Condit								
Barrel Temperature, <sup>0</sup> C								
240	245	250	255	260				
Hold I	Pressure,							
700	700 600 500							
Injection	ı P, bar	Screw V	V, m/min					
1000	900	3	33					
Mold	T, <sup>0</sup> C	Coolin						
80	)	-	15					



Figure A1.49 Number Average Fiber Length Distribution



Figure A1.50 Weight Average Fiber Length Distribution



Figure A2.1 Weight Average Fiber Length Distribution Curves for Barrel Temperature



Figure A2.2 Weight Average Fiber Length Distribution Curves for Injection Pressure



Figure A2.3 Weight Average Fiber Length Distribution Curves for Hold Pressure



Figure A2.4 Weight Average Fiber Length Distribution Curves for Mold Temperature



Figure A2.5 Weight Average Fiber Length Distribution Curves for Cooling Time



Figure A2.6 Weight Average Fiber Length Distribution Curves for Screw Speed



Figure A3.1 Dependence of Impact Strength on Crystallinity and Barrel Temperature



Figure A3.2 Dependence of Elongation at Break on Crystallinity and Barrel Temperature



Figure A3.3 Dependence of Impact Strength on Crystallinity and Mold Temperature



Figure A3.4 Dependence of Elongation at Break on Crystallinity and Mold Temperature



Figure A3.5 Dependence of Impact Strength on Crystallinity and Cooling Time



Figure A3.6 Dependence of Elongation at Break on Crystallinity and Cooling Time



Figure A4.1 Differential Scanning Calorimetry result for 3REF



Figure A4.2 Differential Scanning Calorimetry result for 3A1



Figure A4.3 Differential Scanning Calorimetry result for 3A2



Figure A4.4 Differential Scanning Calorimetry result for 3A3



Figure A4.5 Differential Scanning Calorimetry result for 3A4



Figure A4.6 Differential Scanning Calorimetry result for 3D1



Figure A4.7 Differential Scanning Calorimetry result for 3D2



Figure A4.8 Differential Scaning Calorimetry result for 3D3



Figure A4.9 Differential Scanning Calorimetry result for 3D4



Figure A4.10 Differential Scanning Calorimetry result for 3E1



Figure A4.11 Differential Scanning Calorimetry result for 3E2



Figure A4.12 Differential Scanning Calorimetry result for 3E3



Figure A4.13 Differential Scanning Calorimetry result for 3E4

## **A5. Tabulated Experimental Results**

Inject	ion		_	-	_	_	<b>D</b> 00	UDT	<b>N</b>			
Moldi	ing	Exp.	a <sub>iN</sub>	$\sigma_{c}$	ε <sub>b</sub>	E	DSC	HDI	VISC.	VV <sub>f</sub>	Lw	Ln
Parameters		Code	kJ/m²	MPa	%	MPa	Xc	°C	-	%	μ	μ
	-20	3.a.1	13.00	147.4	3.73	8934	24.11	196.9	1.726	29.45	174	140
Barrel Temp. (⁰C)	-10	3.a.2	13.21	148.9	3.69	8941	26.28	197.1	1.723	29.55	183	140
	Ref	Ref	13.31	153.6	3.53	9221	28.87	197.7	1.727	29.52	179	149
	+10	3.a.3	13.60	150.5	3.58	8985	25.73	195.3	1.729	29.67	182	147
	+20	3.a.4	14.01	151.7	3.56	9007	26.51	196.2	1.735	29.58	188	153
	-400	3.b.1	14.32	155.1	3.66	9292	-	198.1	1.722	29.45	185	150
Injection	-200	3.b.2	14.06	154.8	3.68	9270	-	197.9	1.725	29.48	182	145
Pressure	Ref	Ref	13.31	153.6	3.53	9221	-	197.7	1.727	29.52	179	149
(bar)	+200	3.b.3	13.95	150.2	3.74	9027	-	196.9	1.727	29.44	181	146
	+400	3.b.4	13.72	148.3	3.77	9001	-	196.5	1.772	29.50	175	141
-300	-300	3.c.1	13.42	151.2	3.60	9047	-	196.7	1.723	29.45	178	147
Hold	-150	3.c.2	13.50	150.4	3.53	9067	-	196.5	1.731	29.50	180	140
Pressure	Ref	Ref	13.31	153.6	3.53	9221	-	197.7	1.727	29.52	179	149
(bar)	+150	3.c.3	13.57	155.0	3.55	9227	-	197.3	1.722	29.55	180	143
	+300	3.c.4	13.79	153.2	3.43	9054	-	196.2	1.719	29.89	177	150
	-40	3.d.1	13.28	155.1	3.62	9285	32.33	198.3	1.729	29.54	177	139
Mold	-20	3.d.2	13.55	154.5	3.60	9280	30.56	197.9	1.725	29.50	177	138
Temp.	Ref	Ref	13.31	153.6	3.53	9221	28.87	197.7	1.727	29.52	179	149
(°C)	+20	3.d.3	13.86	151.5	3.40	9076	26.92	196.4	1.728	29.41	180	140
	+40	3.d.4	13.90	149.7	3.55	8940	25.56	195.8	1.721	29.58	182	142
	-10	3.e.1	13.61	150.8	3.62	9047	25.54	196.7	1.723	29.52	181	133
Cooling	-5	3.e.2	13.88	152.3	3.64	9117	25.66	197.5	1.724	29.45	182	141
time	Ref	Ref	13.31	153.6	3.53	9221	28.87	197.7	1.727	29.52	179	149
(s)	+5	3.e.3	13.96	152.5	3.53	9126	24.80	197.7	1.732	29.63	185	144
	+10	3.e.4	14.51	152.7	3.32	9130	25.92	197.9	1.719	29.31	187	153
	-8	3.f.1	14.45	153.7	3.51	9155		197.9	1.718	29.43	182	149
Screw	-4	3.f.2	14.30	151.2	3.57	9100	-	196.5	1.721	29.53	182	144
Speed	Ref	Ref	13.31	153.6	3.53	9221	-	197.7	1.727	29.52	179	149
(rpm)	+4	3.f.3	13.46	149.5	3.68	8940	-	196.1	1.723	29.58	174	141
	+8	3.f.4	13.04	149.1	3.71	8908	-	195.8	1.727	29.49	167	139