MICROMORPHOLOGY-TENSILE BEHAVIOR RELATIONSHIP IN INJECTION MOLDED GENERAL PURPOSE POLYSTYRENE

by

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ABSTRACT

Study of micromorphology-tensile behavior relationship for general purpose polystyrene is carried out by using a single-stage reciprocating screw injection molding machine. The research investigated the effects of processing conditions i.e. varying injection speed from 2.5 in/s to 3.0 in/s on the development of structural hierarchy of GPPS, by using two different mold designs; a 2-cavity and a 4-cavity mold. From the tensile bars that were produced by using different injection speeds and mold designs, tensile properties were calculated. After comparing the tensile properties of close to sprue and away from sprue in 4-cavity mold there was no significant difference in any of the tensile properties. By comparing the two mold designs it was concluded that the specimens at an injection speed of 2.5 in/s from a 2-cavity mold are stronger compared to samples produced in an asymmetric 4-cavity mold at the same injection speed. Mackerel bands are observed in all specimens which are close to sprue in 4-cavity mold but these bands are observed only at injection speed 3.0 in/s for away from sprue and 2-cavity mold. This research concludes that by using a symmetric mold at slow injection speeds, the intensity of crazes can be decreased and thus improve the tensile properties

DEDICATION

This thesis is dedicated with lots of love and affection to

My Parents

Prakashrao Prattipati and Lizzie Heber Kantha Prattipati

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First of all, I would like to gratefully acknowledge Dr. Cynthia S. Hirtzel, Dean, Rayen College of Engineering & Technology for giving me the opportunity to work with the brand new machine and providing financial support.

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CHAPTER 1

INTRODUCTION

The modern world without plastics would be unimaginable due to their ability to be fabricated into complex structures and high strength properties. Plastics are polymers consisting of large molecules made up of linked series of repeated smaller molecules called monomers. Organic polymeric materials are of two types, i.e. natural plastics and synthetic plastics. Natural polymers, such as starch and cellulose, have been used throughout history. More recently, with the invention and production of synthetic polymers, the use of natural plastic has been reduced while synthetic plastics have increased dramatically.

Synthetic plastics are classified based upon their physical properties related to heating. The two types encountered are thermosets and thermoplastics. Thermoplastics, which are predominantly used, can go through repeated cycles of melting and solidification. The practical number of melting cycles that a thermoplastic can endure before appearance or properties are affected is determined by the chemical makeup of the plastic. Thermosets, on the other hand, undergo an irreversible chemical change called cross-linking during heating and cannot be melted again. Thermosets are used to make pan handles, many electrical products, and dinnerware.

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INTRODUCTION

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For over a century plastics have successfully competed with other materials such as metals and wood in numerous types of applications. Within the plastics industry itself there are different plastics competing against each other. There are various fabricating processes using the same raw material to fabricate the same product. Thus, the expansion of the plastics industry is spurred by this process-to-process materials competition. Injection molding is one key manufacturing process used to produce plastic components. This technique is able to produce components rapidly, while maintaining high product quality at a relatively low cost.

Injection molding is one of the most important and widely used processing techniques by which polymeric materials, either pure or in blends, are fabricated into various plastics components. The history of injection molding dates back approximately 130 years. The first patent involving injection molding was issued in 1872, and the first plunger machine was built in 1926 (Johannaber 1983). The first injection molding machines were built in the 1930's and machines with all the characteristics of those used today were built in 1956.

The two common types of injection molding machines are the single-stage reciprocating screw and the two-stage or pre-plasticating screw, which are shown in Figures 1.1 and 1.2. These two types of injection molding machines are principally operated with a horizontal injection and single clamping units. The driving force for injecting plastic into a mold is delivered by machines having either hydraulic, electric, or hybrid (combination of hydraulic and electric) power.

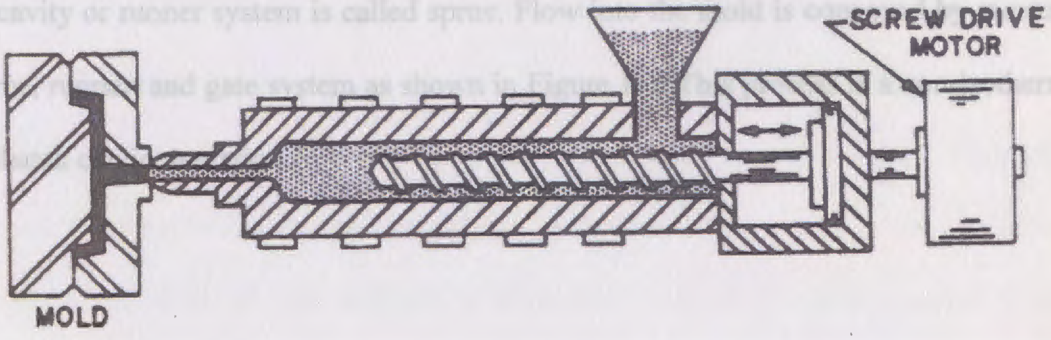


Figure 1.1 Single Stage or Reciprocating Screw (Rosato *et al.* 2001)

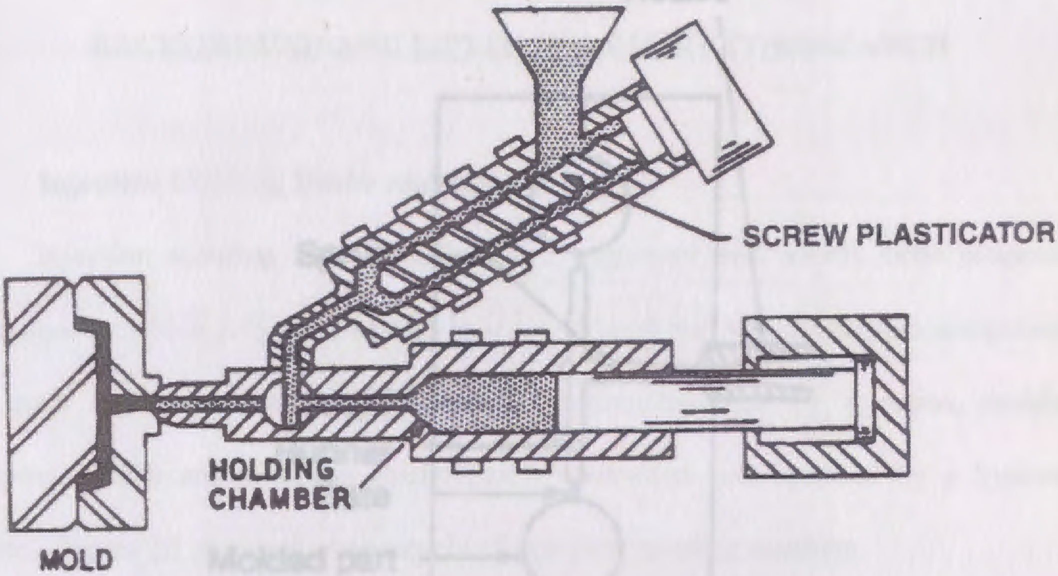


Figure 1.2 Two-Stage or Pre-Plasticating Screw (Rosato *et al.* 2001)

The selection of the type and size of injection molding machine is dependent on the molded product dimensions and the volume of the plastic delivered. Injection molding is a continuous and repetitive process in which the plastic is injected into the mold cavity where it is held under pressure until the plastic in the mold solidifies and is then ejected. The important function of the injection molding is to duplicate the cavity of the mold as it permits the manufacture of a great variety of shapes, from simple to three dimensional ones. The feed opening provided in injection molding between the nozzle and cavity or runner system is called sprue. Flow into the mold is conveyed by means of a sprue, runner, and gate system as shown in Figure 1.3. This process is a non-isothermal semibatch cyclic operation.

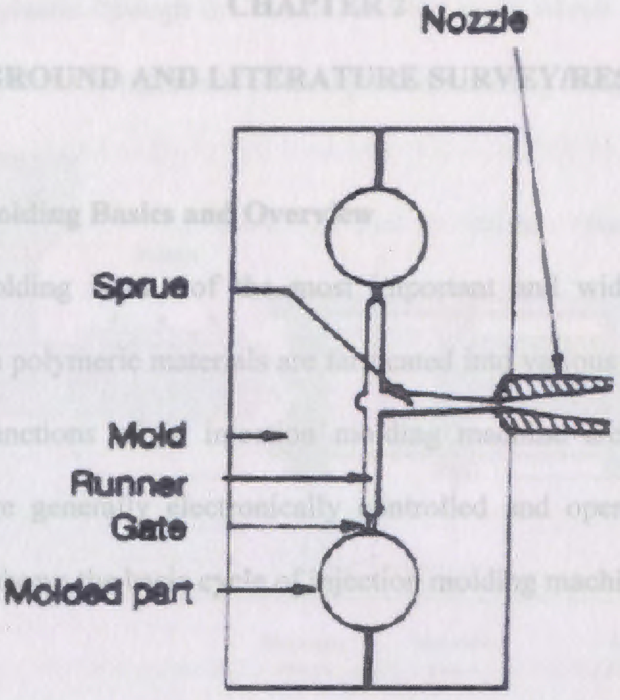


Figure 1-3 **Main Features of a Mold**

This research is a study of the injection molding characteristics of general purpose polystyrene (GPPS). The purpose of this research is to investigate the effect of processing conditions on the development of structural hierarchy in injection molded GPPS. Two factors are of interest; 1) Injection speed and 2) Mold symmetry.

CHAPTER 2

BACKGROUND AND LITERATURE SURVEY/RESEARCH

2.1 Injection Molding Basics and Overview

Injection molding is one of the most important and widely used processing techniques by which polymeric materials are fabricated into various plastics components. The three major functions of an injection molding machine are injection, molding, clamping. Each are generally electronically controlled and operated by a hydraulic system. Figure 2.1 shows the basic cycle of injection molding machine.

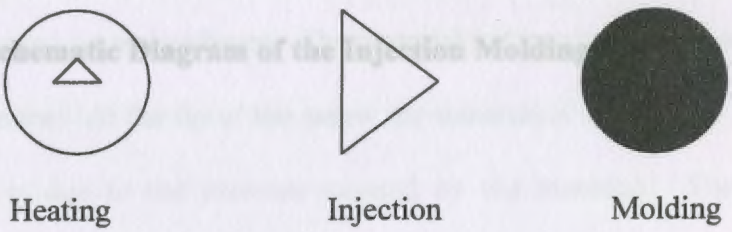


Figure 2.1 The Basic Cycle (Roasto, *et al* 2001)

2.2 Detailed description of injection molding machine:

The most recent injection molding machines are all hybrid (electrical and hydraulic). Because of ever growing demand for plastics the companies are trying to produce more cost-efficient products by using injection molding machines.

The type of injection molding machine that was used for this research is reciprocating (single-stage) screw machine. The primary components of this machine are a hopper which holds the raw material, a screw which delivers the raw material, a barrel which heats the raw material to its melting point using heating bands, a drive unit which delivers the molten plastic through the nozzle, and the mold which shapes the final part. Figure 2.2 shows the basic components of an injection molding machine.

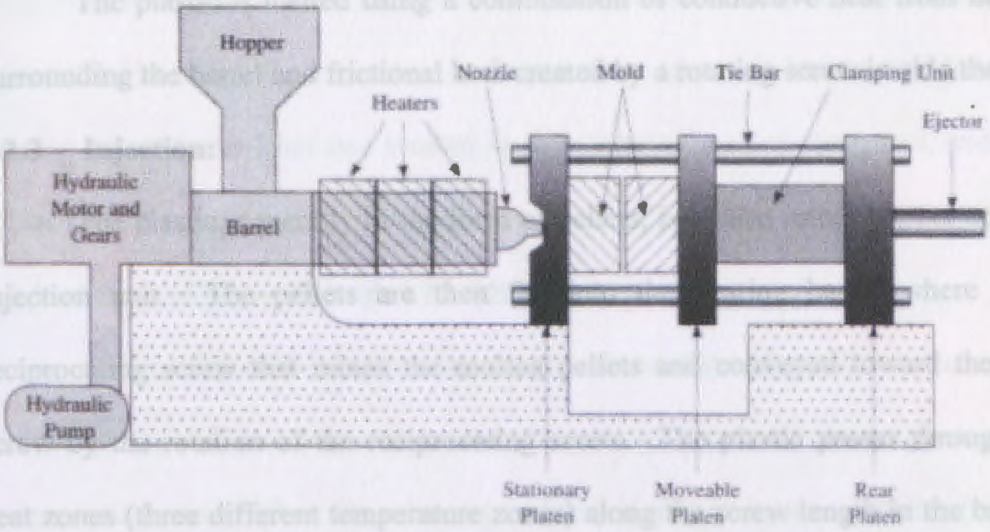


Figure 2.2 Schematic Diagram of the Injection Molding Machine

2.2.1 Drying:

Before using the polymer to make the desired product, moisture must first be removed. Successful molding of reinforced thermoplastics requires adequate drying. Inadequate drying can cause extremely erratic molding conditions and less than perfect molded parts. Excessively wet materials outgas and can undergo a viscosity change during processing. This may cause brittleness, blisters, voids, silver streaking, and poor surface finish. Condensed surface moisture can dramatically affect high temperature molded parts.

2.2.2 Heating:

The plastic is melted using a combination of conductive heat from heater bands surrounding the barrel and frictional heat created by a rotating screw in side the barrel.

2.2.3 Injection:

The plastic, generally in the form of pellets, is loaded into a hopper on top of the injection unit. The pellets are then fed into the heating barrel where there is a reciprocating screw that mixes the molten pellets and conveyed toward the tip of the screw by the rotation of the reciprocating screw. The plastic passes through different heat zones (three different temperature zones) along the screw length in the barrel where the pellets are heated up and softened. The material is forced down the screw channel by rotation of the screw. At the tip of the screw the material is completely melted and flow of the material is due to the pressure exerted by the machine. The injection stage primarily affects the cosmetics of the molded parts.

2.2.4 Reciprocating screw:

A reciprocating screw for an injection molding machine includes a heating extruder barrel in which the reciprocating screw is mounted. The barrel has an extruder head and a tail portion. The hopper is coupled with the tail portion of the barrel for feeding plastic granules into the barrel. The screw rotates in the barrel so as to move the plastic granules from tail portion to the extruder head, where the plastic melts gradually in the barrel to form a molten plastic, and extruding the molten plastic from the extruder head. A reservoir causes the screw to be forced backward in a linear motion. Once the amount of material in this reservoir reaches the prescribed shot or volume size, the rotation of the screw is stopped and the screw is forced forward by the hydraulic system. This force pushes the material in the reservoir through a nozzle.

A check valve in the extruder head prevents the return flow of the molten plastic material. The reciprocating screw is shaped as an eccentric screw, and has a threaded portion which has a front end located in the extruder head of the barrel, and a rear end located in the tail portion of the barrel.

2.2.5 Usage of Screw Injection Molding

A screw injection machine improves melt homogeneity, reduces variations in the molded parts, and minimizes degradations and cold spots of the polymer melt. The reciprocating screw offers the advantage of being able to inject a smaller percentage of the total shot (amount of melted resin in the barrel). A ram injector, in contrast, must typically inject at least 20% of the total shot while a screw injector can inject as little as 5% of the total shot. Essentially, the screw injector is better suited for producing smaller parts.

2.2.6 Molding and Clamping

The clamping unit holds the mold under pressure during the injection and cooling. Basically it holds the two halves of the injection mold together. Once the material leaves the nozzle, it goes into the cavity of the mold. Once inside the mold, the plastic may be held at temperature for a prescribed amount of time, called dwelling. The mold generally consists of a sprue, runner, gate, and mold system. The melt flows from the nozzle through the sprue, runners, gates, and to the molded part cavity, respectively. A hydraulic clamping unit supplies enough pressure to the mold to prevent premature opening of the mold cavity. As the polymer cools down, a holding pressure is applied to the melt to compensate for the material shrinkage during cooling. Once the material has been in the mold for the specified holding time, the mold is opened and the part is removed generally by the ejector pins, or manually if the part sticks to the mold walls and can not be removed automatically. The holding stage affects the dimensions of the molded parts.

During the entire processes, shown schematically in Figure 2.3, the material experiences a rather complicated flow, pressure, and temperature history. This range of processing conditions could lead to degradation of the material if the process is not monitored and controlled carefully.

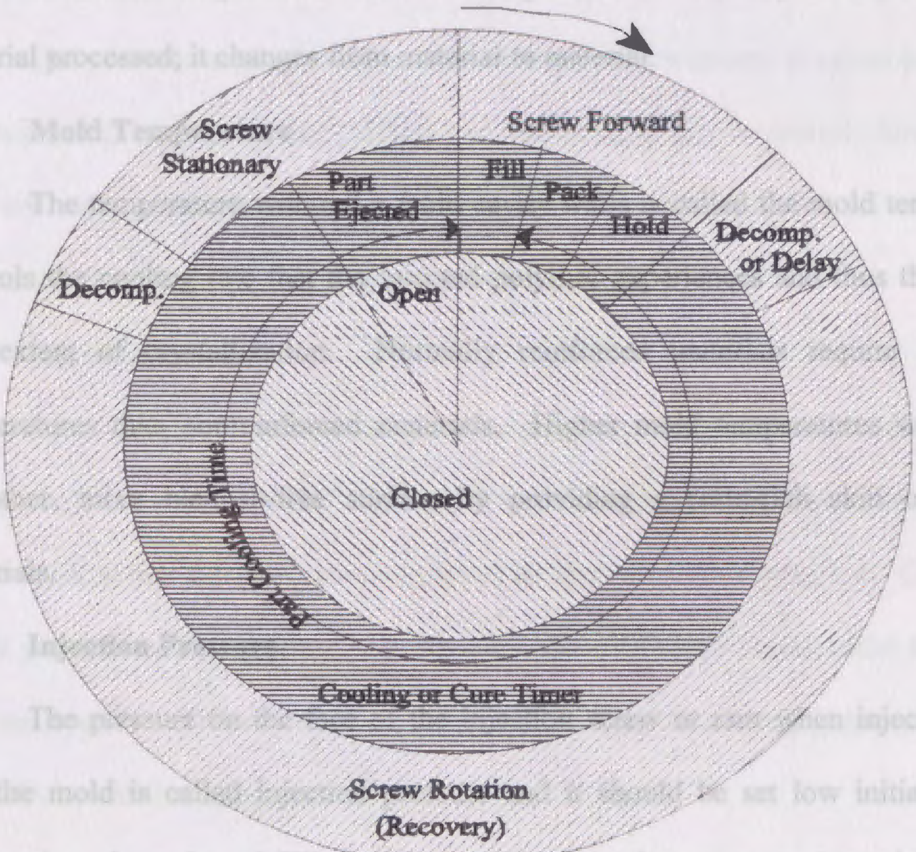


Figure 2.3 The Injection Molding Cycle

2.3 Parameters in Injection Molding

The main objective of any molder is to produce parts in a minimum cycle time and have a high quality. The following are the important variables that govern the quality of the parts, which can change from material to material.

2.3.1 Barrel Temperature

Typically the rear zone or zones are set 10-20 °F (6-12 °C) cooler than the front zone and nozzle. Some modifications may be needed depending on part size and configuration.

2.3.2 Melt Temperature

The melt temperature chosen during injection molding is dependent on the material processed; it changes from material to material.

2.3.3 Mold Temperature

The temperature within the mold cavity walls is called the mold temperature. It controls the cooling rate that the injected polymer experiences and thus the level, type and extent of crystallization. Normally reinforced materials require higher mold temperatures than nonreinforced materials. Higher mold temperatures will achieve a smoother, more blemish-free surface by providing a resin-rich skin on reinforced materials.

2.3.4 Injection Pressure

The pressure on the face of the injection screw or ram when injecting material into the mold is called injection pressure and it should be set low initially and then increased to the point of filling the part. The injection pressure depends on the flow resistance within the runners, gates, and mold cavity. This pressure differs from the hydraulic pressure.

2.3.5 Holding Pressure

The pressure exerted on the molded part while it is in the mold is called the holding pressure. The length and magnitude of this pressure determines the dimensional and cosmetic quality of the product. This pressure is generally responsible for providing additional material into the cavity during cooling to compensate for the shrinkage of the solidified layers. For the quality of the molded parts, compression and holding pressure are more important than the injection pressure.

2.3.6 Back Pressure

The pressure applied to the plastic during screw recovery is called back pressure. By increasing back pressure, mixing and plasticating are improved; however, screw recovery rates are reduced.Low back pressure (approximately 50 psi or 0.34 MPa) minimizes fiber breakage and property deterioration.

2.3.7 Injection speed

Injection speed is the velocity of the screw by which the molten material moves forward and fills out the mold. This speed is proportional to the flow rate and inversely proportional to the fill time (injection time) as shown in the Figure 2.4. Generally, the fastest possible cavity fill time is preferred. The difference between the fast and slow injection speeds are clearly shown in Figure 2.5. This minimizes glass orientation and maximizes weld line integrity.

2.3.8 Screw Rotational Speed

The lowest possible rotational speed is recommended to minimize fiber breakage and screw recovery should be set accordingly. A slower rotational speed results in a more uniform melt by minimizing shear heat buildup.

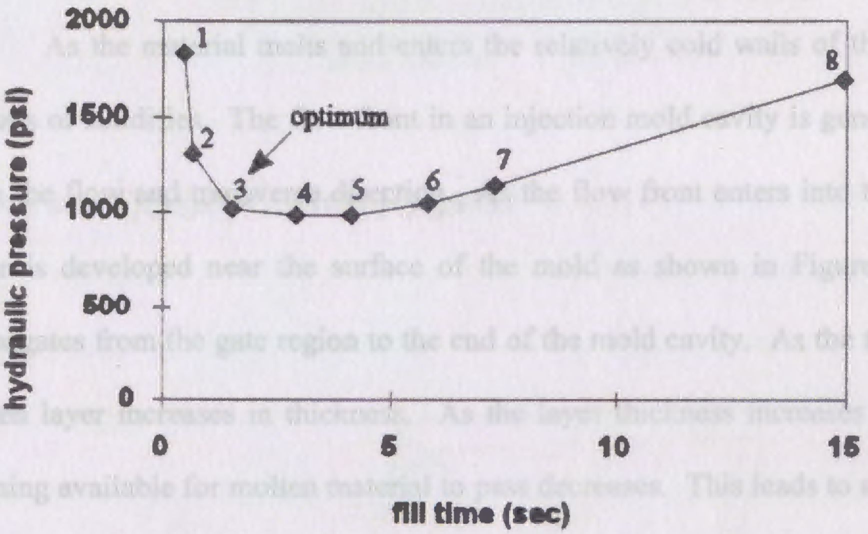


Figure 2.4 Fill Time is Inversely Proportional to Injection Velocity

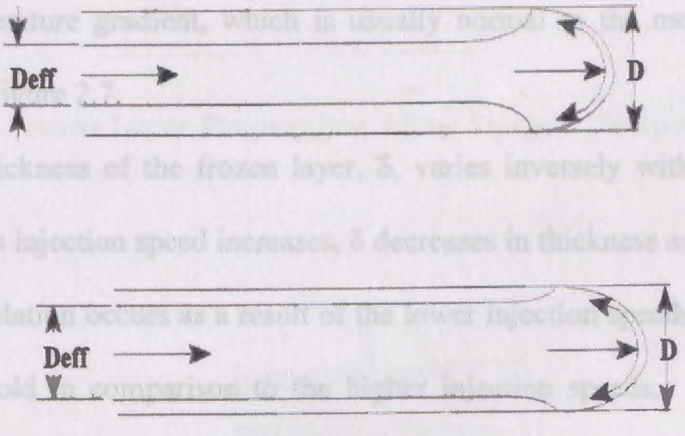


Figure 2.5 Flow Path for Slow and Fast Injection Speeds, Respectively

2.4 Frozen Layer Development

The processing variables affect the structural, mechanical and physical properties of any material, but the internal structure of the material plays an important role in the quality of the molded part and thus it is important to study the internal structure with great care.

As the material melts and enters the relatively cold walls of the mold it quickly freezes or solidifies. The flow front in an injection mold cavity is generally parabolic in both the flow and transverse direction. As the flow front enters into the mold, a frozen layer is developed near the surface of the mold as shown in Figure 2.6. This layer propagates from the gate region to the end of the mold cavity. As the time increases this frozen layer increases in thickness. As the layer thickness increases near the gate the opening available for molten material to pass decreases. This leads to a bell-like velocity profile in areas behind the flow front. The thickness direction is effected much more by this phenomenon than the width direction. This frozen layer propagates along the steepest temperature gradient, which is usually normal to the mold surface as clearly shown in the Figure 2.7.

The thickness of the frozen layer, δ, varies inversely with injection speed. In other words, as injection speed increases, δ decreases in thickness as shown in Figure 2.8. This inverse relation occurs as a result of the lower injection speeds having more time to cool in the mold in comparison to the higher injection speeds. Taking this one step further, at lower injection speeds polymers experience higher shear rates due to it having less of melt cross section area to the flow through. The injection speed and the solidification front governs the formation near the skin region.

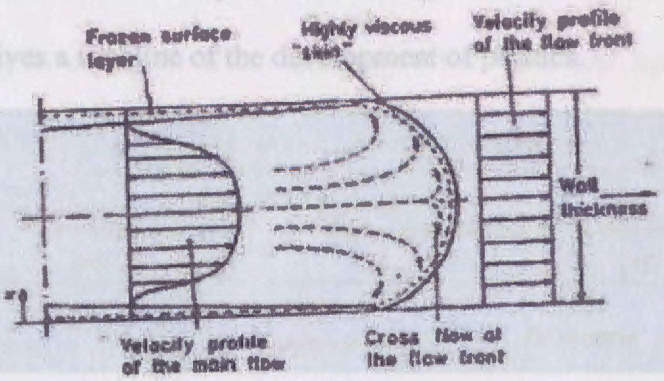


Figure 2.6 Frozen Layer Development

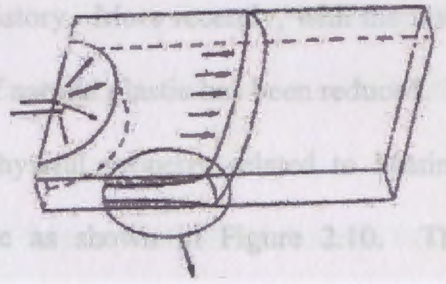


Figure 2.7 Frozen Layer Propagation Along Steepest Temperature Gradient

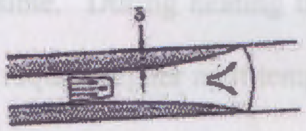


Figure 2.8 Thickness of Frozen Layer

2.5 Types of Plastics Used in Injection Molding

Figure 2.9 gives a timeline of the development of plastics.

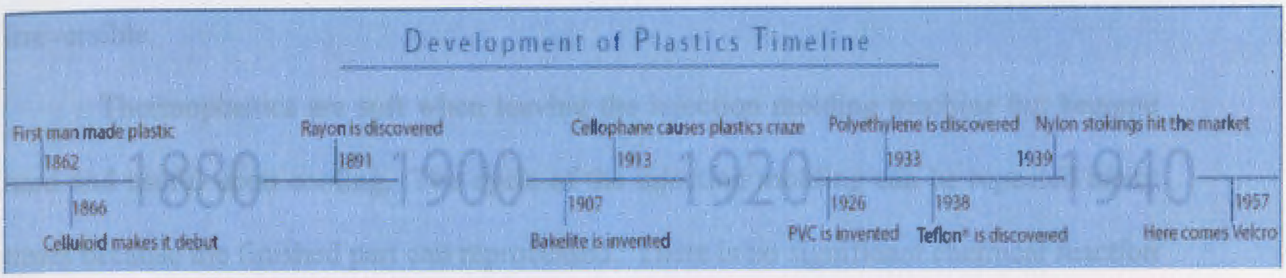


Figure 2.9 Brief History of Plastics

A compound consisting of large molecules made up of linked series of repeated smaller molecules called monomers. Organic polymers materials are of two types i.e. natural plastic and synthetic plastics. Natural polymers, such as starch and cellulose, have been used throughout history. More recently, with the invention and production of synthetic polymers, the use of natural plastic has been reduced. The synthetic plastics are classified based upon the physical property related to heating are of two types i.e. thermosets and thermoplastic as shown in Figure 2.10. Thermoplastics which are predominantly used can go through repeated cycles of heating and melting at least up to 500 °F and cooling and solidification. The different thermoplastics have different practical limitations on the number of heating and cooling cycles before appearance or properties are affected. Thermosets upon their final heating at least to 248 °F become permanently insoluble and infusible. During heating they undergo a chemical or cross linking change. Certain plastics require higher melt temperatures.

A thermoset plastic is one in which cross linking is stopped early in the reaction. The reaction either will not continue, or will continue at a very slow rate, under normal conditions. Its is an advantage by using the injection molding machine as the temperature will be high and the reaction will complete in seconds. Once the reaction is complete, the material will not again soften to allow molding. This is a one time process and is irreversible.

Thermoplastics are soft when leaving the injection molding machine but become hard and useful upon cooling. The cycle of the injection molding can be repeated many times because the finished part can reprocessed. There is no significant chemical reaction during the processing of thermoplastics other then some degradation of the physical properties. Common thermoplastics are seen in every day life. Most jars and bottles containing liquids or medicines are made of thermoplastics such as polyethylene or polystyrene.

There are many more molders processing thermoplastics than are processing thermosets simply because thermoplastics can be recycled whereas thermosets can be used only once. Crystalline and amorphous types of thermoplastics are used in the injection molding. The type of thermoplastic that is used in this research is crystalline.

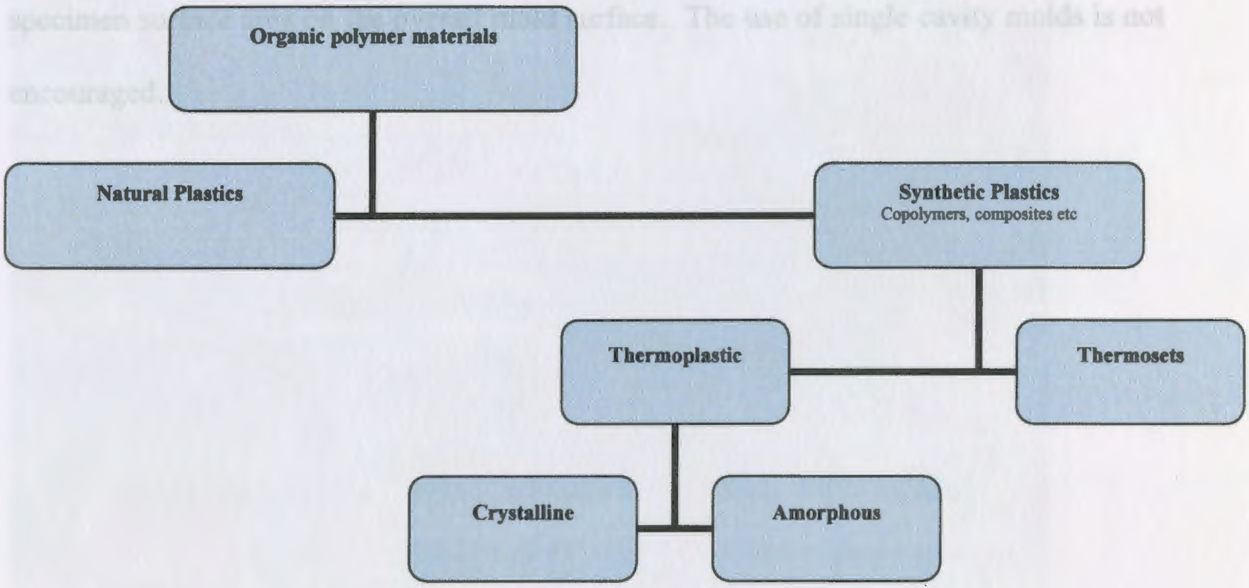


Figure 2.10 Classification of Organic Polymer Materials

2.6 Mold design

Most of the mold cores and cavities for injection molding is stainless steel. Type 420 stainless steel is used but mostly 414 prehardened stainless steel has been found to have good chemical resistance, is easily repairable. 316 stainless steel molds were used in this research. The moving parts of the mold are made from hardened steel and plated.

In this research two different molds were used; a two-cavity (Figure 2.11) and a four-cavity mold (Figure 2.12). Both the molds have been designed by MYCO PLASTICS (Newton Falls, OH). One the goals of the research are to compare any differences which arise by the design of the mold on the mechanical properties of the final product.

The design of the mold is one of the more critical variables affecting specimen properties. Optimum reproducibility requires that identical molds be used in order to get comparable results. Multi-cavity molds with identical cavities are recommended. The cavity layout should be such that there is a uniform and symmetrical distribution of specimen surface area on the overall mold surface. The use of single cavity molds is not encouraged.

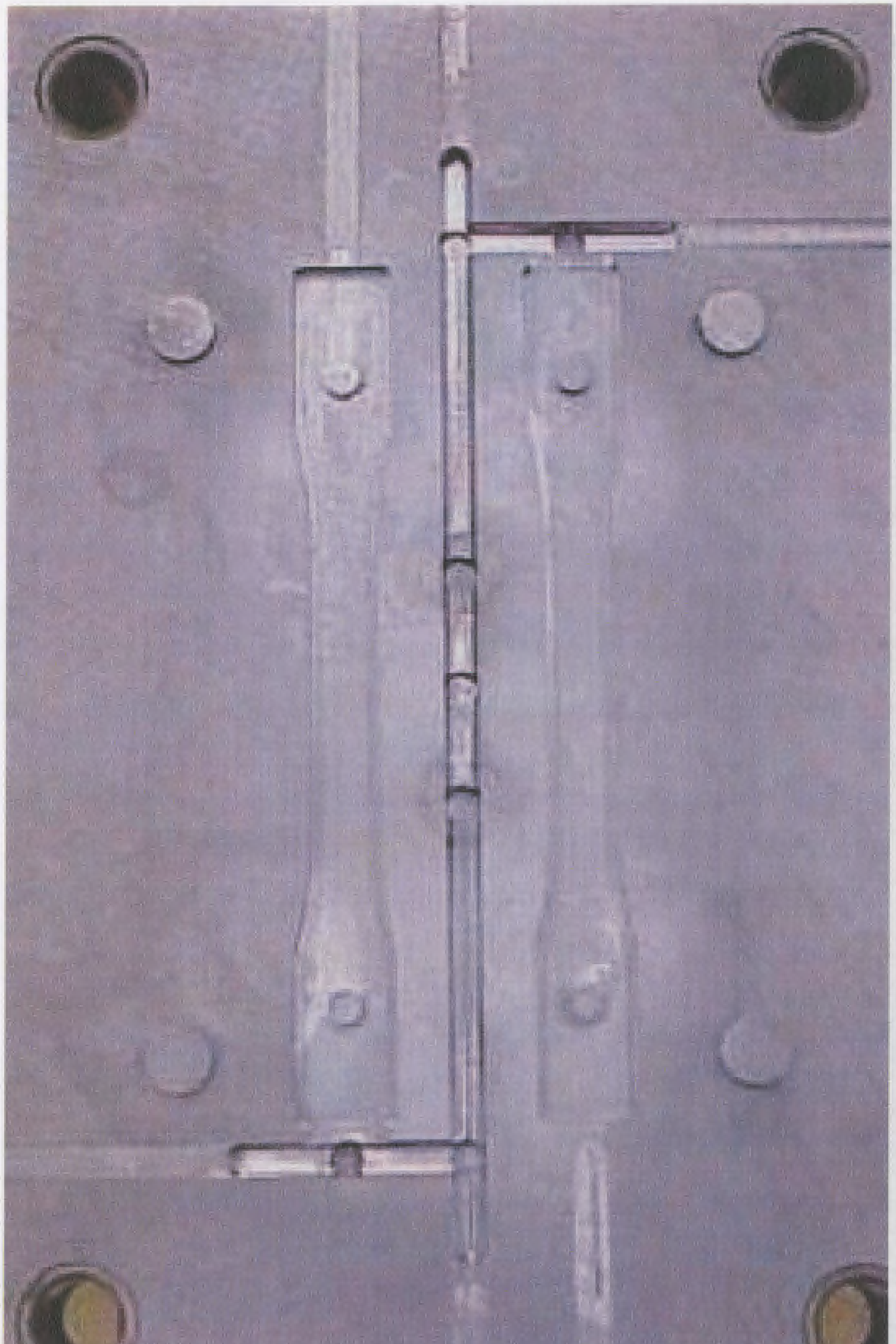


Figure 2.11 Two-Cavity Mold Design

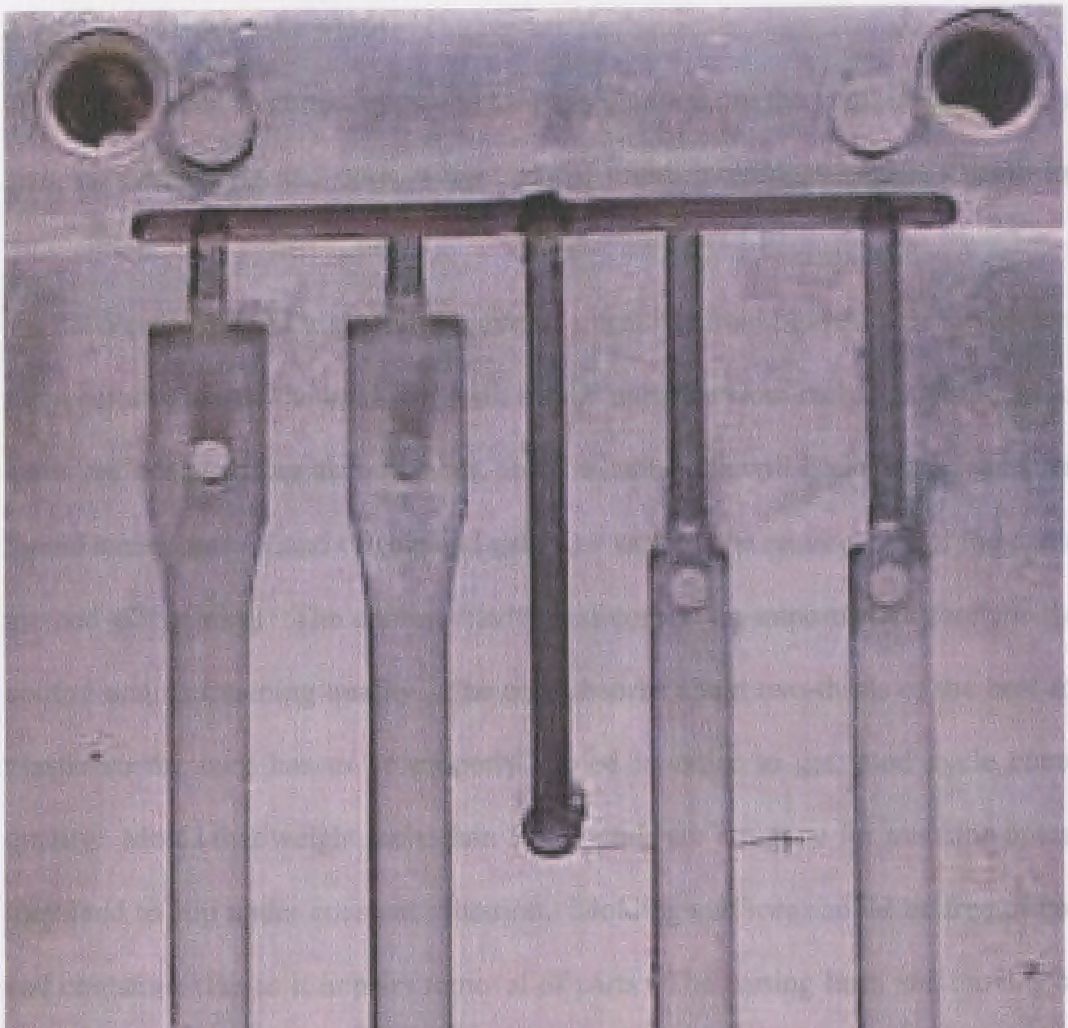


Figure 2.12 Four-Cavity Mold Design

2.7 Features of the Mold

The mold features that need close examination are the vent, land of gate and gate size, cooling cavity and core, weight of the mold, molding surfaces, parting line, and moving sections.

Vents are used to permit the displacement of air and gases from the cavity so that the incoming plastic material will form a solid part free from included gas pockets. If the vents are not in proper size, number, and location there will be lot of deficiencies in the manufactured part. Land of gate and gate size vary by the requirement of the part and the method of molding. The cooling cavity and core is an important feature for the cycle control and maintaining quality. The core absorbs about two-thirds of the heat from the plastic so the core has to be properly cooled in order to get good cycle control and quality. Molds that weight more than 500 pounds are not good for machine operation as they tend to slip under constant vibration. Molding surfaces should be free of corrosion and contamination as it impairs removal of parts. The parting lines and moving sections in the mold should be as smooth as possible as it may impair smooth operation.

2.8 General Purpose Polystyrene (GPPS)

General-purpose polystyrene is produced by joining styrene monomer molecules into long polymer chains with each chain representing one large molecule. Chain lengths may vary, depending on manufacturing conditions, but most commercial products have between 100 and 5,000 monomer units per chain. The GPPS used in this research was in pellet form and supplied by Capco Polymer Industries (Columbiana, OH).

2.9 Properties of GPPS

GPPS has excellent clarity, rigidity and dimensional stability (John, Duane 2003, 248) and is easy to mold. Its extreme clarity, ability to be colored and high refractive index gives it a glass-like sparkle, but it is brittle and cracks easily. It is used when optical attractiveness and low cost are sought, and the mechanical loading is light. Cosmetic comapcts, transparent but disposable glasses, cassettes of all kinds (Michael and Kara 2003) are commonly made of this material. GPPS provides a balance of good flow properties for ease of molding and good mechanical properties (Edward 1996) and its low water absorption makes it easy for molding as well as testing. Tables 2.1 and 2.2 list the chemical compatibilities and mechanical properties of GPPS.

Table 2.1 Resistance of General Purpose Polystyrene on Chemicals

Dilute acid	Good
Dilute alkalis	Very good
Oils and greases	Good
Aliphatic hydrocarbons	Very good
Aromatic hydrocarbons	Poor
Halogenated hydrocarbons	Poor
Alcohols	Moderate

Table 2.2 Mechanical Properties of General Purpose Polystyrene (Brydson, 2002)

Property	Test Method	Value
Tensile strength (M pa)	ASTM D-638	40 - 48
Elongation (%)	ASTM D-638	1.0 - 2.5
Modulus in tension (M pa)	ASTM D-638	35
Yield strength (M pa)	ASTM D-638	5 - 10
Total Elongation (%)		1.0 - 2.5
Density (g/cm^3)		1.11 - 1.12

2.10 Advantages of GPPS

The use of GPPS compared to other synthetic polymers has the following advantages:

- Excellent general properties: exceptional clarity, attractive light-transmission properties, chemical resistance and radiation stability
- Optimum lot-to-lot consistency: continuous process proprietary to Dow ensures superior consistency in clarity, processability, and reliable end-product performance.
- Economic advantages: easier flow processing can decrease machine wear and increase energy efficiency. Lot-to-lot consistency increases quality yields and improves overall productivity

2.11 Crazing

During the mechanical loading, glassy polymers show the formation of narrow, long bands-so called crazes as seen in Figure 2.13. There is conclusive evidence that crazing is a precursor to fracture in a wide range of glassy polymers (Berry 1961, 1962; Spurr and Niegisch 1962; Rabinowitz and Beardmore 1972).

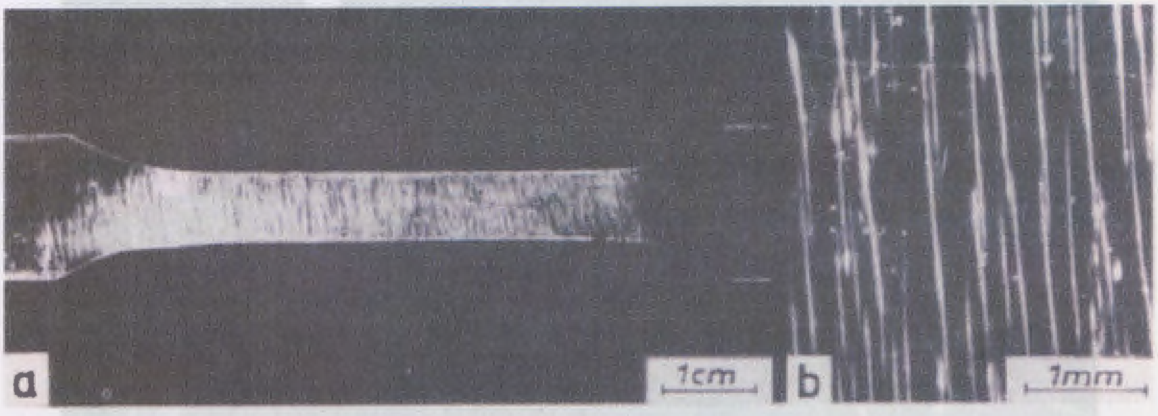


Figure 2.13 Tensile sample of Polystyrene with crazes a) Total view; b) small light optical magnification (Michler 1985)

The fracture surface can be divided into two main regions; the smooth mirror region associated with the propagation of the crack within the pre-existing first craze in which brittle fracture in nucleated, and a rough region, usually called hackle, which is associated with the propagation of the crack through bundles of crazes which form ahead of the crack tip (Hull 1970; Bevis and Hull 1970).The direction of propagation is from tip to the centre. Within the hackle bands the relatively smooth regions of the type indicated at *Y* are similar in morphology to the region *X* of the mirror region, shown in Figure 2.14. In general the regions corresponding to *X* and *Y* also exhibit ridges which tend to be parallel to the tip *T-T* of the craze. This kind of morphology is usually referred to as the patch pattern and a specific variant of patch is the mackerel pattern (Murray and Hull 1970).

Figure 2.14 Mirror and Hackle Regions

From criteria for craze formation (Sternstein, Ongchin and Silverman 1969; Bevis and Hull 1970) it follows that new crazes are not nucleated directly ahead of the crack tip but from a region slightly removed from it. Thus when the crack propagates outside the first-formed craze it is necessary for the crack to jump in an irregular way into the closely adjacent crazes which have formed near the crack tip.

A schematic diagram of a craze-controlled fracture process is shown in Figure 2.15 and illustrates the ridged fractured surface corresponding to the patch/mackerel region. Figure 2.15 clearly shows how the initiation region and mackerel regions looks before and after tensile testing.

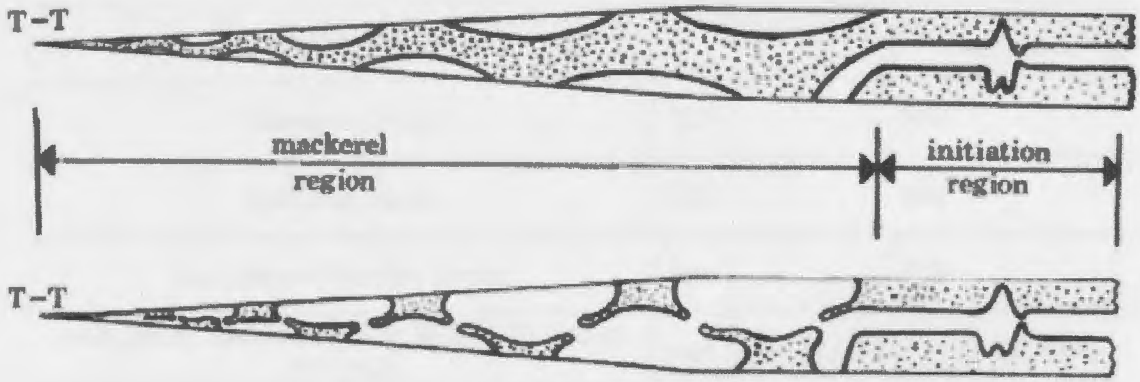


Figure 2.15 Schematic of Craze-Controlled Fracture Process Illustrating the Craze Morphology Just Before, and After, Failure.

The close similarity between the morphology of the fracture surfaces in the outer zone of the mirror region and in the hackle region indicates that similar mechanisms of craze breakdown are involved The study of the micro morphology on general purpose polystyrene tensile specimens is done by injection molding machine in this research.

CHAPTER 3

TEST METHODS AND PROCEDEURES

3.1 Injection Molding Procedure

The injection molding machine that is used in the research was purchased from Van Dorn Demag Plastics Group. The unit is a 55-ton hydraulic Ergotech EXTRA 50-200, with a 3-ounce shot size capacity. More technical data of the injection molding machine that has been used in the research is given in Table 3.1

Table 3.1 Technical Data of ErgoTech Injection Molding Machine

Model Description		Ergotech Extra 50-200
International Size Classification		500-200, 500-310
Clamping Unit		50
Clamping Force	KN	500
Locking Force	KN	500
Maximum Opening Stroke	mm	400
Minimum Mold Mounting Height/Reduced (ZE 214)	mm	210/(160/135 with ZE 214)
Maximum Mold Mounting Height	mm	-
Maximum Daylight Between Platens	mm	610
Overall Size Platens, H x W	mm	480 x 480
Clear distance between tie bars, H x W	mm	355 x 355
Maximum Mold Weight	kg	400
Maximum Weight on the Moving Mold Mounting Platen	kg	270

To operate the unit, the hold and back pressure, shot size, mold and melt temperatures, injection pressure and speed were first set on the digital control panel. The nozzle temperature was set to a temperature of 420 °Fahrenheit, approximately ten minutes after the thermocouples along the barrel read the same temperature, and then the injection molding cycle was started. The cure time that is used for GPPS is 45 seconds.

There are three different temperature zones inside the barrel; BZ3, the zone nearest to the nozzle, BZ2, the middle zone, and BZ1, the zone nearest to the feed. The actual temperatures used for GPPS (BZ1, BZ2, and BZ3) were 370, 380, and 390 °F, respectively. The feed temperature was 150 °F. The injection speed was varied from 3.0 to 2.5 in/second for the two different molds (see Chapter 2 for description) that were used. Care was taken to keep the oil temperature at a steady value of 170 °F. The cooling system was activated as soon as the injection molding machine is turned to keep the oil temperature to a steady value.

The injection unit was moved forward until the nozzle was flush with the sprue. Polymeric melt was then injected into the mold by the injection unit. The ram was retracted, while allowing the melt to cool in the mold, and the screw was refilled. Finally, the mold was opened and parts ejected. After the start of each new processing condition, the first samples were discarded before starting to collect molded samples. This procedure assured establishment of equilibrium within the machine. For each processing condition ten to twelve samples were obtained.

The mold was connected to a portable chiller and to a heating system to keep the mold at constant temperature. The portable chiller (IMS Model 108141 Temkon-SS, Chagrin Falls, OH) was set at 60 °F.

3.2 Standard Test Method for Tensile Properties of Plastics (D638-03):

3.2.1 Tensile testing:

This test method covers the determination of the tensile properties of unreinforced and reinforced plastics in the form of standard dumbbell-shaped test specimens when tested under defined conditions of pretreatment, temperature, humidity and testing machine speed. This test method is designed to produce tensile property data for the control and specification of plastic materials

3.2.2 Apparatus

Tensile testing was performed on an INSTRON Universal Testing Machine (Model 2512-304) which can test up to 150 kN. Five samples were pulled for each unique processing condition and the results were averaged. A crosshead speed of 5 mm/min was used. The samples were conditioned at 23 ± 2° C and 50 ± 5% relative humidity for not less than 40 hours prior to test the in accordance with the ASTM D-638-03 Method. Tensile testing was conducted at 23 ± 2° C and 50 ± 5% relative humidity. The software used to control the machine and calculate the results was Instron Series IX, from which the load, displacement, stress, strain, Young's modulus were calculated.

3.2.3 Test specimens

The test specimens conformed to the dimensions shown in the Figure 3.1 and Table 3.2.

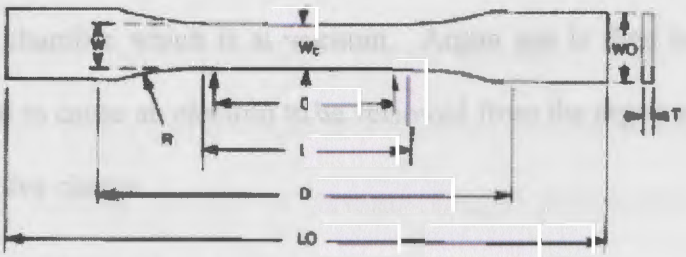


Figure 3.1 Type I Specimen

Table 3.2 Type I Specimen Dimensions for Thickness, T, mm. [in.]

Dimensions (see Figure 3.1)	Type I mm [in]
W - Width of Narrow Section	13 [0.50]
L - Length of Narrow Section	57 [2.25]
WO - Width Overall	19 [0.75]
LO - Length Overall, minimum	165 [6.5]
G - Gage Length	50 [2.00]
D - Distance Between Grips	115 [4.5]
R - Radius of Fillet	76 [3.00]

3.3 Scanning Electron Microscopy (SEM)

3.3.1 Sample Preparation

Since the SEM uses electrons to produce an image, most conventional SEM's require that the samples be electrically conductive. Specially designed SEM's called environmental SEM's are now available which can be used to view non-conductive or even wet samples. All metals are conductive and require no preparation to be viewed using a SEM. In order to view non-conductive samples such as ceramics or plastics, the sample is covered with a thin layer of a conductive material for which a small device called a sputter coater. An example of such a device is shown in Figure 3.2.

The sputter coater uses argon gas and a small electric field. The sample is placed in a small chamber which is at vacuum. Argon gas is then introduced and an electric field is used to cause an electron to be removed from the argon atoms thus producing ions with a positive charge.

Figure 3.2 Sputter Coater

The positively charged argon ions are then attracted to a negatively charged foil of palladium. The argon ions act like sand in a sandblaster, knocking palladium atoms from the surface of the foil. These palladium atoms now settle onto the surface of the sample, producing a palladium coating.

After the tensile testing the samples are cut to 0.25-inch size to obtain a surface with preserved morphology. All water, solvents, or other materials that could vaporize while in the vacuum must be removed. The samples were mounted on a specimen stub before the sputter coating procedure. The samples were sputter-coated with palladium by using a sputter coater and analyzed in a scanning electron microscope under a voltage of 25 KV and working distance as 10 mm. Digital photographs were then taken of the specimens.

CHAPTER 4

RESULTS AND CONCLUSIONS

The mechanical properties of two-cavity and four-cavity molds have been calculated individually and also these properties have been compared with each other. The mechanical properties that are taken into account for this research using GPPS are load, displacement, stress, strain and Young's modulus. These properties have been calculated at different injection speeds ranging from 3.0 to 2.5 in/second for each mold.

4.1 Four-Cavity Mold

For samples produced using the four-cavity mold, the mechanical properties were calculated for specimens located near and away from the sprue to determine if the position within the mold has a significant affect. The mechanical properties were determined with the Instron testing machine and Series IX software, both of which are described in Chapter 3. For each process condition, five samples were tested according to ASTM D-638 method and averaged. The injection speed was varied from 2.5 to 3.0 in/second, and the displacement at peak, load at peak, stress at peak, strain at break, and Young's modulus were determined for each sample.

4.2 Two-Cavity Mold

According to the literature a two-cavity mold where each cavity is equidistant from the sprue should provide a more uniform sample set than the inherently asymmetric four-cavity mold. Samples from the two-cavity mold were designated by the cavity from which they were formed in order to determine if there was any asymmetry within the mold itself. The two cavities were identified as either *upper* or *lower*. The results from the two-cavity mold and four cavity mold are listed in Tables 4.2 - 4.19.

4.3 Stress-Strain diagrams

Following ASTM D-638 Method, the load and elongation (displacement) data were collected and plotted against each other as shown in Figures 4.6 - 4.29. The nominal or engineering stress can be calculated from the recorded data by dividing the applied load p by specimen's original cross-sectional area A_0. This calculation assumes that the stress is constant over the cross section and throughout the region between the gauge points. Engineering strain is the elongation per unit length.

Materials that exhibit little or no yielding before failure are referred to as brittle materials and GPPS is an example of brittle material. Figure 4.1 shows a stress/strain curve commonly encountered with brittle materials. Initially, the fracture takes place at an imperfection or microscopic crack and then spreads rapidly across the specimen causing complete fracture. As a result of this failure, GPPS does not have a well-defined tensile fracture stress, since the appearance of cracks in a specimen is quite random.

Stress versus strain curves for different types of polymer were classified some years ago by Carswell and Nason in to five main groups

1. Weak and Soft
2. Hard and Brittle
3. Hard and Strong
4. Soft and Tough
5. Hard and Tough, Ideal Elastomer

GPPS has a fairly high tensile strength and quite high moduli of elasticity at room temperature, but often breaks with an elongation of no more than 1%.

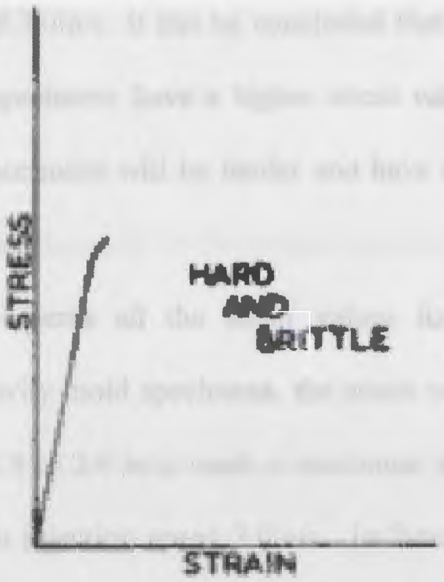


Figure 4.1 Stress-Strain Diagram for Hard and Brittle Materials

The stress-stain graph is very steep and almost linear, and flattens only slightly near the break point, which is similar to metals. These materials deform only to a small extent at relatively high loads. All the stress-strain diagrams that were collected in this research are similar to that in Figure 4.1

The average values from the results in Tables 4.2 - 4.19 are tabulated in Table 4.20 (close to sprue for the 4-cavity mold), Table 4.21 (away from sprue for the 4-cavity mold), and Table 4.22 (2-cavity mold). When examining the data for the four-cavity mold found in Tables 4.20 and 4.21, it can be seen that there is no significant difference in the stress and strain for the specimens close to and away from sprue. Comparing the 4-cavity mold to the 2-cavity mold, as shown in Figures 4.54 - 4.56, the stress values for 2-cavity mold samples are higher than the 4-cavity mold as the injection speed increases from 2.5 in/s to 2.8 in/s. The stress values are almost linear and reach a maximum at the injection speed 2.8 in/s, after which the stress values decreased and became nearly equal at an injection speed of 3.0in/s It can be concluded that in a 2-cavity mold at injection speed of 2.8 in/s the specimens have a higher stress value than any of the specimens, indicating that these specimens will be harder and have more resistance upon load than the rest of the specimens.

Figure 4.57 compares all the strain values for 2-cavity and 4-cavity mold specimens. In the 4-cavity mold specimens, the strain values are linear as the injection speed increases from 2.5 to 2.9 in/s, reach a maximum value at injection speed 2.9in/s, and then decrease at an injection speed 3.0in/s. In 2-cavity mold the strain values are maintained at a steady value. At an injection speed 3.0 in/s for the 4-cavity mold there will be less elongation than any of the specimens in both the molds. At an injection speed of 2.9 in/s for the 4-cavity mold there will be more elongation than any of specimens in both molds. It can be concluded at injection speed 3.0in/s for a 4-cavity mold the specimens will be more brittle than any of the specimens in both the molds and at injection speed 2.9 in/s for a 4-cavity mold the specimens will be less brittle than any of the specimens in both the molds.

The stronger the bond in the material the higher the Young's modulus. Unlike other mechanical properties, a material's modulus of elasticity is not affected by microstructure but is only affected by the bond strength between the atoms. Figure 4.58 compares the Young's modulus values as the injection speed increases from 2.5 to 3.0 in/s. Young's modulus values are almost steady at injection speeds from 2.6 to 2.9 in/s for a 2-cavity mold but it has a higher value at an injection speed of 2.5 in/s and a lower value at injection speed 3.0 in/s. It can be concluded that as the injection speed increases the bond strength decreases. The specimens obtained at an injection speed 2.5 in/s in a 2-cavity mold have a higher value of Young's modulus than any of the specimens in any of the molds. It can be concluded that the specimens at injection speed 2.5 in/s from a 2-cavity mold will be stronger and more brittle whereas the specimens from the 4-cavity mold at injection speed 2.5in/s will be the weaker and more brittle.

4.4 T-Test Results

Engineers and scientists are often interested in comparing two different conditions to determine whether either condition produces a significant effect on the response that is observed. These conditions are sometimes called treatments. Displacement, load, stress, strain and Young's modulus are compared between the samples fabricated from the two different molds.

Five random test specimens for each injection speed were used for comparison by using a two-sided T-Test with unequal variances. When statistical significance is observed at a risk level of 0.05, it can be concluded that it was the difference in treatments that resulted in the difference in response.

The displacement measurements showed no statistically significant difference except at an injection speed 3.0in/s, where the samples taken from the 2-cavity mold actually showed differences between the two cavities (see Table 4.23). For the load measurements, the only population which showed significant differences was in the 4-cavity mold at an injection speed of 2.8 in/s, shown in Table 4.24. For strain, the only condition resulting in samples having statistically significant differences was the 2-cavity mold at an injection speed of 3.0 in/s (Table 4.25) And finally for the stress measurements, only the 4-cavity mold at 2.8 in/s injection speed showed any differences between the two samples collected from the mold (Table 4.26).

4.5 Scanning Electron Microscopy

Scanning electron microscope observations were made on tensile-tested specimens. Before observation in the scanning electron microscope the fracture surfaces were coated with a thin layer of palladium using the sputter coater described in Chapter 3.

All the samples in this research follow the same pattern and morphology as the patch pattern and a specific variant of patch is the mackerel pattern (Murray and Hull 1970 a) and thus agree with the above-mentioned authors' work.

The morphology of the fracture surfaces of polystyrene tested in uniaxial tension has been described by Wolock and Newman (1964), Bird, Mann, Pogany, and Rooney (1966), Murray and Hull (1970 a, b, c). This research refers to their study and attempts to improve the model and in particular to identify micromorphology detail which can be related to the variation in the micromorphology of crazes detailed in Figure 4.2. It is seen in this figure that the variation in micromorphology along the length of a craze shows the proposed relationship between the micromorphology of the craze and the modes of fracture which occurred in the test specimens. The only difference between prior studies and this research is that the samples have been made by using injection molding machine at different injection speeds.

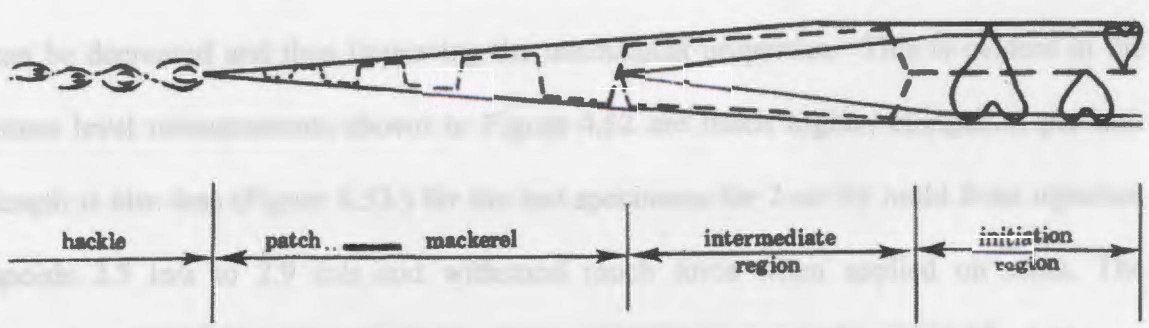


Figure 4.2 The Development of the Model (Beahan *et al.* 1972)

All the test specimens of general purpose polystyrene have crazes in their micro morphology which vary markedly along and through the thickness of a craze. All the test specimens have a similar kind of pattern along the borders of the sample and this research attempts to develop a model based on the thickness of the craze and injection speed. The thickness calculations are presented in Table 4.1 The micrographs relating to the thickness along the border of the specimens are seen in Figures 4.59 - 4.62 and the measurements are listed in Table 4.1. No statistically significant differences were seen between the samples for this measurement.

The fracture process occurs on three levels; 1) the bottom of the craze, 2) the center of the craze and 3) the top of the craze. The fracture in the intermediate region results in the formation of steps on the fracture surface which are parallel to the overall direction of crack propagation. The formation of steps was not observed in the 2-cavity mold except for one sample at an injection speed 3.0 in/sec. In the 4-cavity mold all the test specimens that were close to sprue had this pattern while all the samples that were away from the sprue did not have this pattern except the one produced at an injection speed 3.0 in/sec. The samples from the 2-cavity mold using an injection speed 2.5 to 2.9 in/sec clearly contradict the work done by Beahan, Bevis and Hull. This research concludes that by using a balanced mold at slow injection speeds, the intensity of crazes can be decreased and thus improving the mechanical properties. This is evident in the stress level measurements shown in Figure 4.52 are much higher, elongation per unit length is also less (Figure 4.53.) for the test specimens for 2-cavity mold from injection speeds 2.5 in/s to 2.9 in/s and withstand much force when applied on them. The formations of steps in these samples mentioned above are seen in Figures 4.63 - 4.71.

Table 4.1 Average Thickness along the all the Specimens

Injection speed(in/s),position in the mold	Sample code	Average Thickness along the specimens (microns µ)
2-cavity mold		
2.9,Upper	1	296.00
2.9,Lower	2	276.67
2.8,Upper	3	258.86
2.8,Lower	4	398.58
2.7,Upper	5	242.41
2.7,Lower	6	261.54
2.6,Upper	7	321.97
2.6,Lower	8	214.29
2.5,Upper	9	418.18
2.5,Lower	10	256.04
3.0,Upper	11	225.27
3.0,Lower	12	323.24
4-cavity mold.		
2.9,close to sprue	13	228.95
2.9,away from sprue	14	297.53
2.8,close to sprue	15	309.20
2.8,away from sprue	16	273.86
2.7,close to sprue	17	300.00
2.7,away from sprue	18	267.24
2.6,close to sprue	19	336.30
2.6,away from sprue	20	241.21
2.5,close to sprue	21	205.31
2.5,away from sprue	22	222.51
3.0,away from sprue	23	228.70
3.0,close to sprue	24	269.44

Secondary fracture features such as those indicated by ***S*** in Figure 4.3 are observed on all three levels in the slow growth and intermediate regions. Secondary fracture features are not observed in the mackerel and patch regions of the fracture surface.

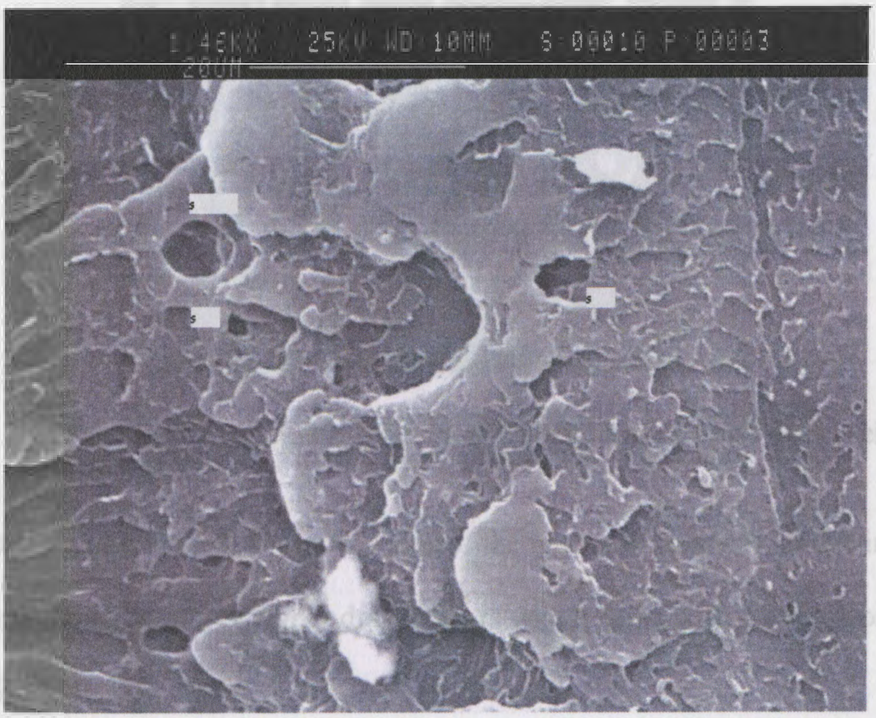


Figure 4.3 Secondary Fracture Process in Slow and Intermediate Regions

There are two additional features of the morphology of the mackerel bands. First, the existence of tails on sections of the top edge of the band which occur predominantly on the edge of the band which occur predominantly on the edge away from the nucleation region of the crack. Secondly, changes in contrast effects occur in the step on the sides of the bands (Beahan, Bevis, Hull 1975). The same pattern is observed in injection molded samples but only in few of the samples of this research. Only samples taken from the 4-cavity mold close to the sprue exhibited this pattern, shown in Figure 4.4

The highly strained material would be expected to result in the preferential absorption of electrons in the scanning electron microscope and this region would appear dark on the micrographs.

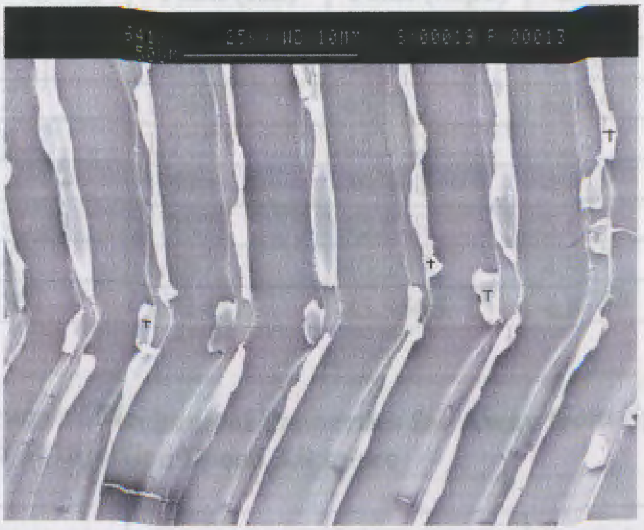


Figure 4.4 **Steps in the Mackerel Region of Craze Failure and Mackerel Bands with Tails**

There is a strong contrast on the sides of the mackerel bands as shown in Figure 4.5; delineating the regions of highly drawn fibers which agree with the work of Beahan, Bevis and Hull (1975).

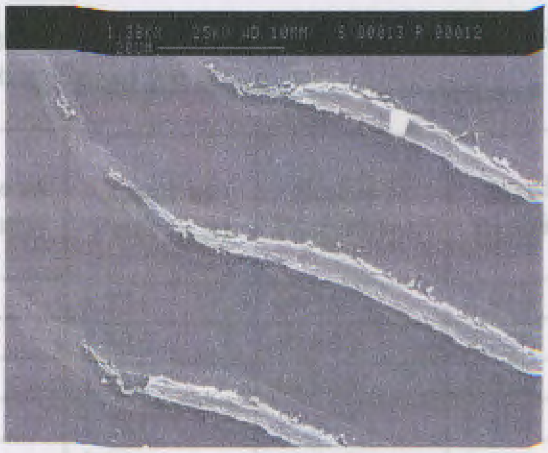


Figure 4.5 **Contrast on the Sides of the Mackerel Bands**

Table 4.2 **Average of Mechanical Properties for Close to Sprue, 4-Cavity Mold at Injection Speed 3.0 in/sec**

Injection Speed, (in/s), Sample ID.	Distance at Peak (mm)	Load at Peak (Kn)	Stress at Peak (Mpa)	Strain at Break (%)	Young's Modulus
3.0, gpps1	1.251	1.618	41.495	2.462	2084.438
3.0, gpps3	3.012	1.767	45.313	6.024	1034.413
3.0, gpps5	2.875	1.775	45.502	5.75	1311.244
3.0, gpps7	2.21	1.572	40.301	4.419	1037.252
3.0, gpps9	2.817	1.787	45.829	5.633	1078.226
3.0, gpps11	2.484	1.767	45.299	4.967	1067.977
Average	**2.4415**	**1.7143**	**43.9565**	**4.8758**	**1268.925**

Table 4.3 **Average of Mechanical Properties for Away from Sprue, 4-Cavity Mold at Injection Speed 3.0 in/sec**

Injection Speed, (in/s), Sample ID.	Distance at Peak (mm)	Load at Peak (Kn)	Stress at Peak (Mpa)	Strain at Break (%)	Young's Modulus
3.0gpps2	1.422	1.758	45.086	2.798	2122.369
3.0gpps4	2.457	1.614	41.375	4.913	1050.451
3.0gpps6	2.743	1.773	45.458	5.485	1054.931
3.0gpps8	2.624	1.79	45.885	5.247	1121.384
3.0gpps10	2.761	1.782	45.684	5.521	1081.284
3.0gpps12	3.093	1.784	45.735	6.187	1086.423
Average	2.516666667	1.750166667	44.8705	5.025167	1252.807

Table 4.4 **Average of Mechanical Properties for Close to Sprue, 4-Cavity Mold at Injection Speed 2.9 in/sec**

Injection Speed, (in/s), Sample ID.	Distance at Peak (mm)	Load at Peak (Kn)	Stress at Peak (Mpa)	Strain at Break (%)	Young's Modulus
2.9gpps1	2.406	1.731	44.387	4.813	1179.599
2.9gpps3	3.644	1.735	44.482	7.288	991.03
2.9gpps5	4.317	1.727	44.285	8.634	1316.946
2.9gpps7	4.247	1.781	45.677	8.494	1161.897
2.9gpps9	4.084	1.783	45.718	8.168	1245.806
Average	3.7396	1.7514	44.9098	7.4794	1179.056

Table 4.5 **Average of Mechanical Properties for Away from Sprue, 4-Cavity Mold at Injection Speed 2.9 in/sec**

Injection Speed, (in/s), Sample ID.	Distance at Peak (mm)	Load at Peak (Kn)	Stress at Peak (Mpa)	Strain at Break (%)	Young's Modulus
2.9gpps2	3.127	1.82	46.667	6.253	1389.791
2.9gpps4	3.71	1.805	46.294	7.42	1321.887
2.9gpps6	3.898	1.734	44.474	7.795	929.936
2.9gpps8	4.224	1.825	46.789	8.448	1281.368
2.9gpps10	4.525	1.791	45.921	9.049	1290.938
Average	3.8968	1.795	46.029	7.793	1242.784

Table 4.6 **Average of Mechanical Properties for Close to Sprue, 4-Cavity Mold at Injection Speed 2.8 in/sec**

Injection Speed, (in/s), Sample ID.	Distance at Peak (mm)	Load at Peak (Kn)	Stress at Peak (Mpa)	Strain at Break (%)	Young's Modulus
2.8gpps1	3.911	1.739	44.6	7.821	1217.345
2.8gpps3	3.878	1.758	45.065	7.756	1279.03
2.8gpps5	3.772	1.766	45.29	7.544	1336.509
2.8gpps7	3.228	1.759	45.092	6.456	1054.532
2.8gpps9	3.425	1.759	45.091	6.85	1308.971
Average	3.6428	1.7562	45.0276	7.2854	1239.277

Table 4.7 **Average of Mechanical Properties for Away from Sprue, 4-Cavity Mold at Injection Speed 2.8 in/sec**

Injection Speed, (in/s), Sample ID.	Distance at Peak (mm)	Load at Peak (Kn)	Stress at Peak (Mpa)	Strain at Break (%)	Young's Modulus
2.8gpps2	3.785	1.774	45.483	7.57	1425.958
2.8gpps4	3.613	1.787	45.825	7.225	1365.868
2.8gpps6	3.765	1.819	46.639	7.53	1219.891
2.8gpps8	3.74	1.795	46.015	7.481	1386.485
2.8gpps10	3.241	1.77	45.391	6.483	1066.671
Average	3.6288	1.789	45.8706	7.2578	1292.975

Table 4.8 Average of Mechanical Properties for Close to Sprue, 4-Cavity Mold at Injection Speed 2.7 in/sec

Injection Speed, (in/s), Sample ID.	Distance at Peak (mm)	Load at Peak (Kn)	Stress at Peak (Mpa)	Strain at Break (%)	Young's Modulus
2.7gpps1	3.411	1.761	45.149	6.821	1267.585
2.7gpps3	3.33	1.764	45.23	6.661	1452.643
2.7gpps5	3.525	1.785	45.764	7.049	1369.636
2.7gpps7	3.474	1.79	45.89	6.948	1338.147
2.7gpps9	3.359	1.76	45.131	6.719	1423.85
Average	3.4198	1.772	45.4328	6.8396	1370.372

Table 4.9 Average of Mechanical Properties for Away from Sprue, 4-Cavity Mold at Injection Speed 2.7 in/sec

Injection Speed, (in/s), Sample ID.	Distance at Peak (mm)	Load at Peak (Kn)	Stress at Peak (Mpa)	Strain at Break (%)	Young's Modulus
2.7gpps2	3.25	1.763	45.204	6.499	1118.677
2.7gpps4	3.428	1.797	46.085	6.855	1330.716
2.7gpps6	3.525	1.812	46.457	7.05	1359.961
2.7gpps8	3.56	1.766	45.285	7.121	1332.877
2.7gpps10	3.809	1.82	46.657	7.618	1341.131
Average	3.5144	1.7916	45.9376	7.0286	1296.672

Table 4.10 Average of Mechanical Properties for Close to Sprue, 4-Cavity Mold at Injection Speed 2.6 in/sec

Injection Speed, (in/s), Sample ID.	Distance at Peak (mm)	Load at Peak (Kn)	Stress at Peak (Mpa)	Strain at Break (%)	Young's Modulus
2.6gpps1	4.057	1.815	46.538	8.114	1289.656
2.6gpps3	3.563	1.76	45.138	7.125	1346.504
2.6gpps5	3.533	1.8	46.164	7.066	1508.002
2.6gpps7	3.528	1.785	45.76	7.055	1357.291
2.6gpps9	3.098	1.789	45.873	6.196	1104.591
Average	3.5558	1.7898	45.8946	7.1112	1321.209

Table 4.11 **Average of Mechanical Properties for Away from Sprue, 4-Cavity Mold at Injection Speed 2.6 in/sec**

Injection Speed, (in/s), Sample ID.	Distance at Peak (mm)	Load at Peak (Kn)	Stress at Peak (Mpa)	Strain at Break (%)	Young's Modulus
2.6gpps2	3.605	1.793	45.974	7.21	1324.604
2.6gpps4	2.897	1.738	44.56	5.795	1127.706
2.6gpps6	2.664	1.79	45.905	5.329	1191.158
2.6gpps8	3.482	1.771	45.421	6.963	1174.693
2.6gpps10	3.248	1.764	45.232	6.496	1090.65
Average	3.1792	1.7712	45.4184	6.3586	1181.762

Table 4.12 **Average of Mechanical Properties for Close to Sprue, 4-Cavity Mold at Injection Speed 2.5 in/sec**

Injection Speed, (in/s), Sample ID.	Distance at Peak (mm)	Load at Peak (Kn)	Stress at Peak (Mpa)	Strain at Break (%)	Young's Modulus
2.5gpps1	3.148	1.74	44.622	6.295	1106.016
2.5gpps3	3.079	1.744	44.725	6.158	972.1
2.5gpps5	3.182	1.777	45.56	6.364	1143.207
2.5gpps7	3.209	1.76	45.138	6.417	1096.637
2.5gpps9	2.898	1.751	44.902	5.796	1074.545
Average	3.1032	1.7544	44.9894	6.206	1078.501

Table 4.13 **Average of Mechanical Properties for Away from Sprue, 4-Cavity Mold at Injection Speed 2.5 in/sec**

Injection Speed, (in/s), Sample ID.	Distance at Peak (mm)	Load at Peak (Kn)	Stress at Peak (Mpa)	Strain at Break (%)	Young's Modulus
2.5gpps2	3.044	1.76	45.128	6.088	1135.122
2.5gpps4	2.125	1.678	43.017	4.25	1189.126
2.5gpps6	3.345	1.778	45.583	6.69	1243.007
2.5gpps8	3.111	1.759	45.099	6.222	1236.645
2.5gpps10	3.163	1.763	45.203	6.326	905.875
Average	2.9576	1.7476	44.806	5.9152	1141.955

Table 4.14 Average Mechanical Properties for Upper and Lower Specimens in 2-Cavity Mold Mechanical Properties at Injection Speed 3.0 in/sec

Injection Speed, (in/s), Sample ID.	Distance at Peak (mm)	Load at Peak (Kn)	Stress at Peak (Mpa)	Strain at Break (%)	Young's Modulus
3.0gpps1u	2.269	1.79	45.905	5.259	1170.284
3.0gpps1L	3.561	1.846	47.321	7.122	1241.823
3.0gpps2u	2.714	1.785	45.768	5.428	1162.883
3.0gpps2L	3.232	1.779	45.611	6.463	971.439
30gpps3u	2.561	1.799	46.129	5.122	1189.434
3.0gpps3L	2.977	1.789	45.883	5.954	1290.039
3.0gpps4u	2.25	1.3808	33.536	4.499	1108.993
3.0gpps4L	3.695	1.816	46.565	7.389	1322.616
3.0gpps5u	3.277	1.78	45.645	6.554	1103.897
3.0gpps5L	2.833	1.82	46.666	5.666	1147.704
Average	2.9369	1.75848	44.9029	5.9456	1170.911

Table 4.15 Average Mechanical Properties for Upper and Lower Specimens in 2-Cavity Mold Mechanical Properties at Injection Speed 2.9. in/sec

Injection Speed, (in/s), Sample ID.	Distance at Peak (mm)	Load at Peak (Kn)	Stress at Peak (Mpa)	Strain at Break (%)	Young's Modulus
2.9gpps1u	3.419	1.846	47.345	6.838	1276.054
2.9gpps1L	2.739	1.793	45.987	5.477	1168.971
2.9gpps2u	3.498	1.8	46.146	6.996	1188.396
2.9gpps2L	3.401	1.819	46.635	6.802	1251.001
2.9gpps3u	3.314	1.786	45.788	6.627	1402.234
2.9gpps3L	3.443	1.813	46.479	6.885	1323.393
2.9gpps4u	3.435	1.8	46.152	6.87	1352.185
2.9gpps4L	3.233	1.788	45.844	6.465	1360.554
2.9gpps5u	3.479	1.827	46.852	6.958	1222.949
2.9gpps5L	3.184	1.845	47.3	6.368	1307.139
Average	3.3145	1.8117	46.4528	6.6286	1285.288

Table 4.16 Average Mechanical Properties for Upper and Lower Specimens in 2-Cavity Mold Mechanical Properties at Injection Speed 2.8 in/sec

Injection Speed, (in/s), Sample ID.	Distance at Peak (mm)	Load at Peak (Kn)	Stress at Peak (Mpa)	Strain at Break (%)	Young's Modulus
2.8gpps1u	3.748	1.849	47.406	7.496	1276.001
2.8gpps1L	3.408	1.875	48.076	6.815	1165.809
2.8gpps2u	3.004	1.884	48.318	6.009	1386.499
2.8gpps2L	3.389	1.835	47.061	6.777	1348.6
2.8gpps3u	3.534	1.864	47.788	7.068	1318.209
2.8gpps3L	2.922	1.845	47.308	5.843	1171.587
2.8gppd4u	3.016	1.87	47.944	6.031	1148.856
2.8gpps4L	2.701	1.835	47.062	5.401	1183.968
2.8gpps5u	3.37	1.85	47.445	6.74	1382.933
2.8gpps5L	2.933	1.846	47.321	5.866	1159.845
Average	3.2025	1.8553	47.5729	6.4046	1254.231

Table 4.17 Average Mechanical Properties for Upper and Lower Specimens in 2-Cavity Mold Mechanical Properties at Injection Speed 2.7 in/sec

Injection Speed, (in/s), Sample ID.	Distance at Peak (mm)	Load at Peak (Kn)	Stress at Peak (Mpa)	Strain at Break (%)	Young's Modulus
2.7gpps1u	3.422	1.815	46.546	6.843	1363.747
2.7gpps1L	2.928	1.835	47.061	5.857	1132.687
2.7gpps2u	2.516	1.824	46.764	5.031	1198.927
2.7gpps2L	3.407	1.871	47.965	6.814	1431.03
2.7gpps3u	3.225	1.837	47.1	6.45	1372.611
2.7gpps3l	3.542	1.827	46.85	7.085	1355.263
2.7gpps4U	3.379	1.857	47.623	6.758	761.09
2.7gpps4l	3.323	1.825	46.807	6.646	1363.366
2.7gpps5u	2.867	1.858	47.642	5.734	1188.271
2.7gpps5L	3.546	1.819	46.645	7.092	1378.035
Average	3.2155	1.8368	47.1003	6.431	1254.503

Table 4.18 **Average Mechanical Properties for Upper and Lower Specimens in 2-Cavity Mold Mechanical Properties at Injection Speed 2.6 in/sec**

Injection Speed, (in/s), Sample ID.	**Distance at Peak (mm)**	**Load at Peak (Kn)**	**Stress at Peak (Mpa)**	**Strain at Break (%)**	**Young's Modulus**
2.6gpps1u	3.836	1.81	46.406	7.671	1216.597
2.6gpps1L	3.577	1.847	47.351	7.154	1385.079
2.6gpps2u	3.329	1.821	46.682	6.658	1285.195
2.6gpps2L	2.791	1.823	46.755	5.582	1151.894
2.6gpps3u	2.798	1.809	46.383	5.596	1178.321
2.6gpps3L	3.262	1.832	46.965	6.525	1420.678
2.6gpps4u	3.364	1.803	46.219	6.727	1294.511
2.6gpps4L	3.279	1.762	45.17	6.558	1058.998
2.6gpps5u	3.525	1.843	47.256	7.049	1430.338
2.6gpps5L	3.499	1.803	46.229	6.999	1287.763
Average	3.326	1.8153	46.5416	6.6519	1270.937

Table 4.19 **Average Mechanical Properties for Upper and Lower Specimens in 2-Cavity Mold Mechanical Properties at Injection Speed 2.5 in/sec**

Injection Speed, (in/s), Sample ID.	**Distance at Peak (mm)**	**Load at Peak (Kn)**	**Stress at Peak (Mpa)**	**Strain at Break (%)**	**Young's Modulus**
2.5gpps1u	3.412	1.835	47.041	6.823	1396.51
2.5gpps1L	3.405	1.814	46.525	6.809	1360.057
2.5gpps2u	3.26	1.806	46.303	6.52	1288.963
2.5gpps2L	3.395	1.777	45.573	6.791	1340.275
2.5gpps3u	3.207	1.762	45.169	6.414	1416.528
2.5gpps3L	3.382	1.811	46.431	6.764	1322.753
2.5gpps4u	3.379	1.781	45.669	6.758	1260.718
2.5gpps4L	3.438	1.826	46.826	6.876	1334.14
2.5gpps5u	3.525	1.791	45.932	7.05	1231.409
2.5gpps5L	3.128	1.786	45.8	6.257	1388.52
Average	3.3531	1.7989	46.1269	6.7062	1333.987

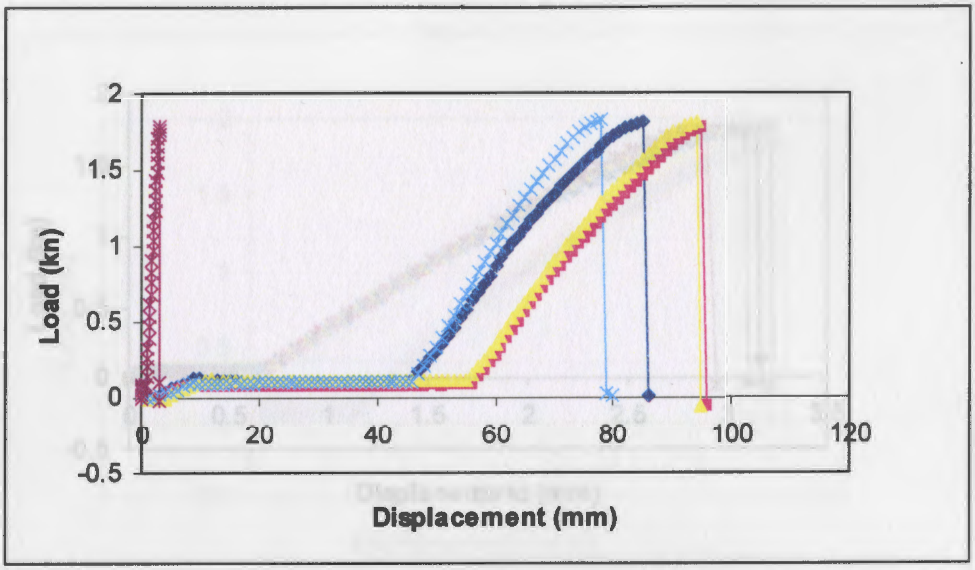


Figure 4.6 Load versus Displacement for the Lower Specimen of 2-Cavity Mold at Injection Speed 2.5 in/sec

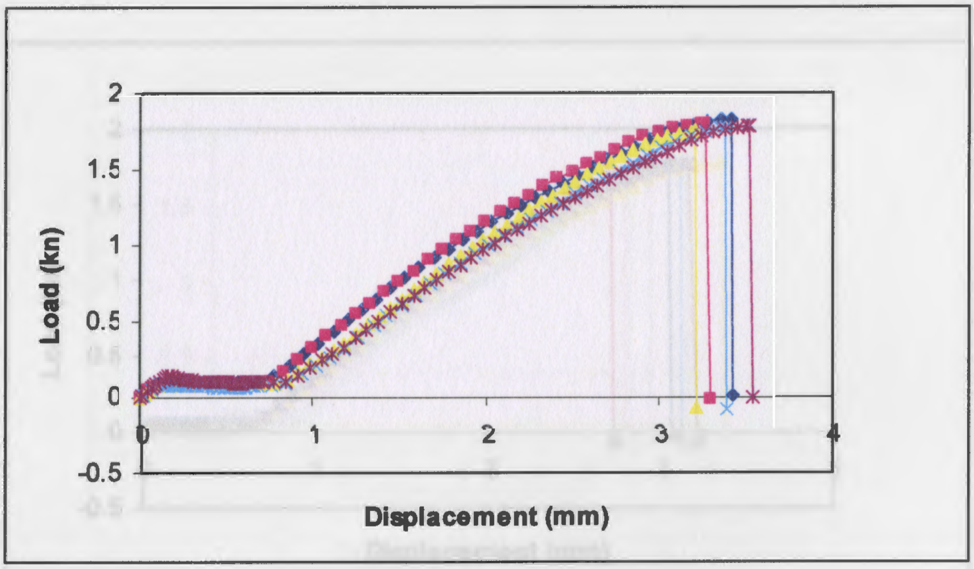


Figure 4.7 Load versus Displacement for the Upper Specimen of 2-Cavity Mold at Injection Speed 2.5 in/sec

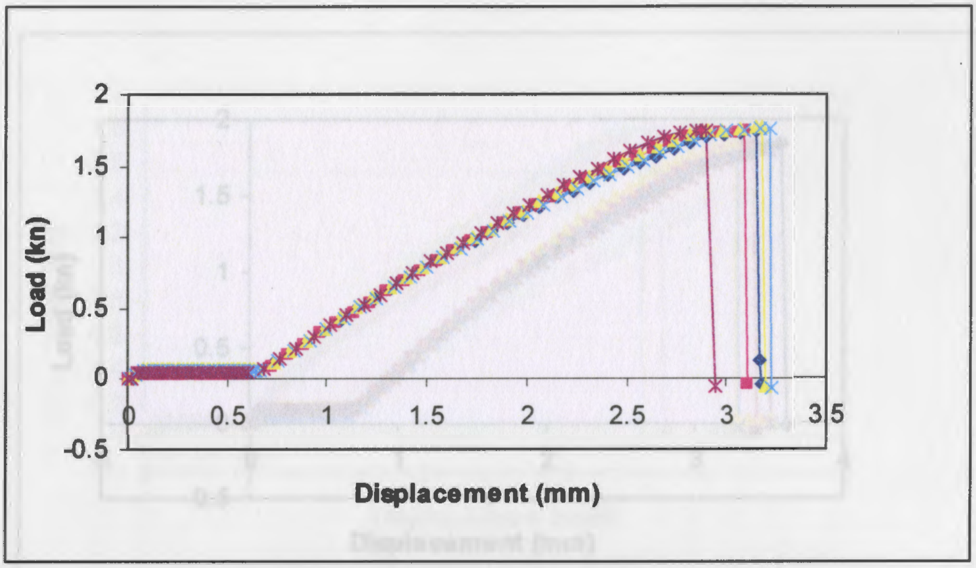


Figure 4.8 Load versus Displacement for the Close to Sprue Specimen of 4-Cavity Mold at Injection Speed 2.5 in/sec

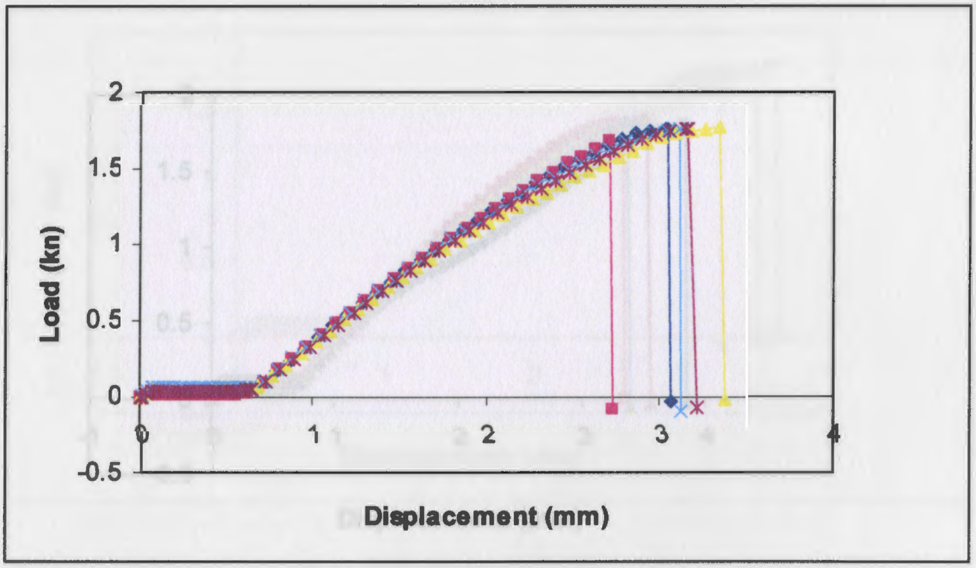


Figure 4.9 Load versus Displacement for the Away from Sprue Specimen of 4-Cavity Mold at Injection Speed 2.5 in/sec

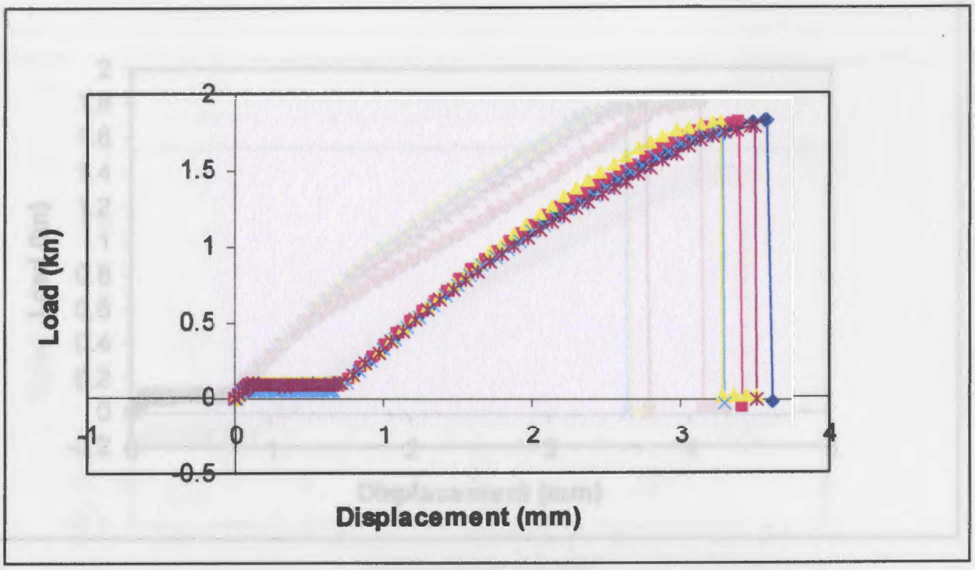


Figure 4.10 Load versus Displacement for the Lower Specimen of 2-Cavity Mold at Injection Speed 2.6 in/sec

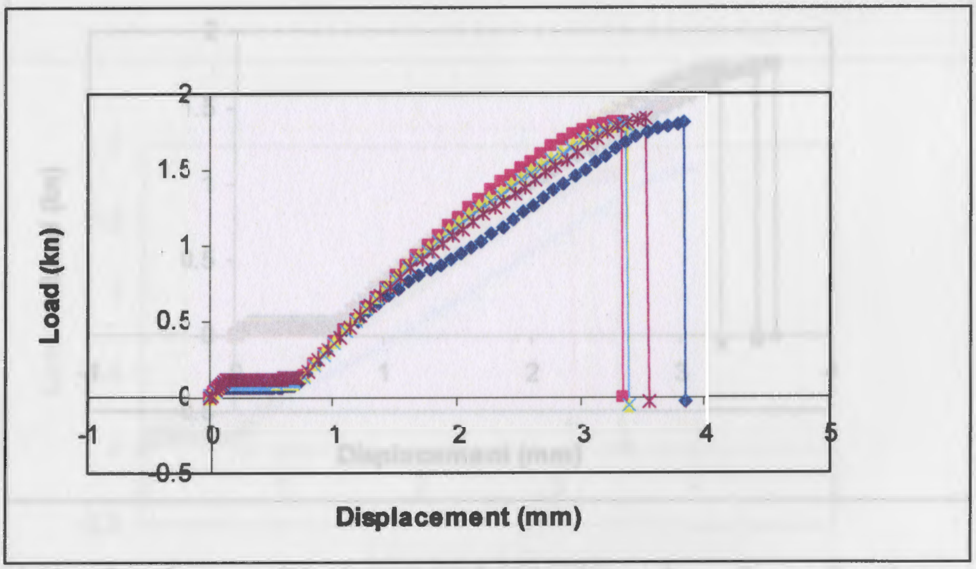


Figure 4.11 Load versus Displacement for the Upper Specimen of 2-Cavity Mold at Injection Speed 2.6 in/sec

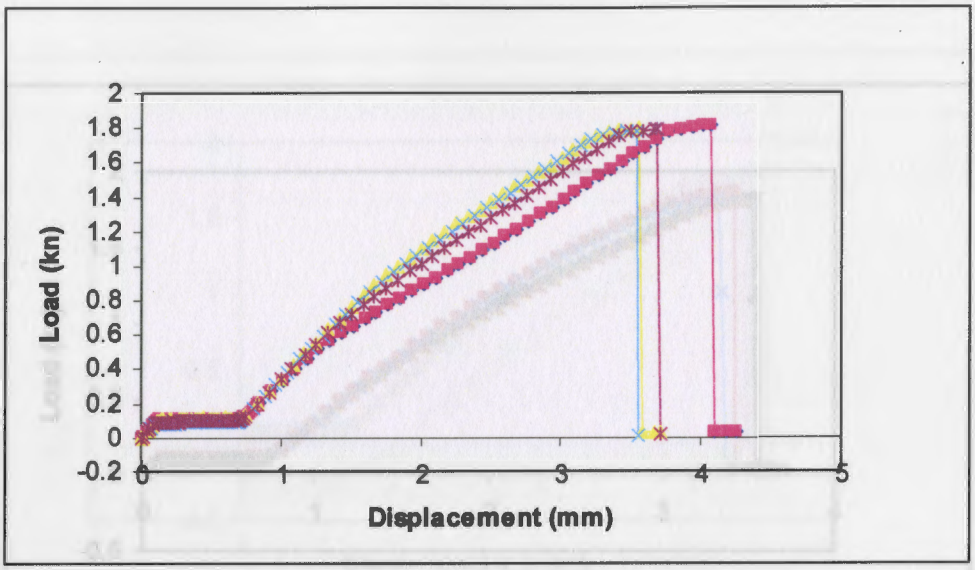


Figure 4.12 Load versus Displacement for the Close to Sprue Specimen of 4-Cavity Mold at Injection Speed 2.6 in/sec

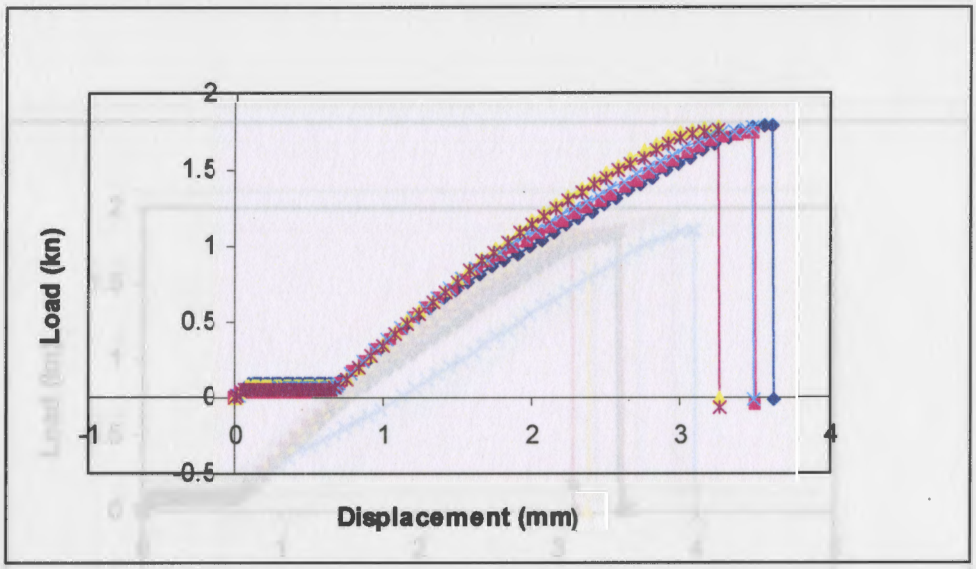


Figure 4.13 Load versus Displacement for the Away from Sprue Specimen of 4-Cavity Mold at Injection Speed 2.6 in/sec

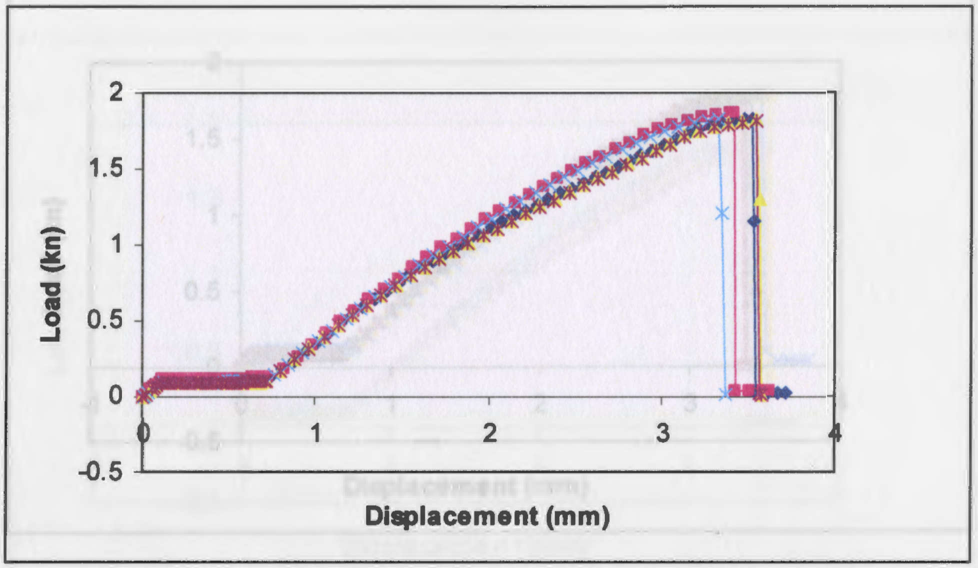


Figure 4.14 Load versus Displacement for the Lower Specimen of 2-Cavity Mold at Injection Speed 2.7 in/sec

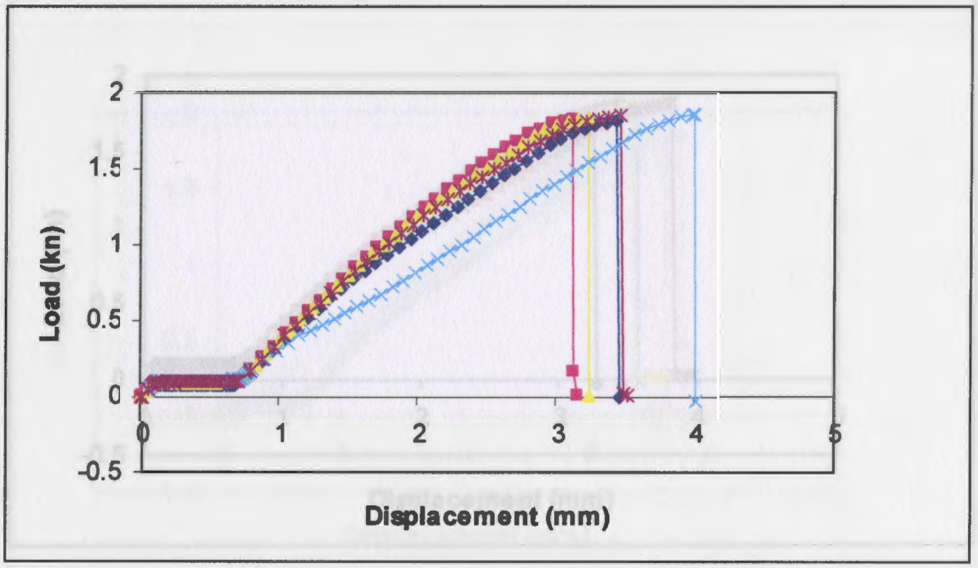


Figure 4.15 Load versus Displacement for the Upper Specimen of 2-Cavity Mold at Injection Speed 2.7 in/sec

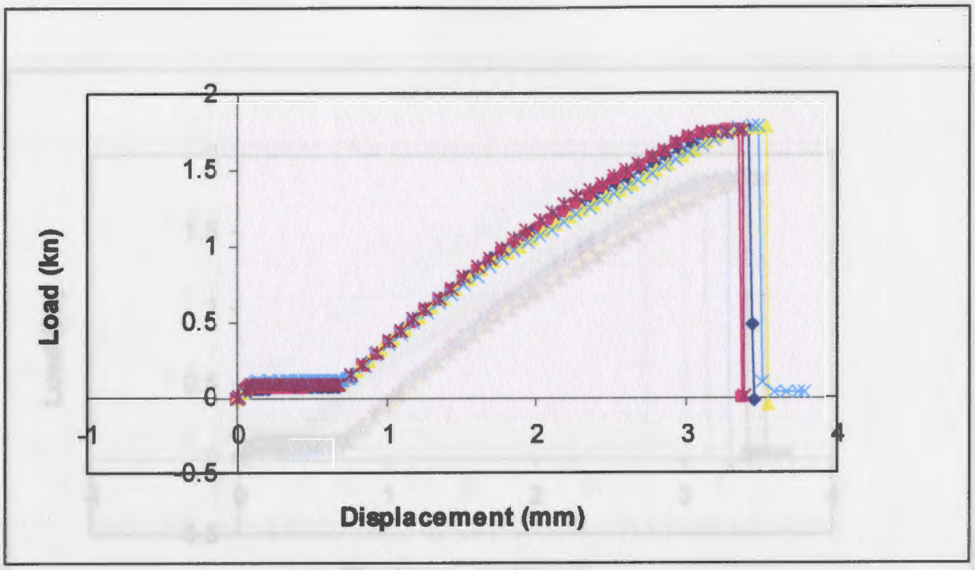


Figure 4.16 Load versus Displacement for the Close to Sprue Specimen of 4-Cavity Mold at Injection Speed 2.7 in/sec

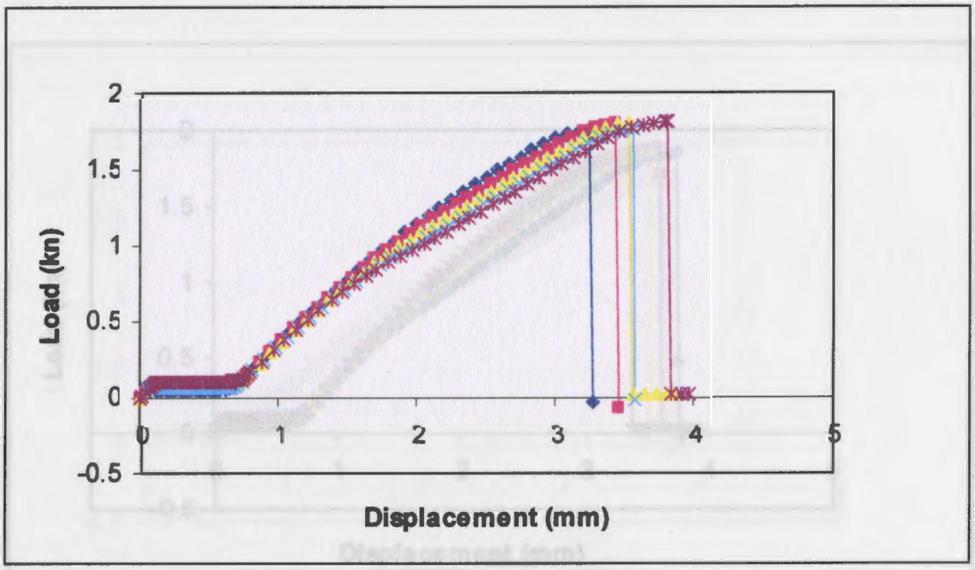


Figure 4.17 Load versus Displacement for the Away from Sprue Specimen of 4-Cavity Mold at Injection Speed 2.7 in/sec

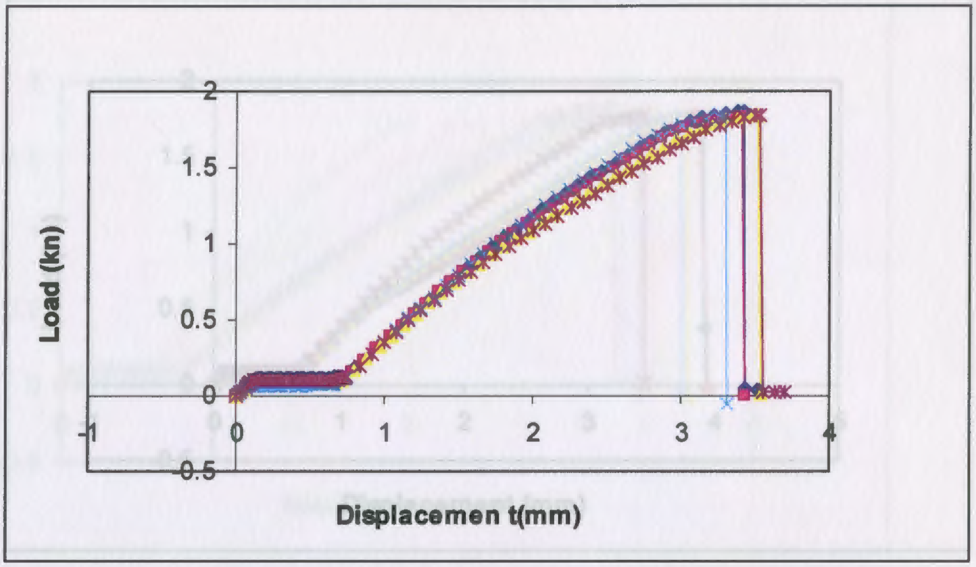


Figure 4.18 Load versus Displacement for the Lower Specimen of 2-Cavity Mold at Injection Speed 2.8 in/sec

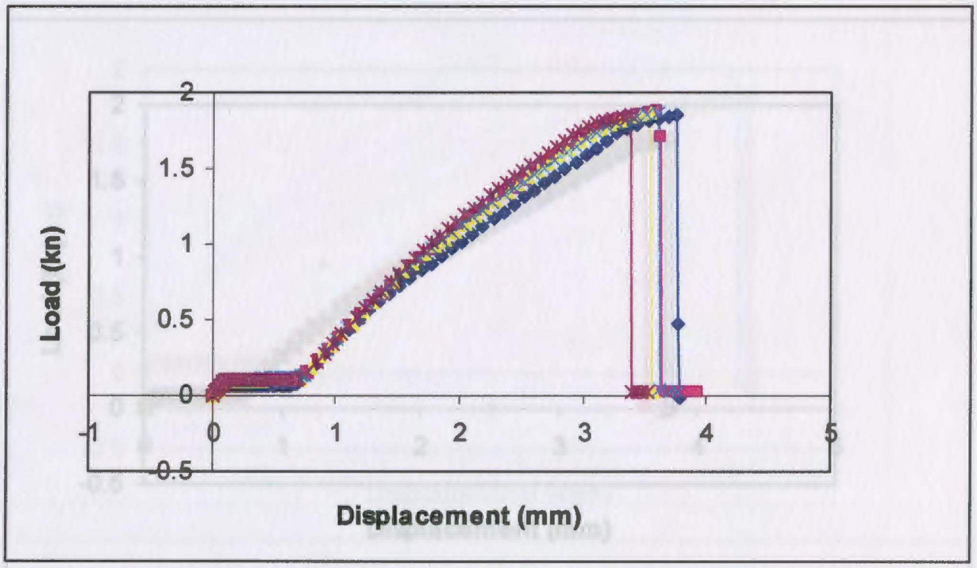


Figure 4.19 Load versus Displacement for the Upper Specimen of 2-Cavity Mold at Injection Speed 2.8 in/sec

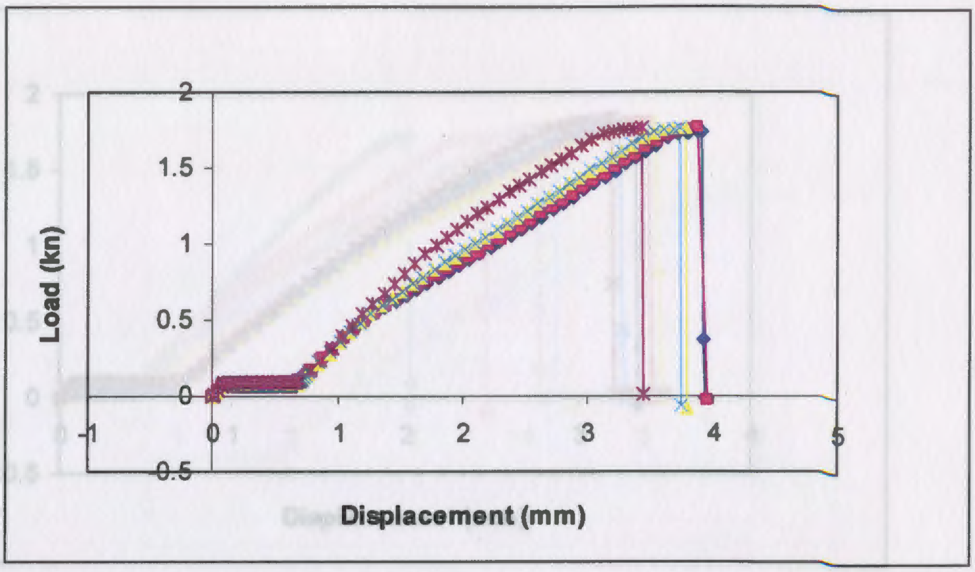


Figure 4.20 Load versus Displacement for the Close to Sprue Specimen of 4-Cavity Mold at Injection Speed 2.8 in/sec

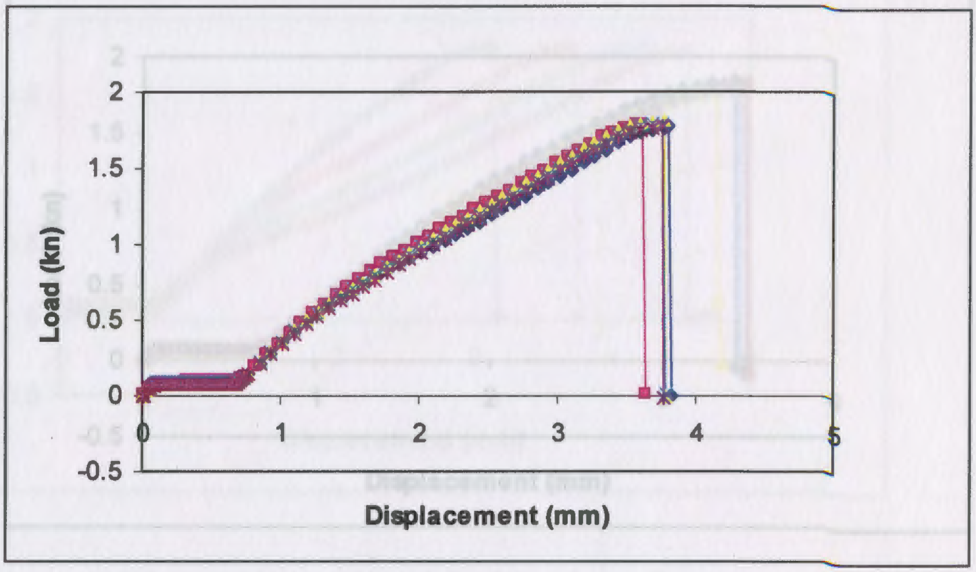


Figure 4.21 Load versus Displacement for the Away from Sprue Specimen of 4-Cavity Mold at Injection Speed 2.8 in/sec

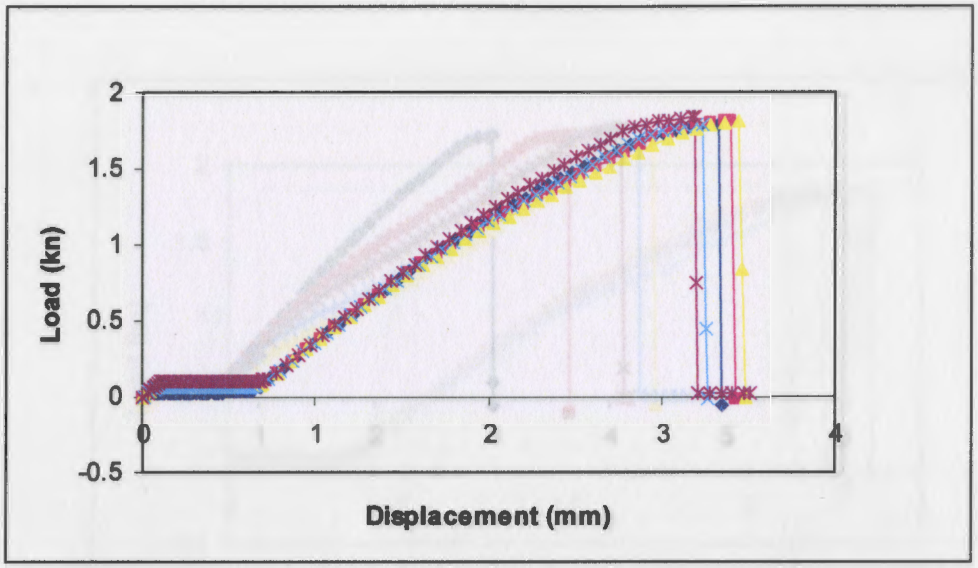


Figure 4.22 Load versus Displacement for the Lower Specimen of 2-Cavity Mold at Injection Speed 2.9 in/sec

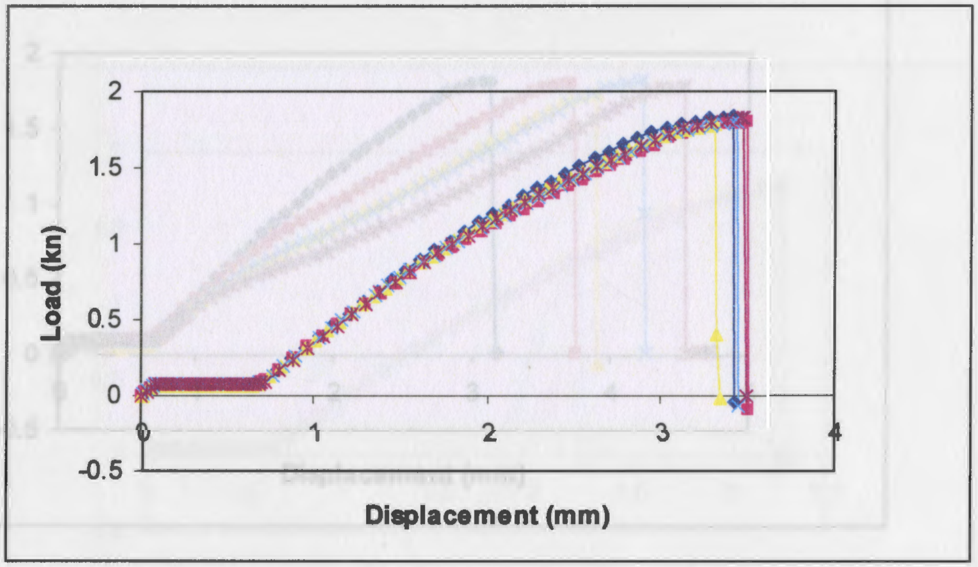


Figure 4.23 Load versus Displacement for the Upper Specimen of 2-Cavity Mold at Injection Speed 2.9 in/sec

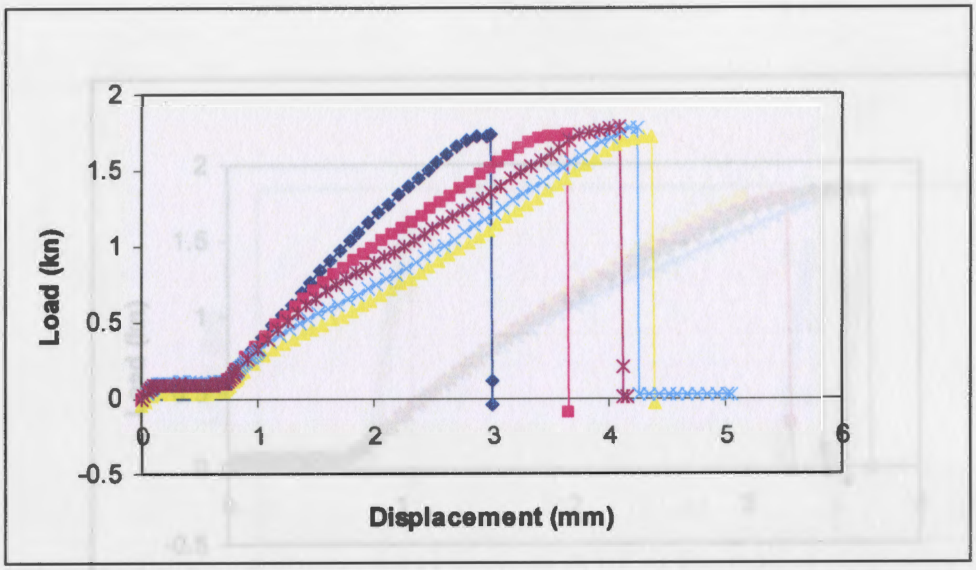


Figure 4.24 Load versus Displacement for the Close to Sprue Specimen of 4-Cavity Mold at Injection Speed 2.9 in/sec

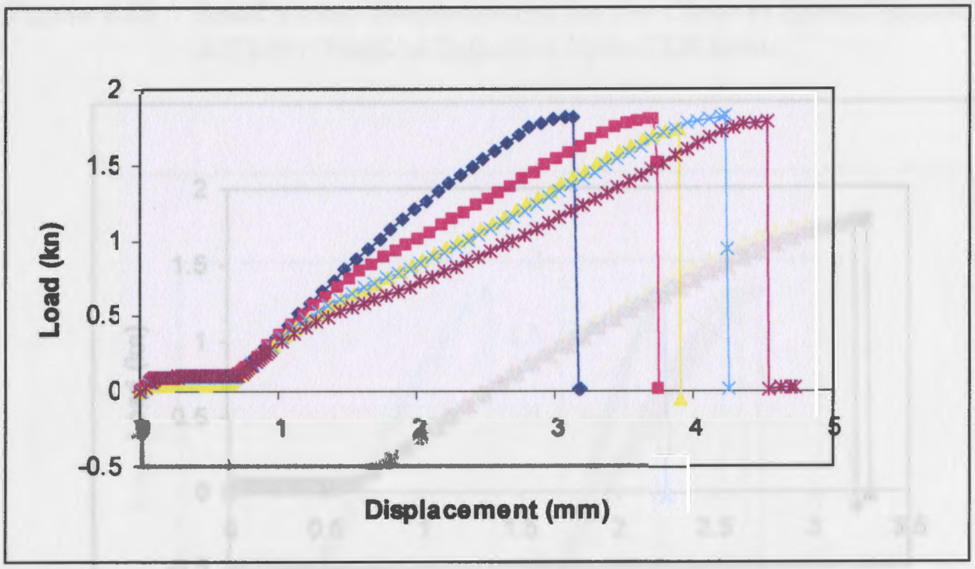


Figure 4.25 Load versus Displacement for the Away from Sprue Specimen of 4-Cavity Mold at Injection Speed 2.9 in/sec

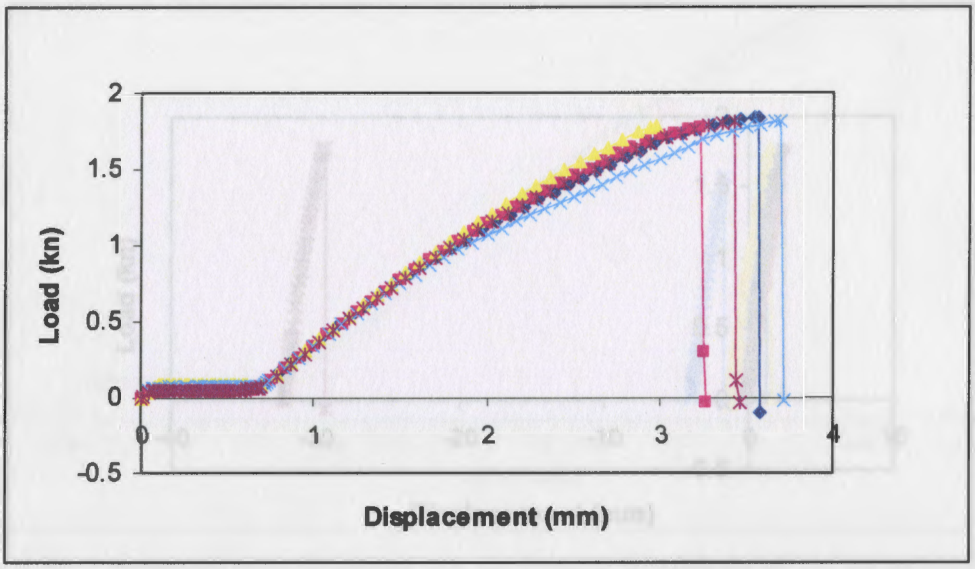


Figure 4.26 Load versus Displacement for the Lower Specimen of 2-Cavity Mold at Injection Speed 3.0 in/sec

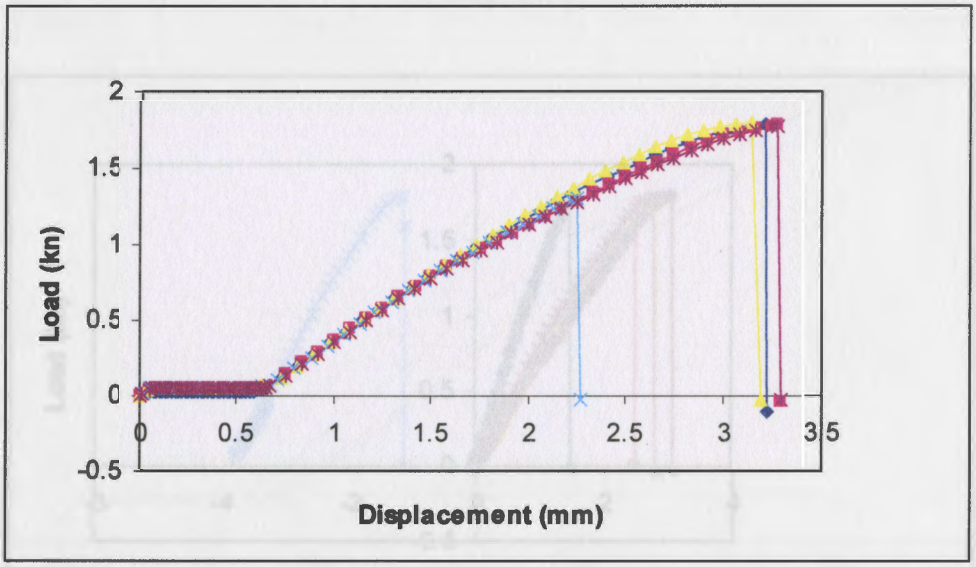


Figure 4.27 Load versus Displacement for the Upper Specimen of 2-Cavity Mold at Injection Speed 3.0 in/sec

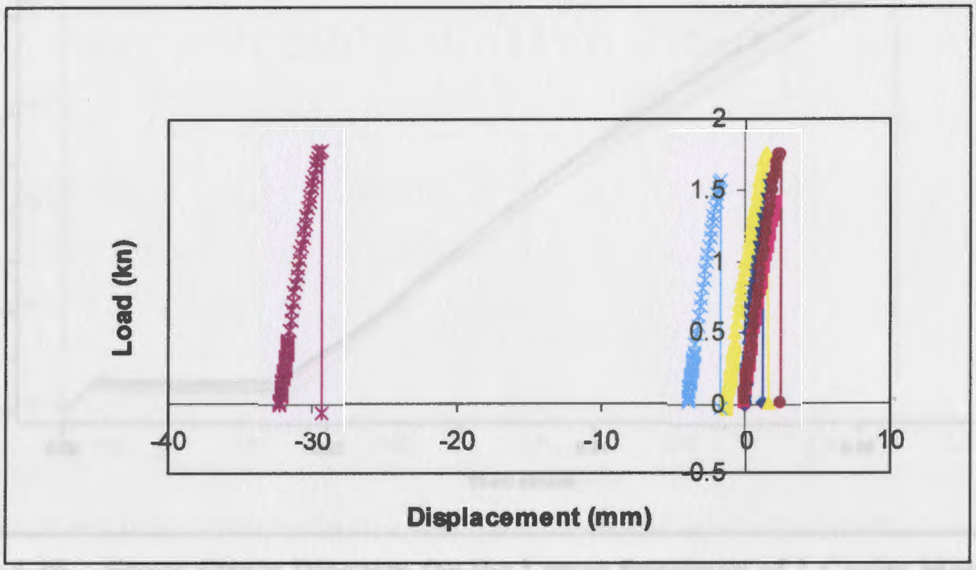


Figure 4.28 Load versus Displacement for the Close to Sprue Specimen of 4-Cavity Mold at Injection Speed 3.0 in/sec

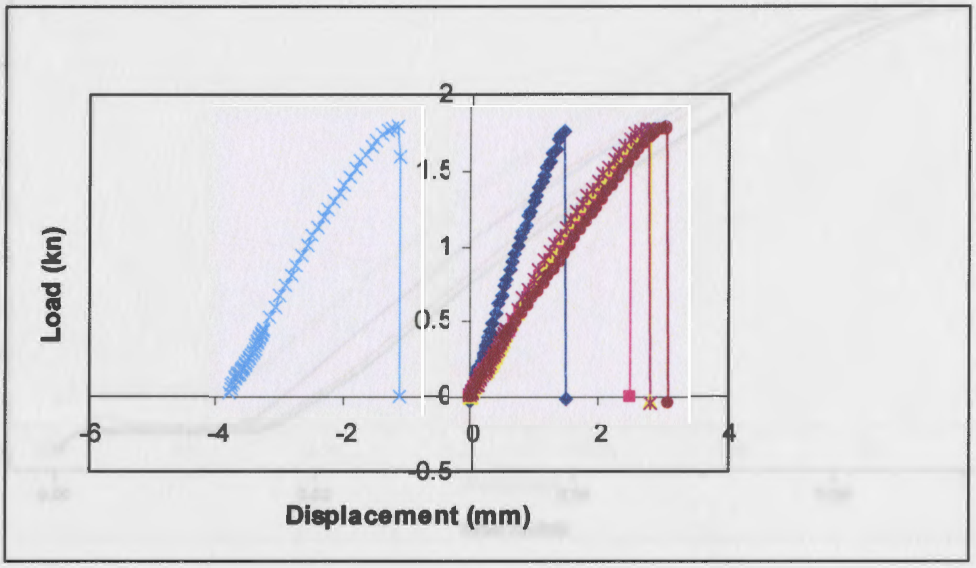


Figure 4.29 Load versus Displacement for the Away from Sprue Specimen of 4-Cavity Mold at Injection Speed 3.0 in/sec

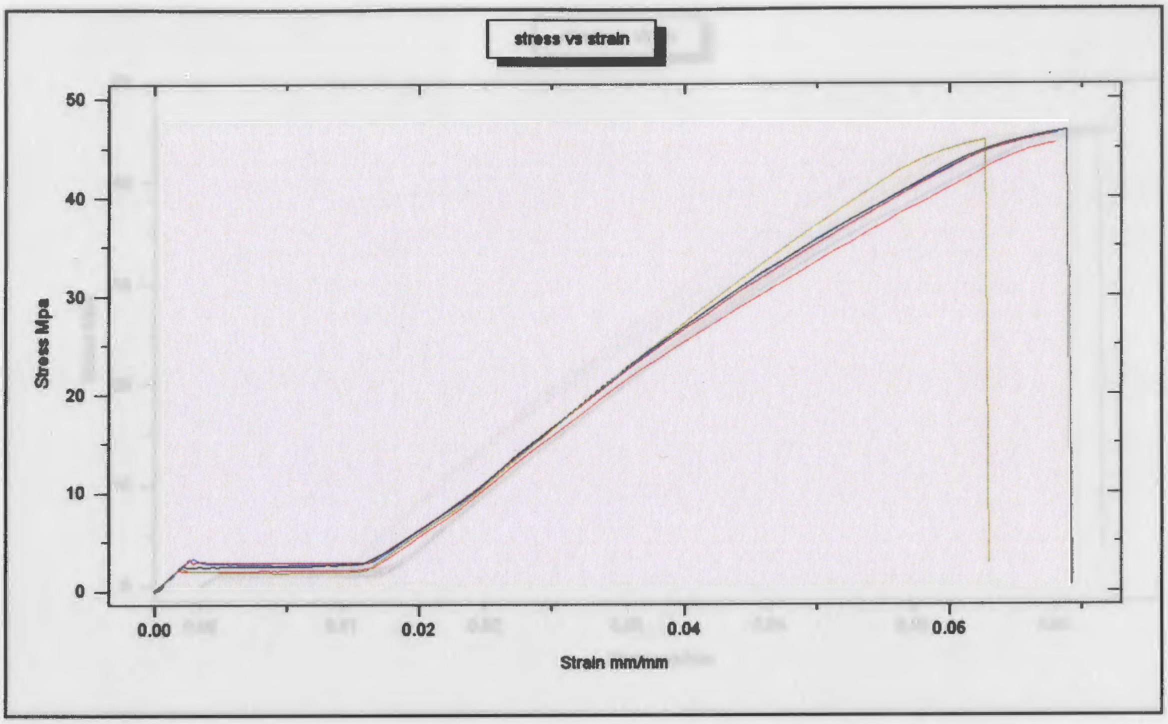


Figure 4.30 Stress-Strain Diagram for the Lower Specimen of 2-Cavity Mold at Injection Speed 2.5 in/sec

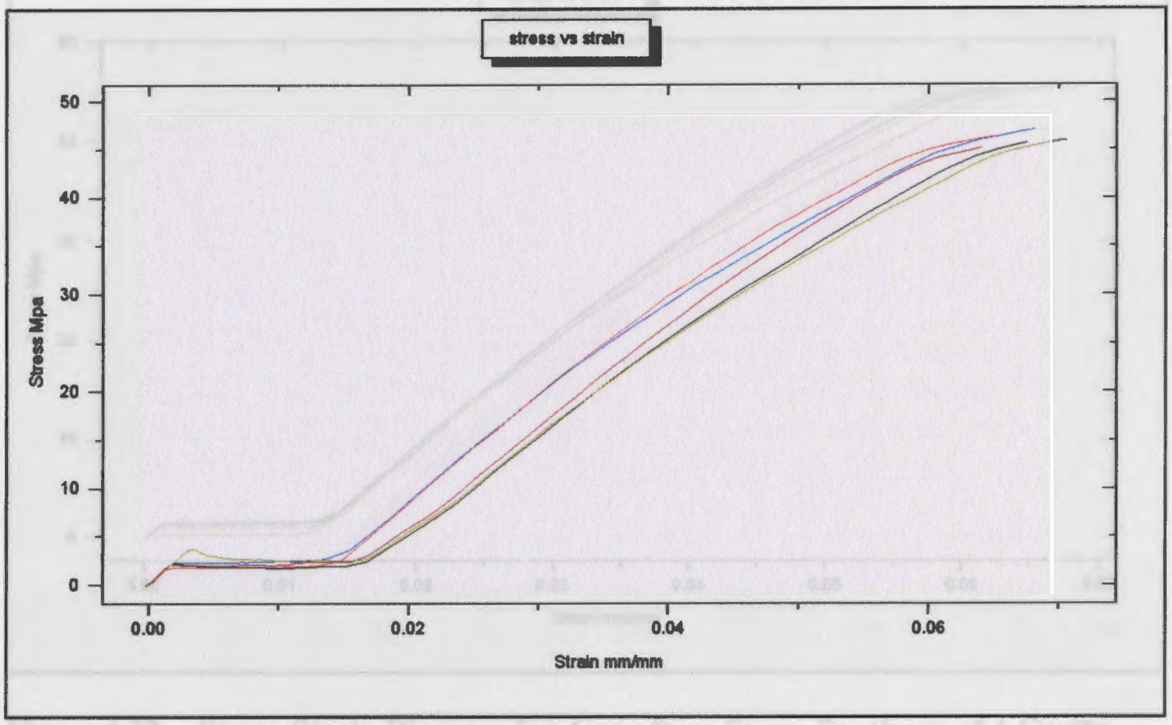


Figure 4.31 Stress-Strain Diagram for the Upper Specimen of 2-Cavity Mold at Injection Speed 2.5 in/sec

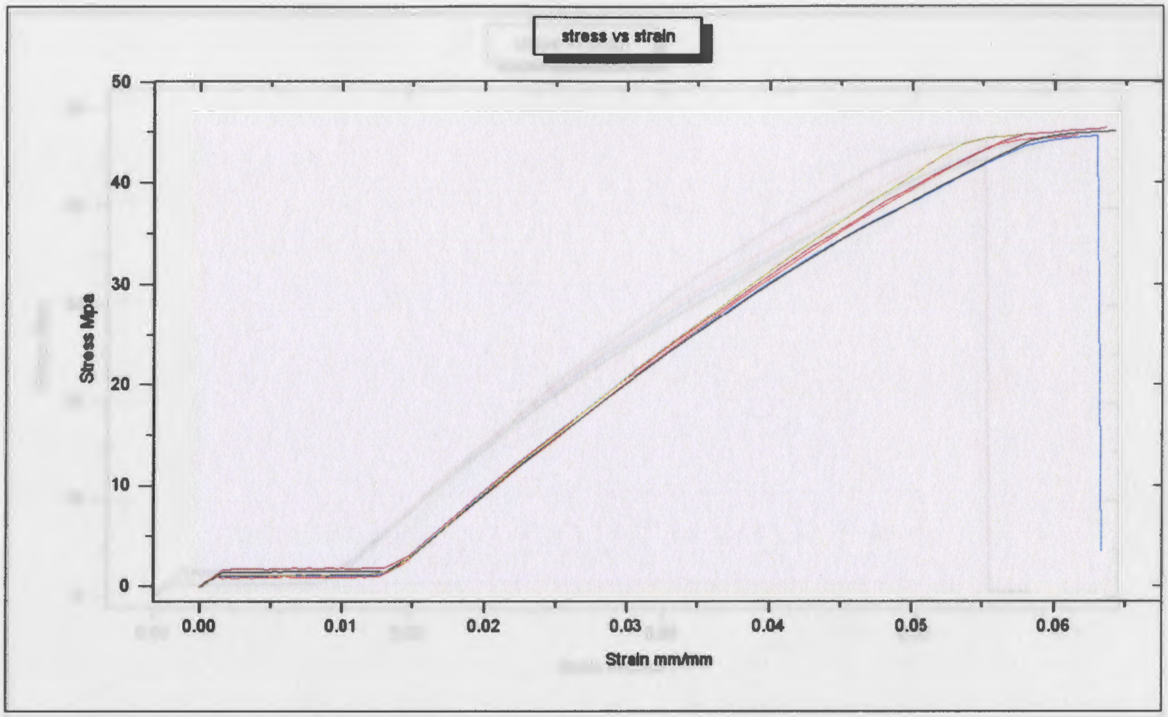


Figure 4.32 Stress-Strain Diagram for the Close to Sprue Specimen of 4-Cavity Mold at Injection Speed 2.5 in/sec

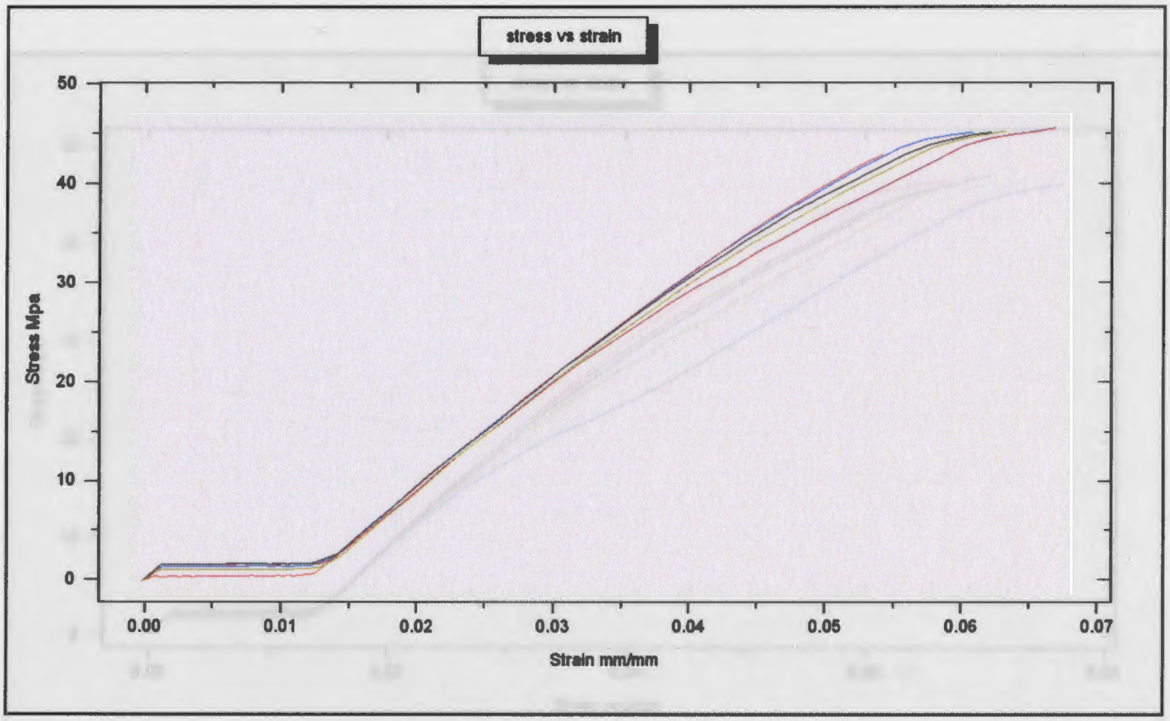


Figure 4.33 Stress-Strain Diagram for Away from Sprue Specimen of 4-Cavity Mold at Injection Speed 2.5 in/sec

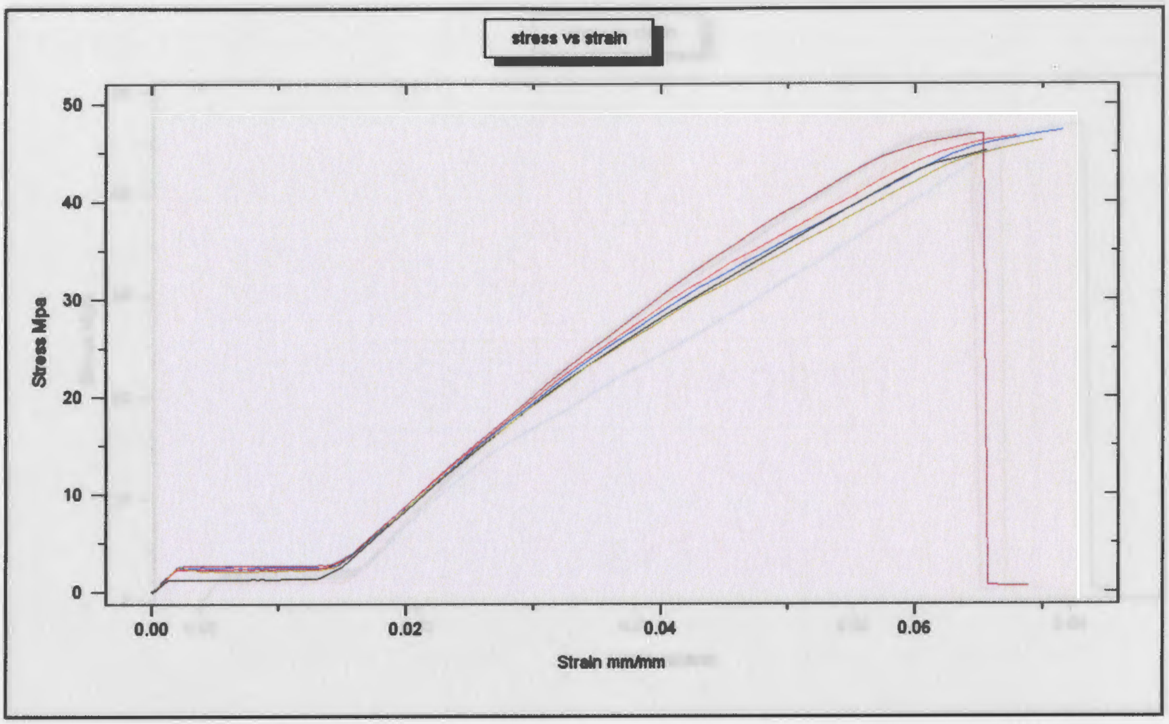


Figure 4.34 Stress-Strain Diagram for the Lower Specimen of 2-Cavity Mold at Injection Speed 2.6 in/sec

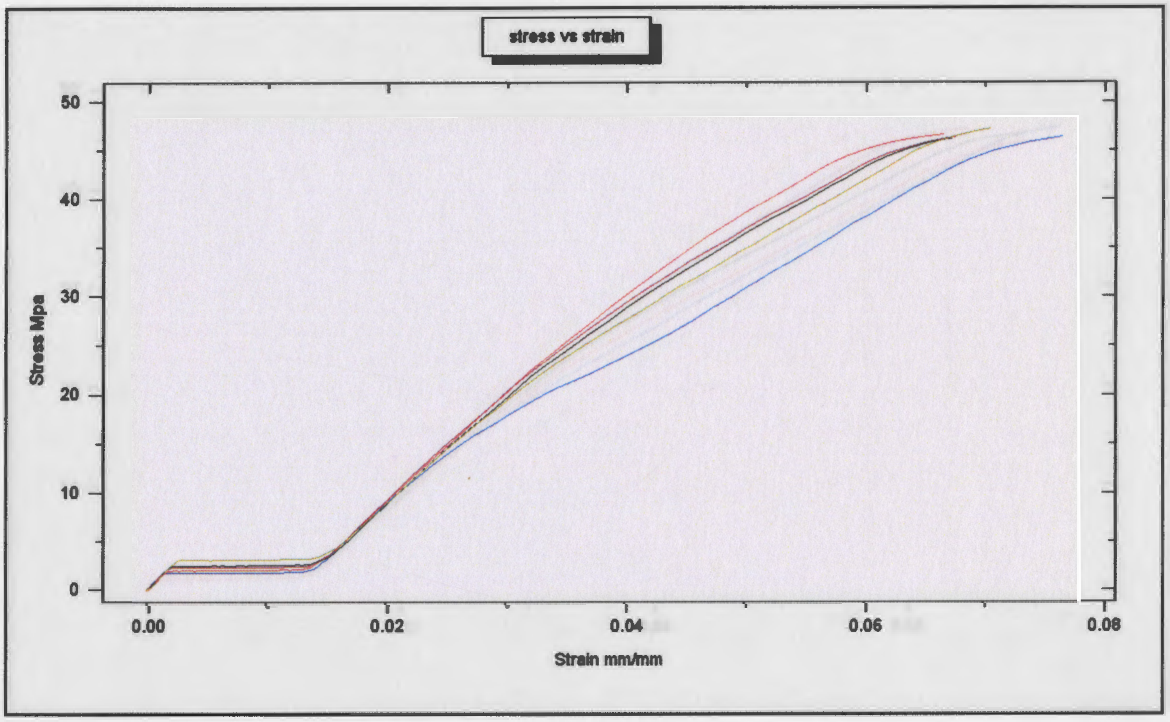


Figure 4.35 Stress-Strain Diagram for the Upper Specimen of 2-Cavity Mold at Injection Speed 2.6 in/sec

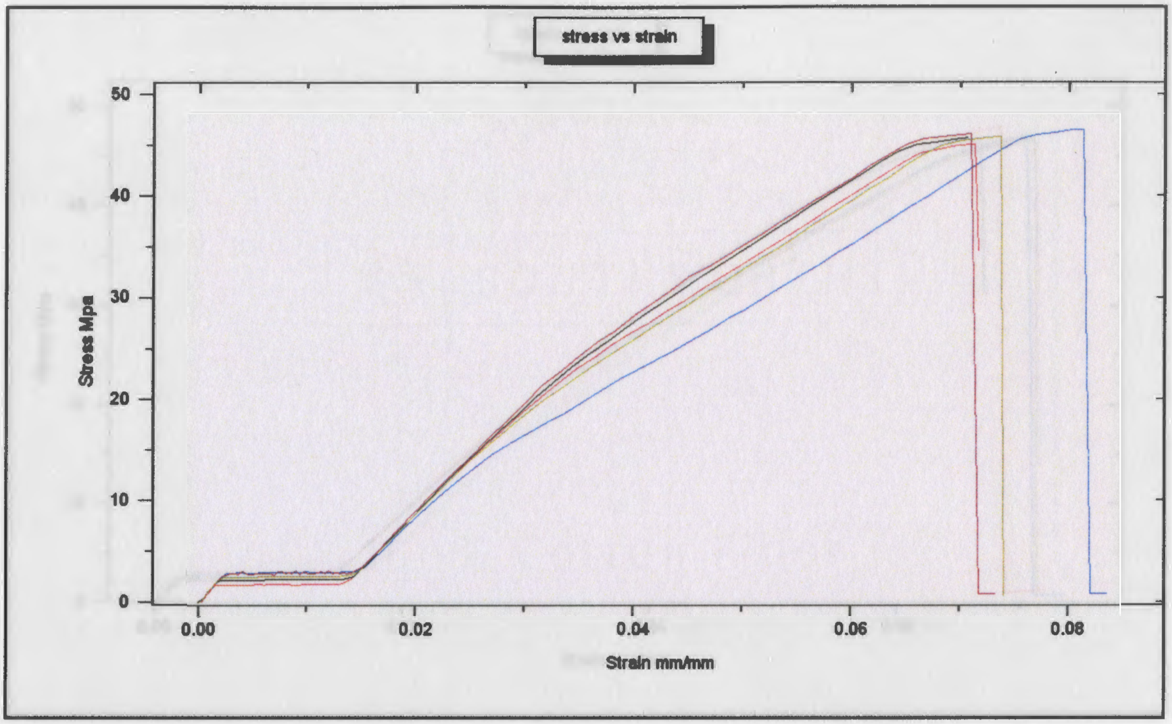


Figure 4.36 Stress-Strain Diagram for the Close to Sprue Specimen of 4-Cavity Mold at Injection Speed 2.6 in/sec

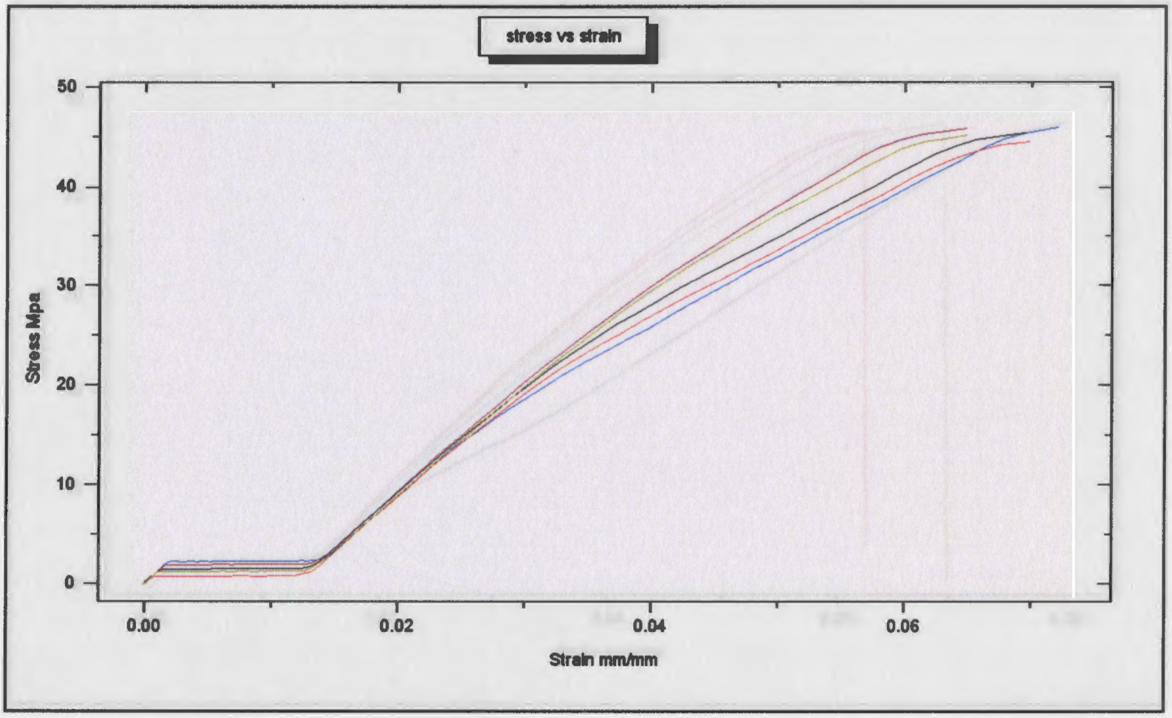


Figure 4.37 Stress-Strain Diagram for Away from Sprue Specimen of 4-Cavity Mold at Injection Speed 2.6 in/sec

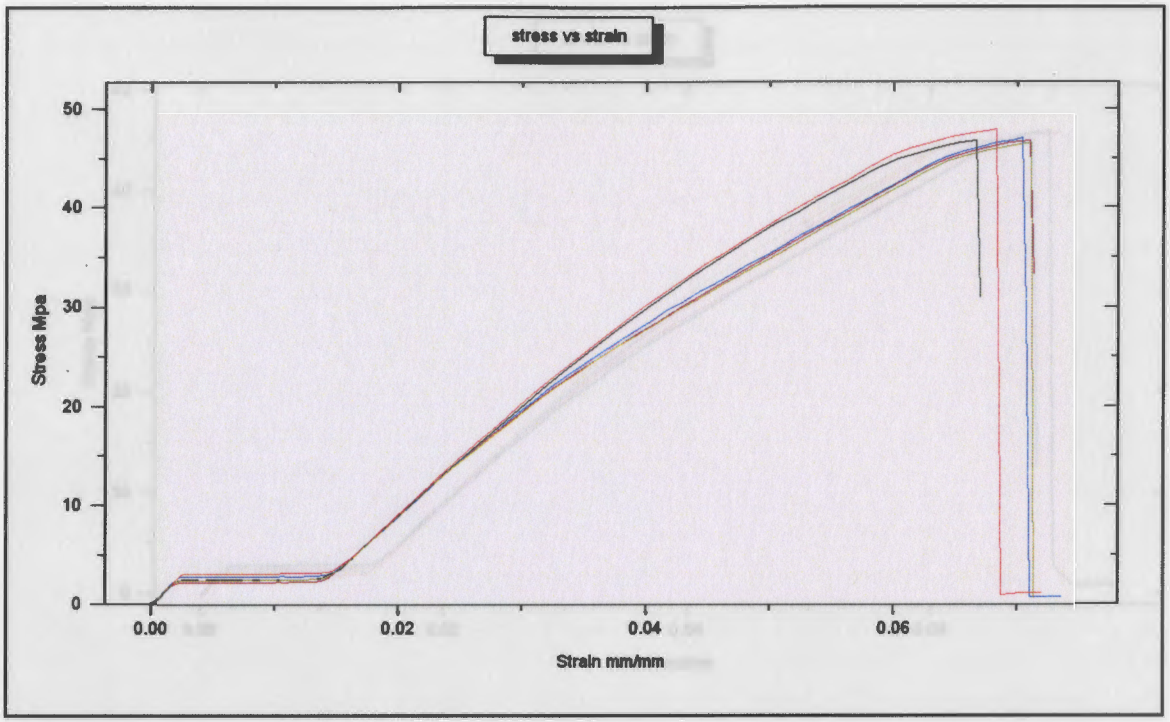


Figure 4.38 Stress-Strain Diagram for the Lower Specimen of 2-Cavity Mold at Injection Speed 2.7 in/sec

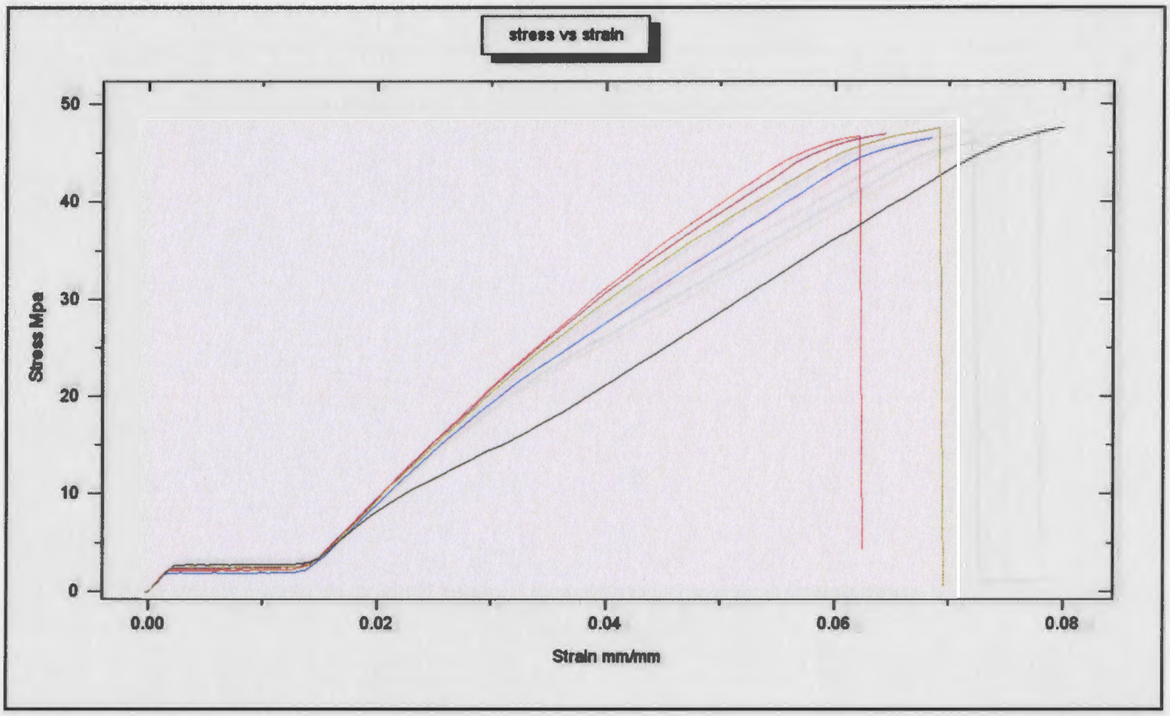


Figure 4.39 Stress-Strain Diagram for the Upper Specimen of 2-Cavity Mold at Injection Speed 2.7 in/sec

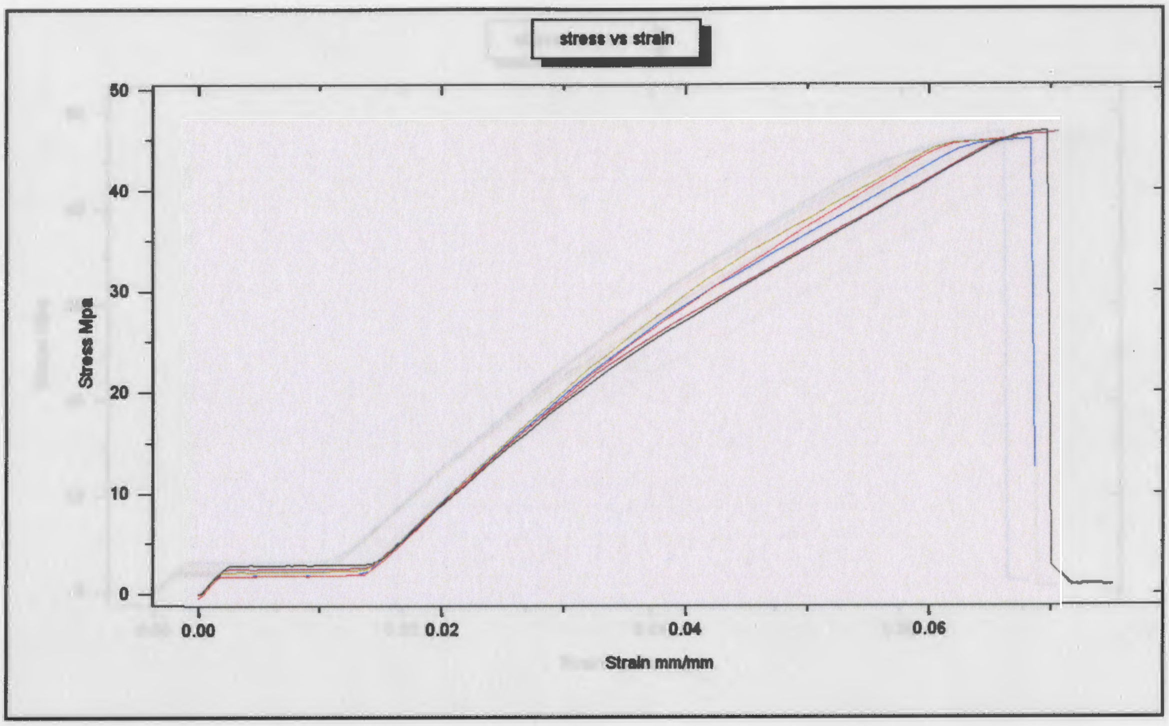


Figure 4.40 Stress-Strain Diagram for the Close to Sprue Specimen of 4-Cavity Mold at Injection Speed 2.7 in/sec

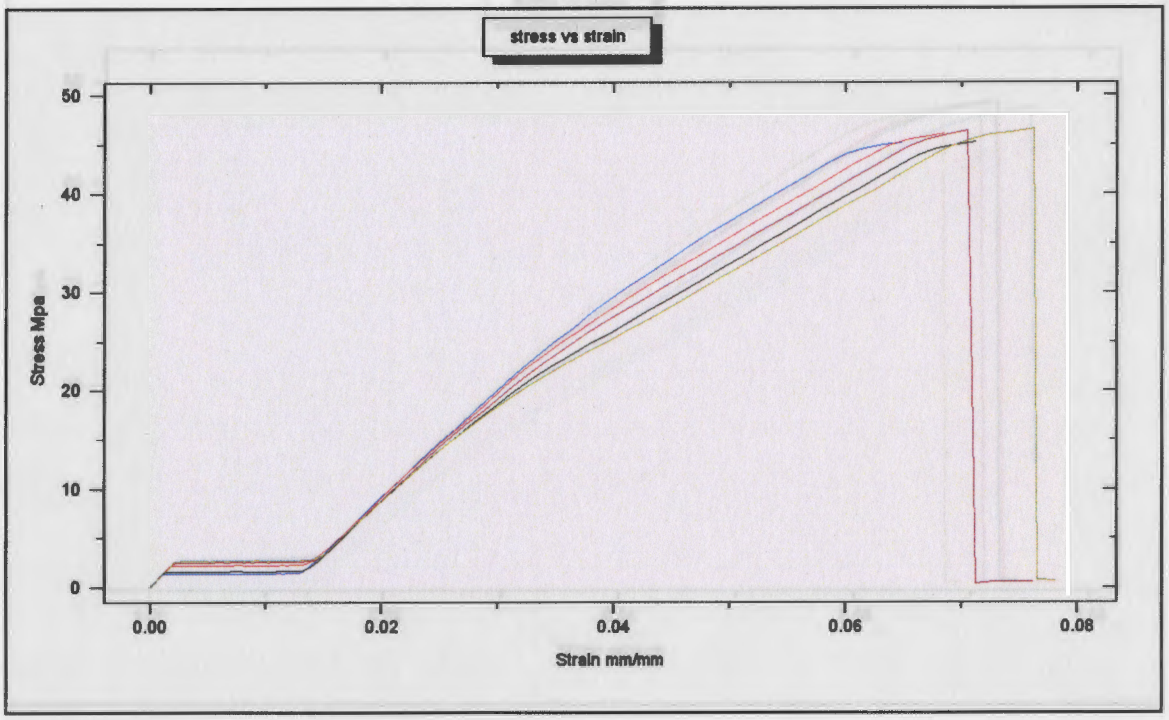


Figure 4.41 Stress-Strain Diagram for Away from Sprue Specimen of 4-Cavity Mold at Injection Speed 2.7 in/sec

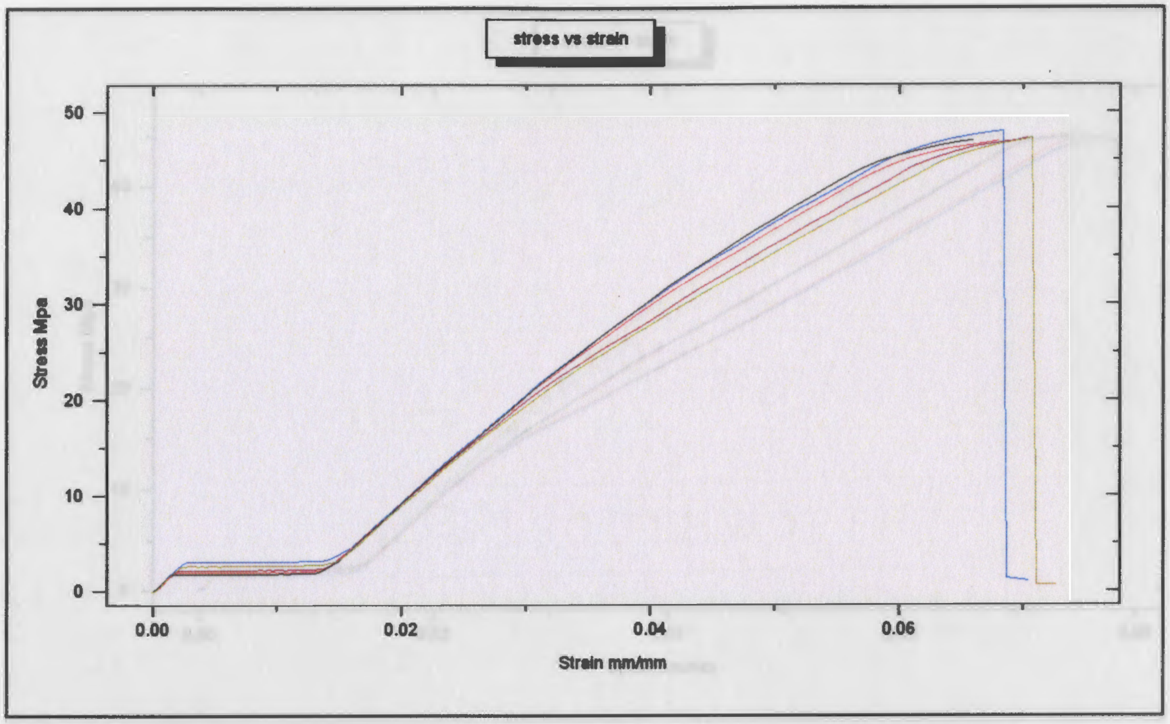


Figure 4.42 Stress-Strain Diagram for the Lower Specimen of 2-Cavity Mold at Injection Speed 2.8 in/sec

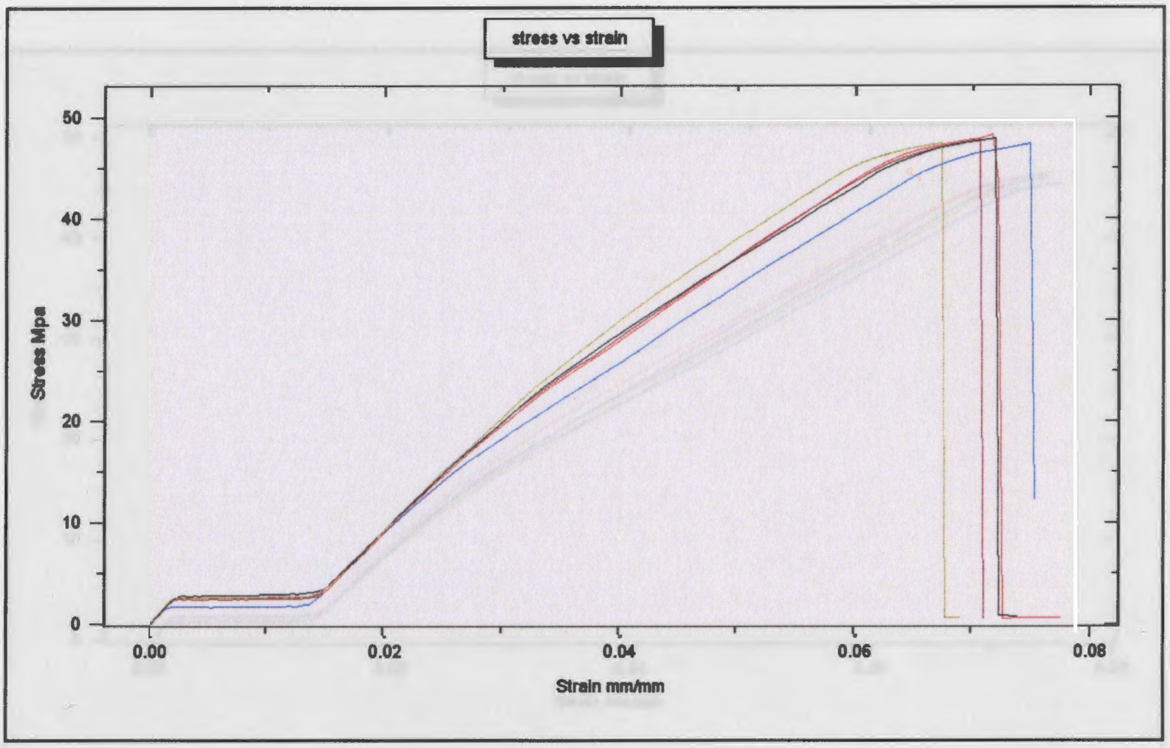


Figure 4.43 Stress-Strain Diagram for the Upper Specimen of 2-Cavity Mold at Injection Speed 2.8 in/sec

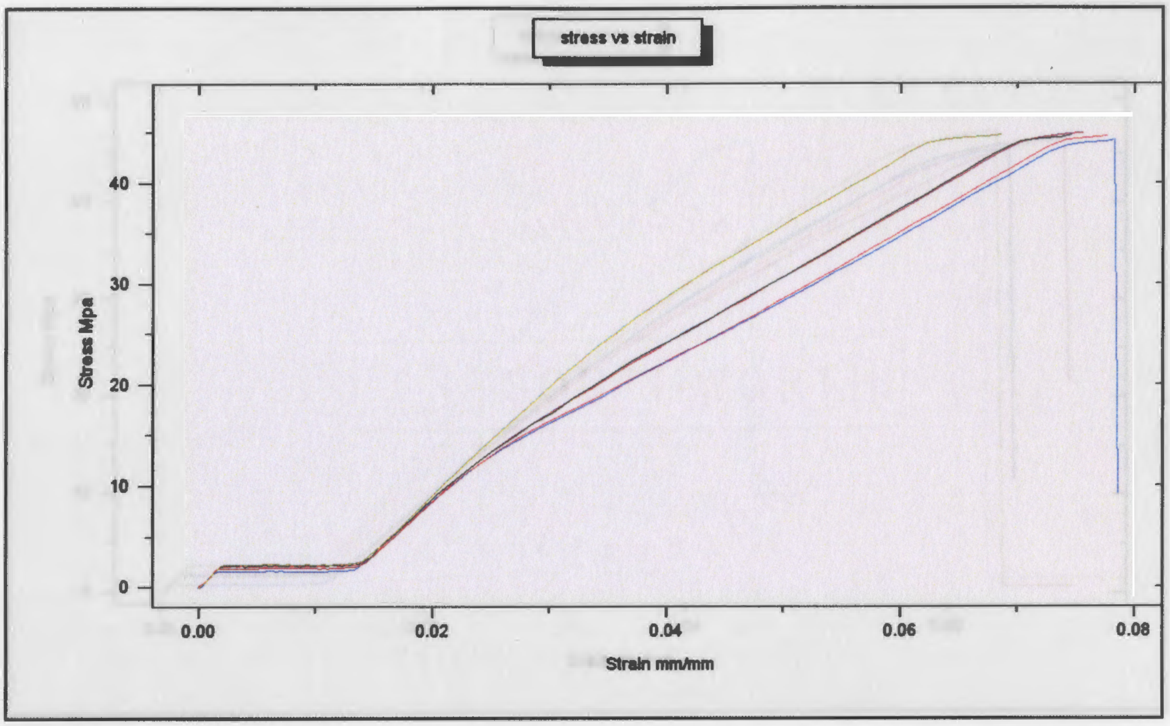


Figure 4.44 Stress-Strain Diagram for the Close to Sprue Specimen of 4-Cavity Mold at Injection Speed 2.8 in/sec

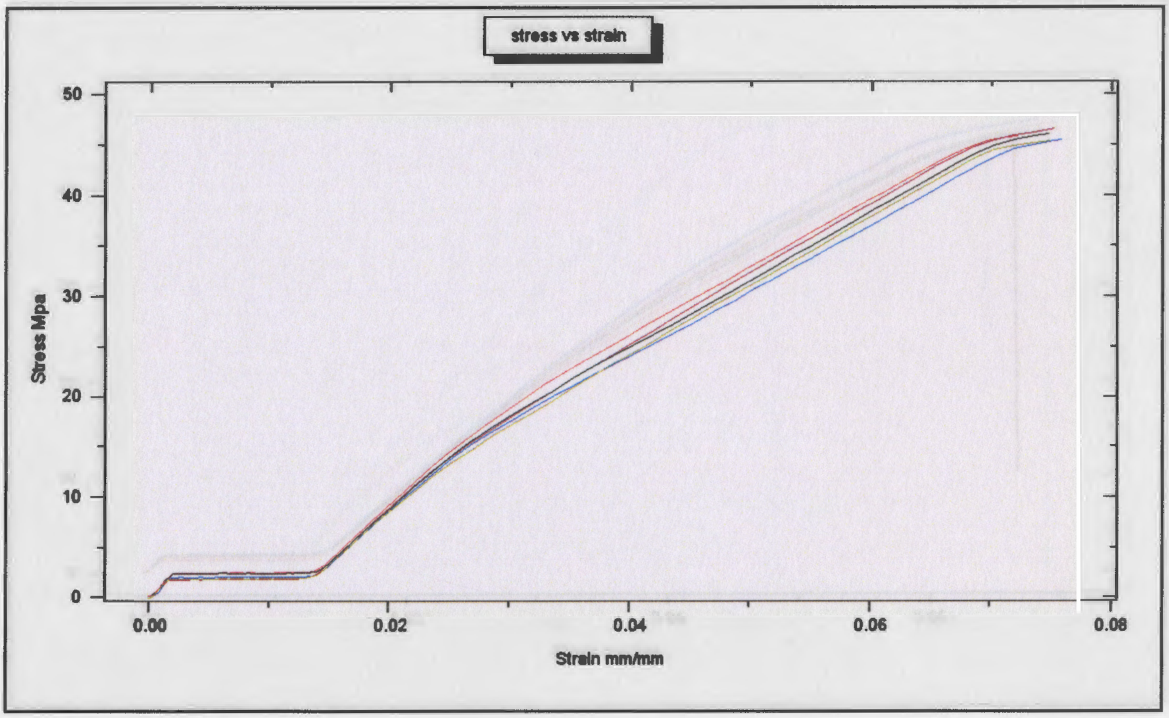


Figure 4.45 Stress-Strain Diagram for Away from Sprue Specimen of 4-Cavity Mold at Injection Speed 2.8 in/sec

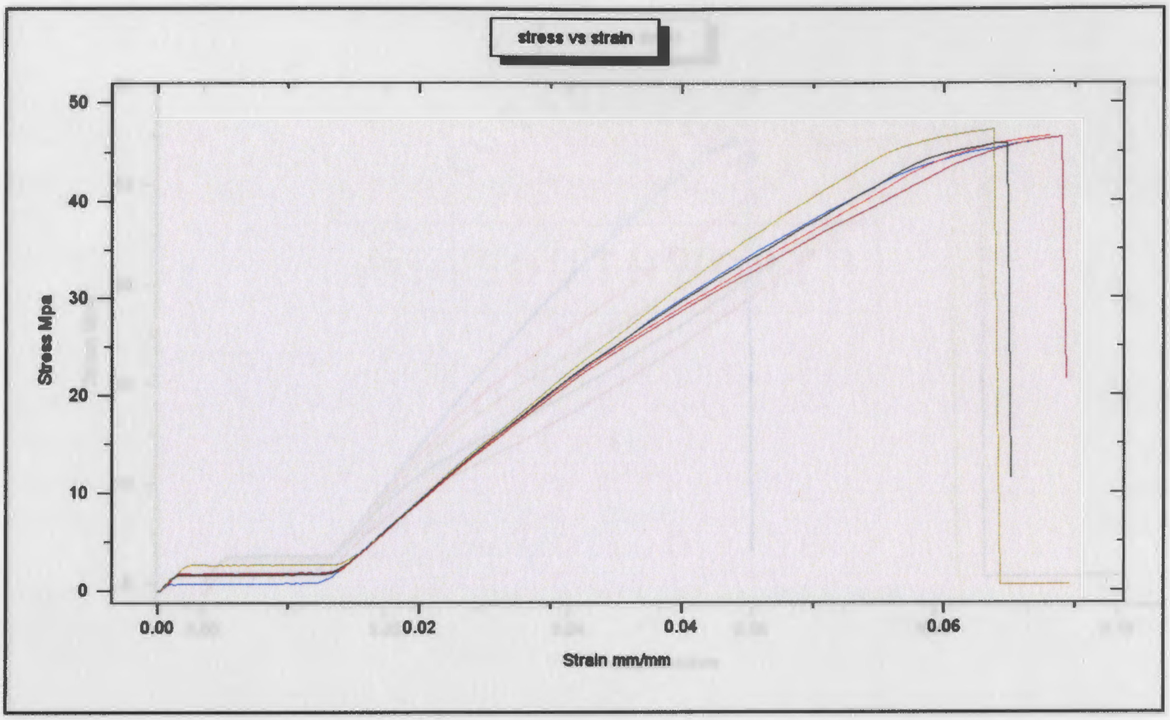


Figure 4.46 Stress-Strain Diagram for the Lower Specimen of 2-Cavity Mold at Injection Speed 2.9 in/sec

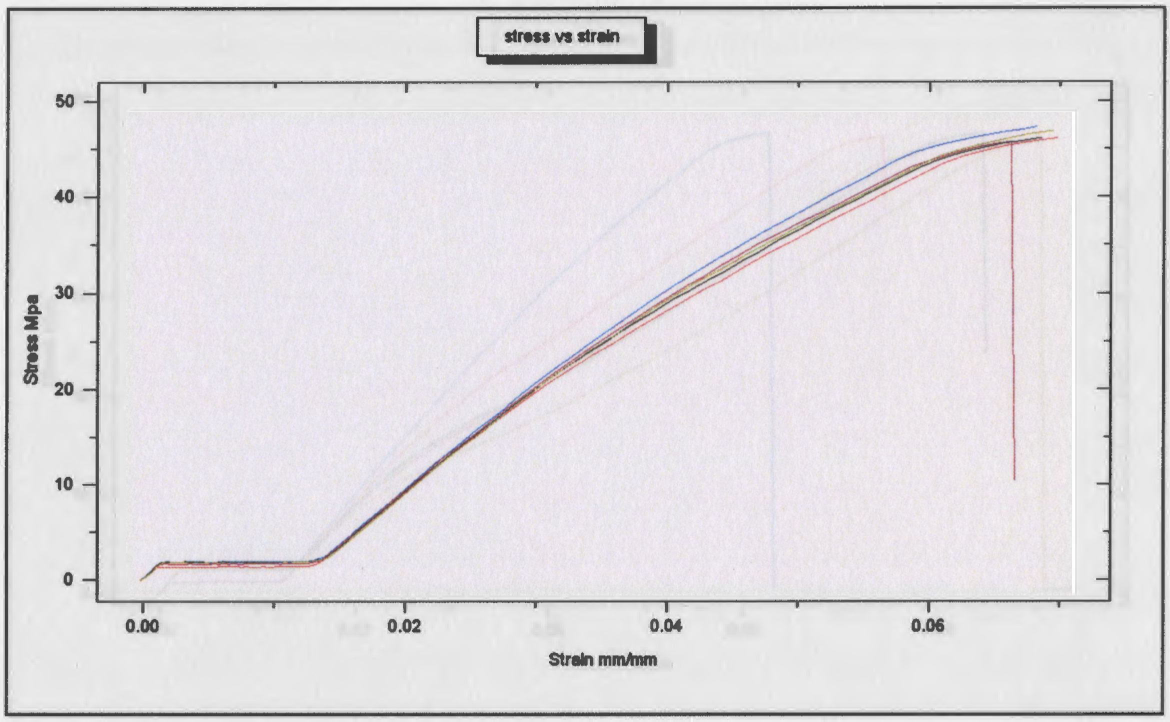


Figure 4.47 Stress-Strain Diagram for the Upper Specimen of 2-Cavity Mold at Injection Speed 2.9 in/sec

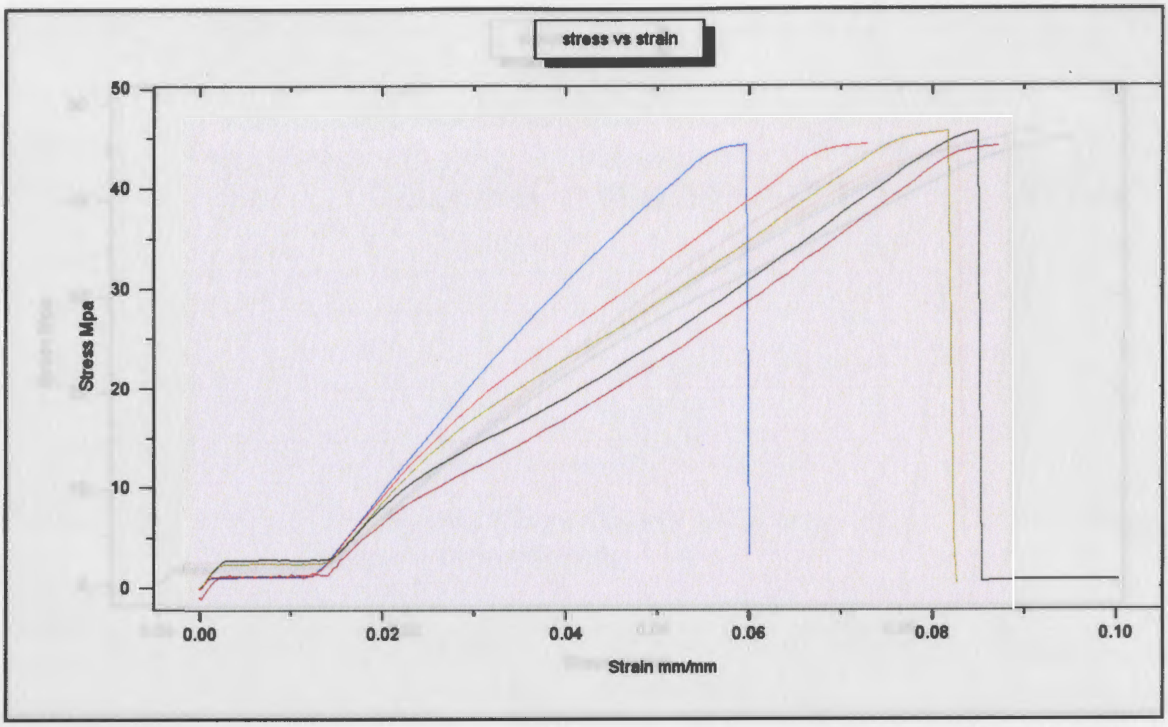


Figure 4.48 Stress-Strain Diagram for the Close to Sprue Specimen of 4-Cavity Mold at Injection Speed 2.9 in/sec

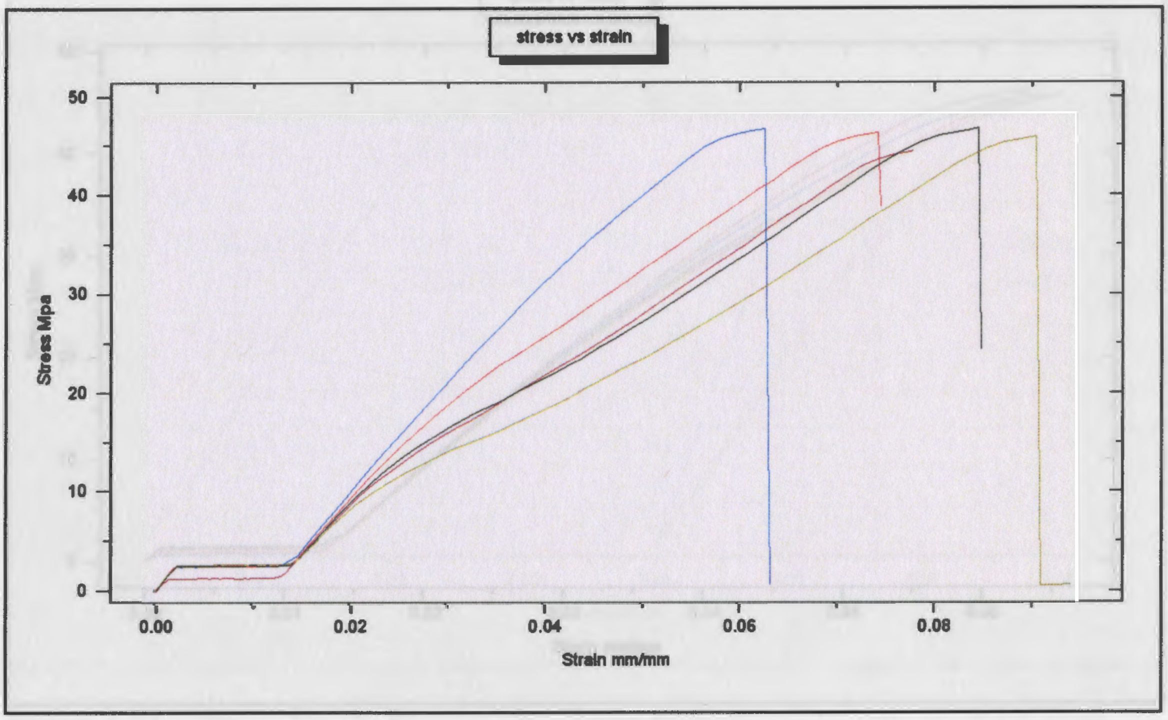


Figure 4.49 Stress-Strain Diagram for Away from Sprue Specimen of 4-Cavity Mold at Injection Speed 2.9 in/sec

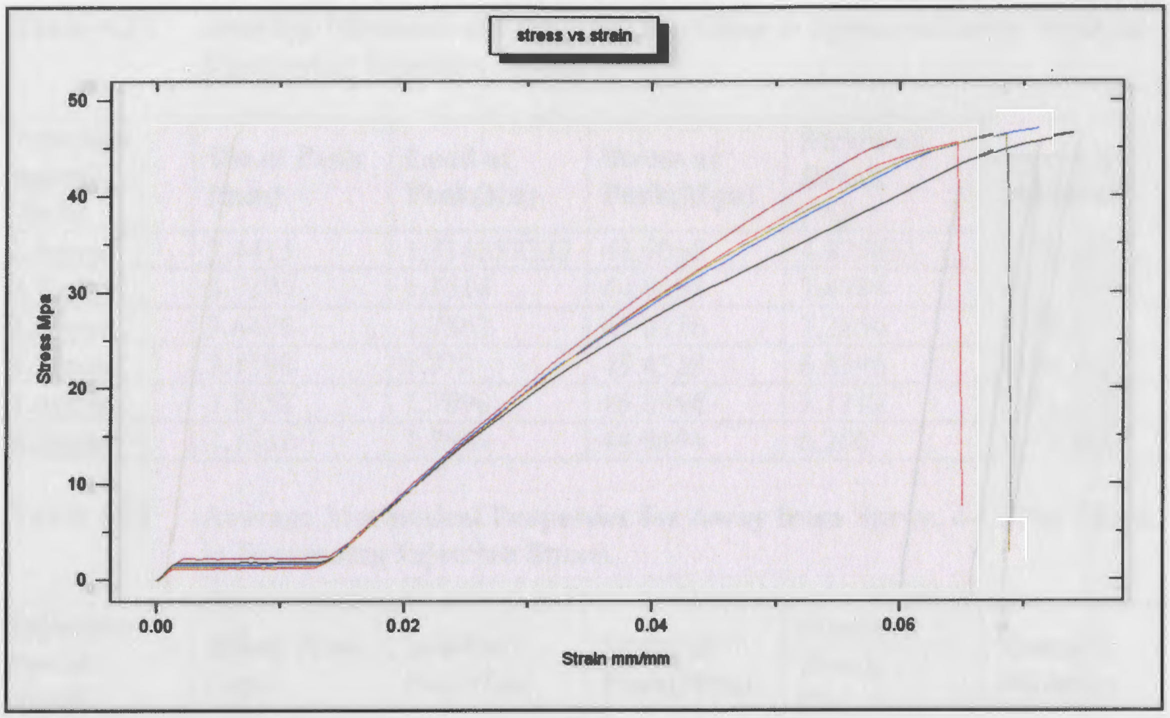


Figure 4.50 Stress-Strain Diagram for the Lower Specimen of 2-Cavity Mold at Injection Speed 3.0 in/sec

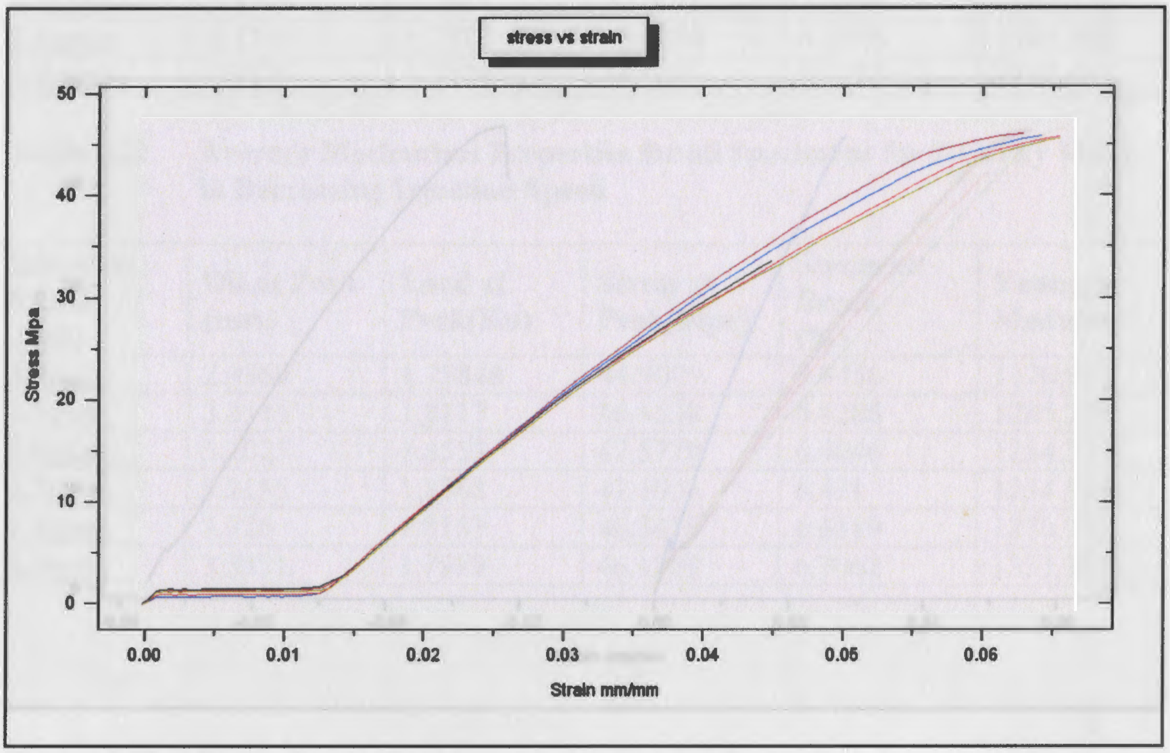


Figure 4.51 Strain-Strain Diagram for the Upper Specimen of 2-Cavity Mold at Injection Speed 3.0 in/sec

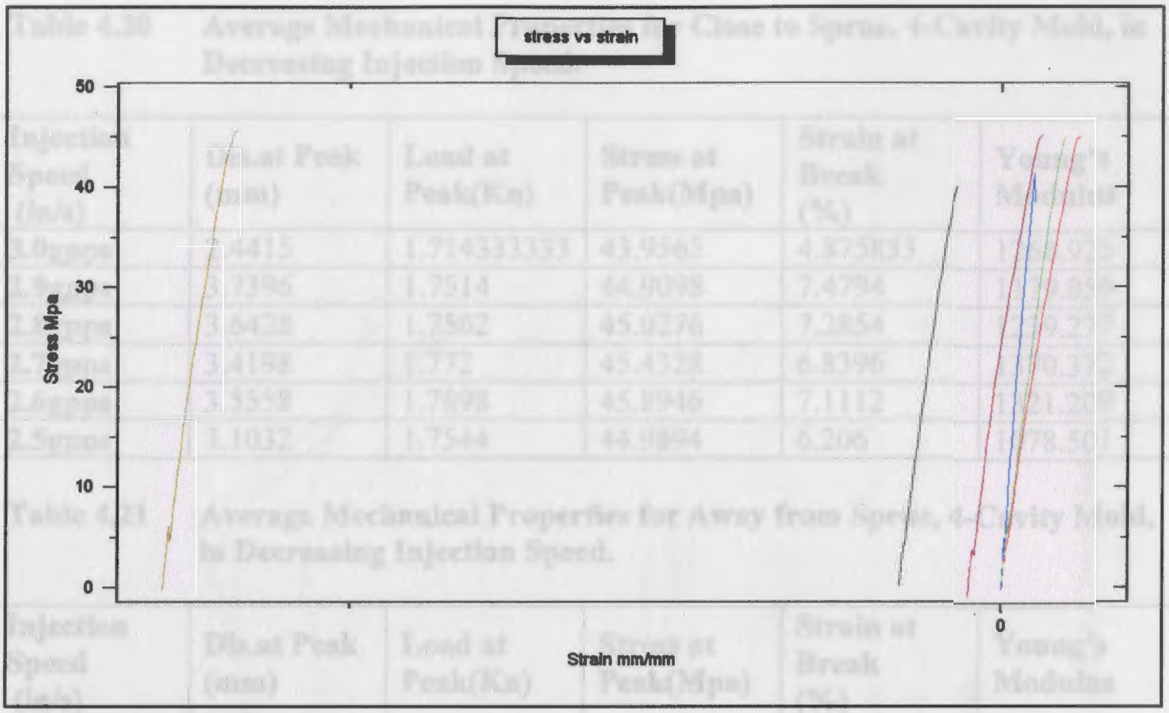


Figure 4.52 Stress-Strain Diagram for the Close to Sprue Specimen of 4-Cavity Mold at Injection Speed 3.0 in/sec

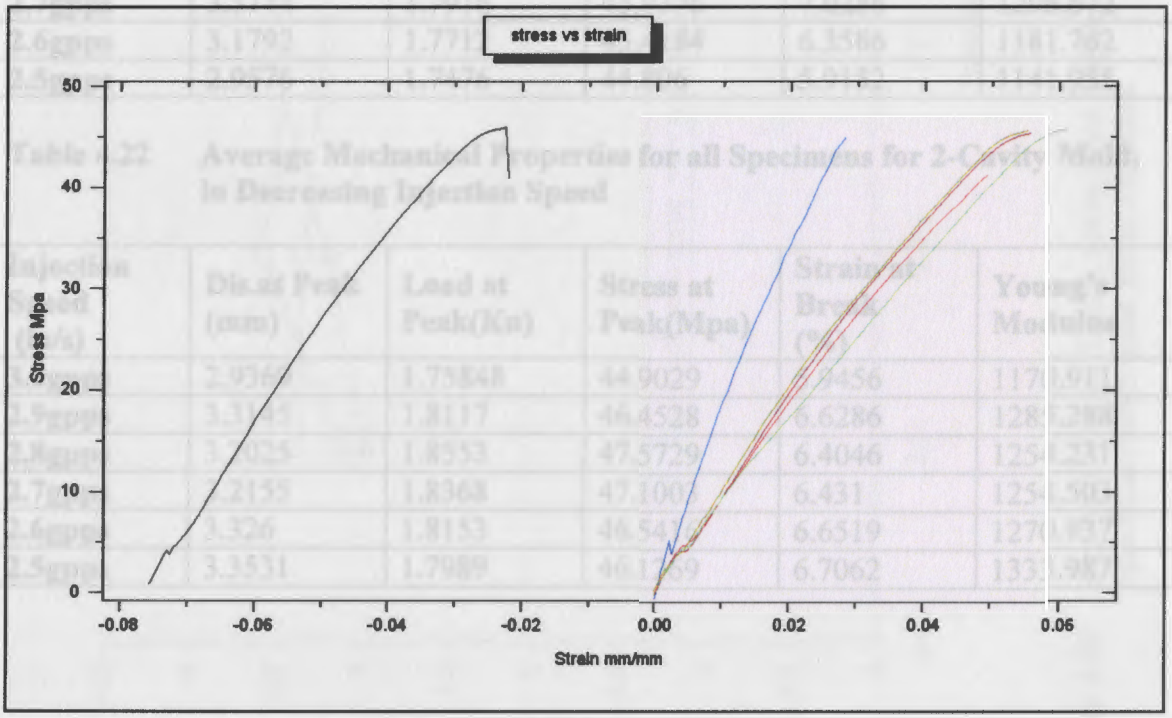


Figure 4.53 Stress-Strain Diagram for Away from Sprue Specimen of 4-Cavity Mold at Injection Speed 3.0 in/sec

Table 4.20 **Average Mechanical Properties for Close to Sprue, 4-Cavity Mold, in Decreasing Injection Speed.**

Injection Speed (in/s)	Dis.at Peak (mm)	Load at Peak(Kn)	Stress at Peak(Mpa)	Strain at Break (%)	Young's Modulus
3.0gpps	2.4415	1.714333333	43.9565	4.875833	1268.925
2.9gpps	3.7396	1.7514	44.9098	7.4794	1179.056
2.8gpps	3.6428	1.7562	45.0276	7.2854	1239.277
2.7gpps	3.4198	1.772	45.4328	6.8396	1370.372
2.6gpps	3.5558	1.7898	45.8946	7.1112	1321.209
2.5gpps	3.1032	1.7544	44.9894	6.206	1078.501

Table 4.21 **Average Mechanical Properties for Away from Sprue, 4-Cavity Mold, in Decreasing Injection Speed.**

Injection Speed (in/s)	Dis.at Peak (mm)	Load at Peak(Kn)	Stress at Peak(Mpa)	Strain at Break (%)	Young's Modulus
3.0gpps	2.516666667	1.750166667	44.8705	5.025167	1252.807
2.9gpps	3.8968	1.795	46.029	7.793	1242.784
2.8gpps	3.6288	1.789	45.8706	7.2578	1292.975
2.7gpps	3.5144	1.7916	45.9376	7.0286	1296.672
2.6gpps	3.1792	1.7712	45.4184	6.3586	1181.762
2.5gpps	2.9576	1.7476	44.806	5.9152	1141.955

Table 4.22 **Average Mechanical Properties for all Specimens for 2-Cavity Mold, in Decreasing Injection Speed**

Injection Speed (in/s)	Dis.at Peak (mm)	Load at Peak(Kn)	Stress at Peak(Mpa)	Strain at Break (%)	Young's Modulus
3.0gpps	2.9369	1.75848	44.9029	5.9456	1170.911
2.9gpps	3.3145	1.8117	46.4528	6.6286	1285.288
2.8gpps	3.2025	1.8553	47.5729	6.4046	1254.231
2.7gpps	3.2155	1.8368	47.1003	6.431	1254.503
2.6gpps	3.326	1.8153	46.5416	6.6519	1270.937
2.5gpps	3.3531	1.7989	46.1269	6.7062	1333.987

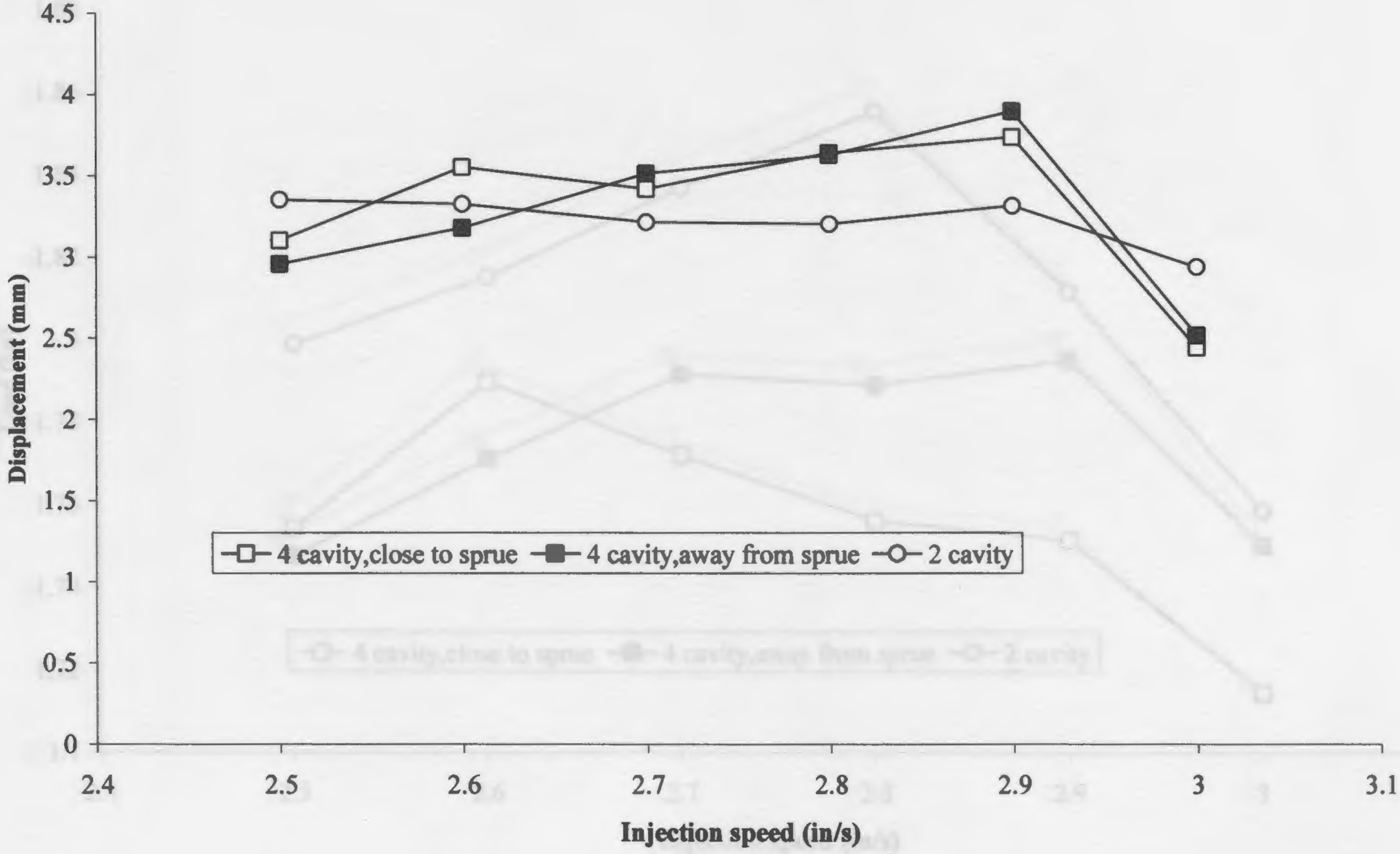


Figure 4.54 Displacement for Close, Away from Sprue in 4-Cavity and 2-Cavity Mold as the Injection Speed Increases from 2.5 to 3.0 in/sec

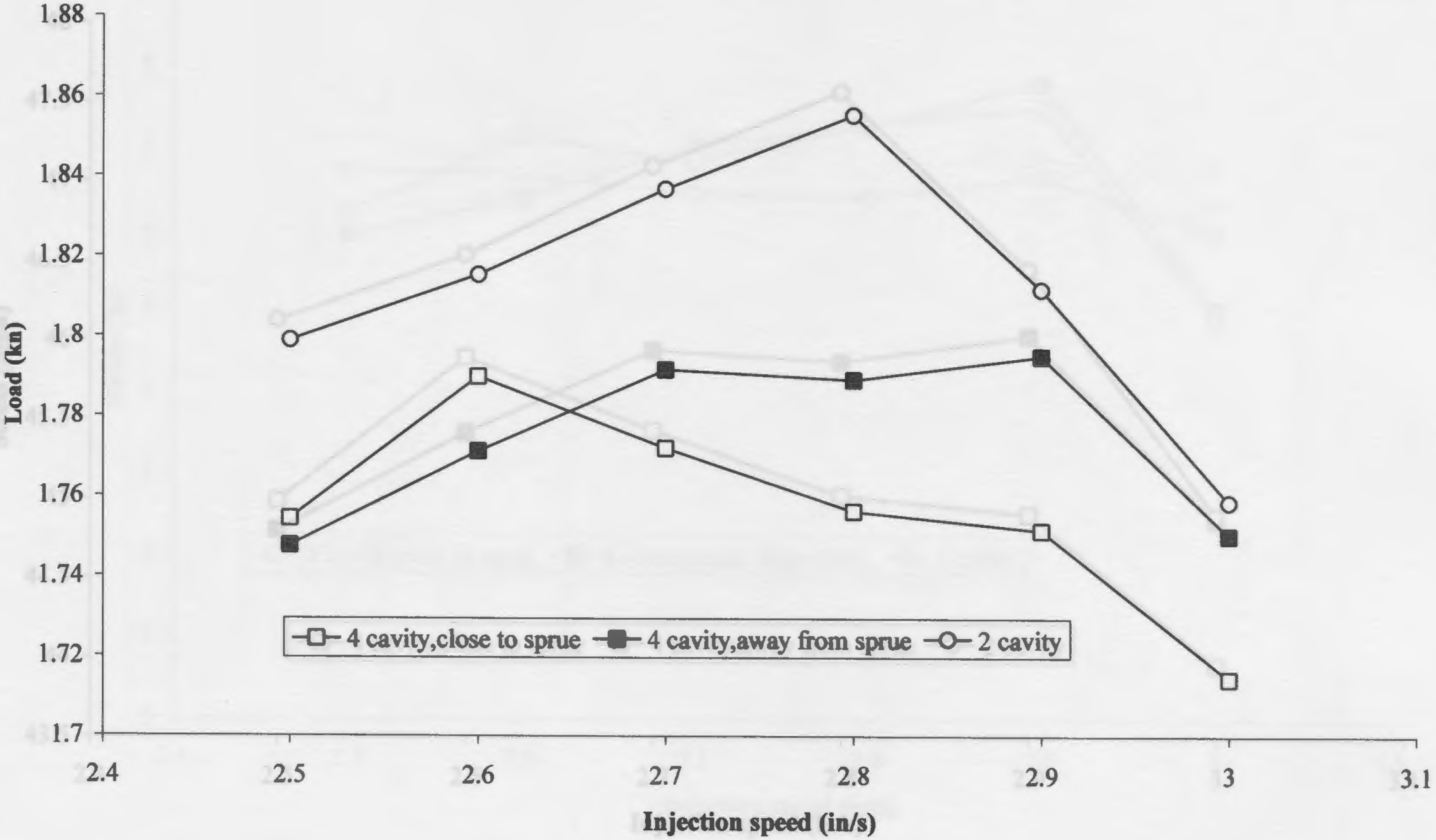


Figure 4.55 Load for Close, Away from Sprue in 4-Cavity and 2-Cavity Mold as the Injection Speed Increases from 2.5 to 3.0 in/sec

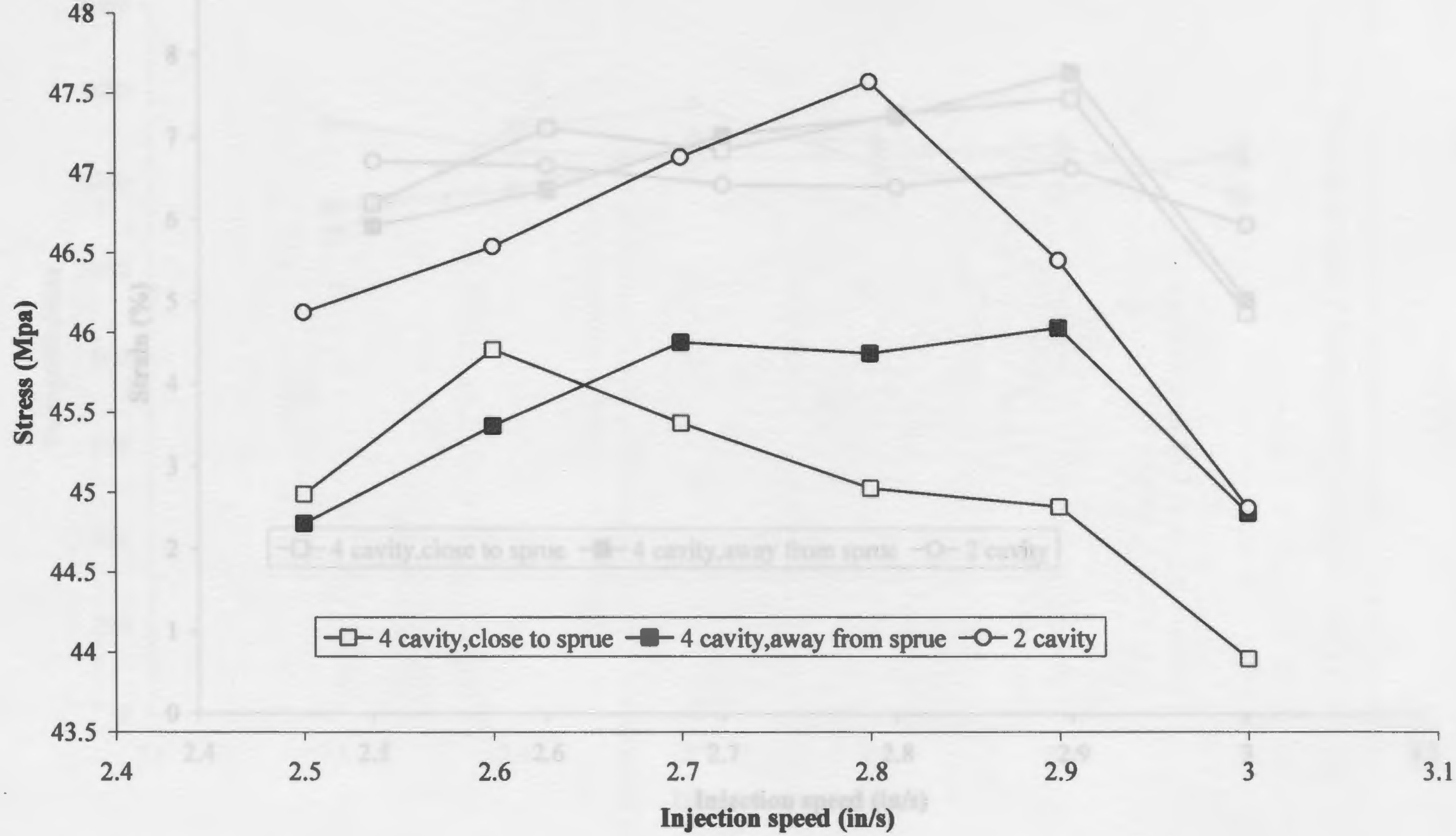


Figure 4.56 Stress for Close, Away from Sprue in 4-Cavity and 2-Cavity Mold as the Injection Speed Increases from 2.5 to 3.0 in/sec

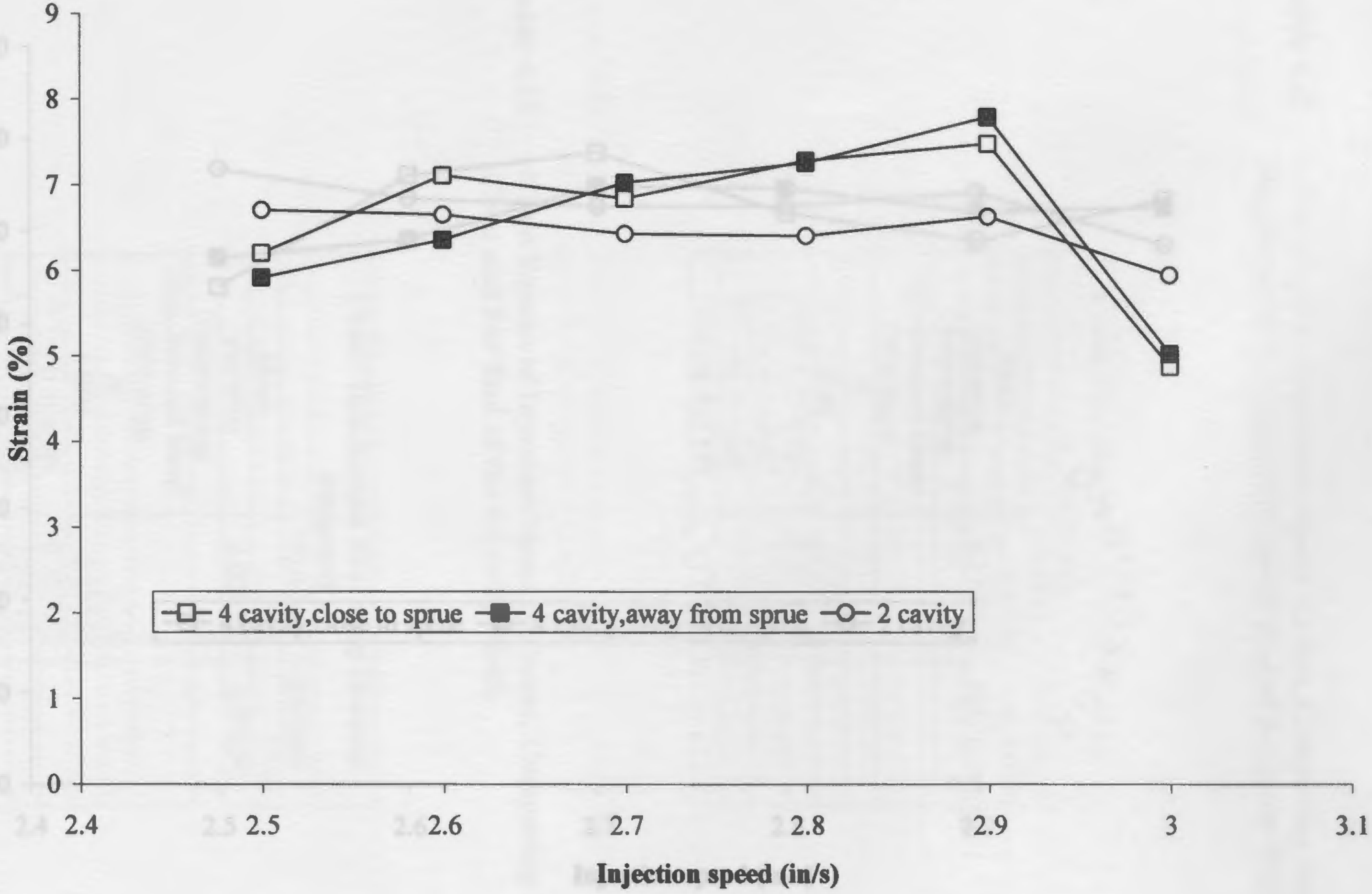


Figure 4.57 Strain% for Close, Away from Sprue in 4-Cavity and 2-Cavity Mold as the Injection Speed Increases from 2.5 to 3.0 in/s

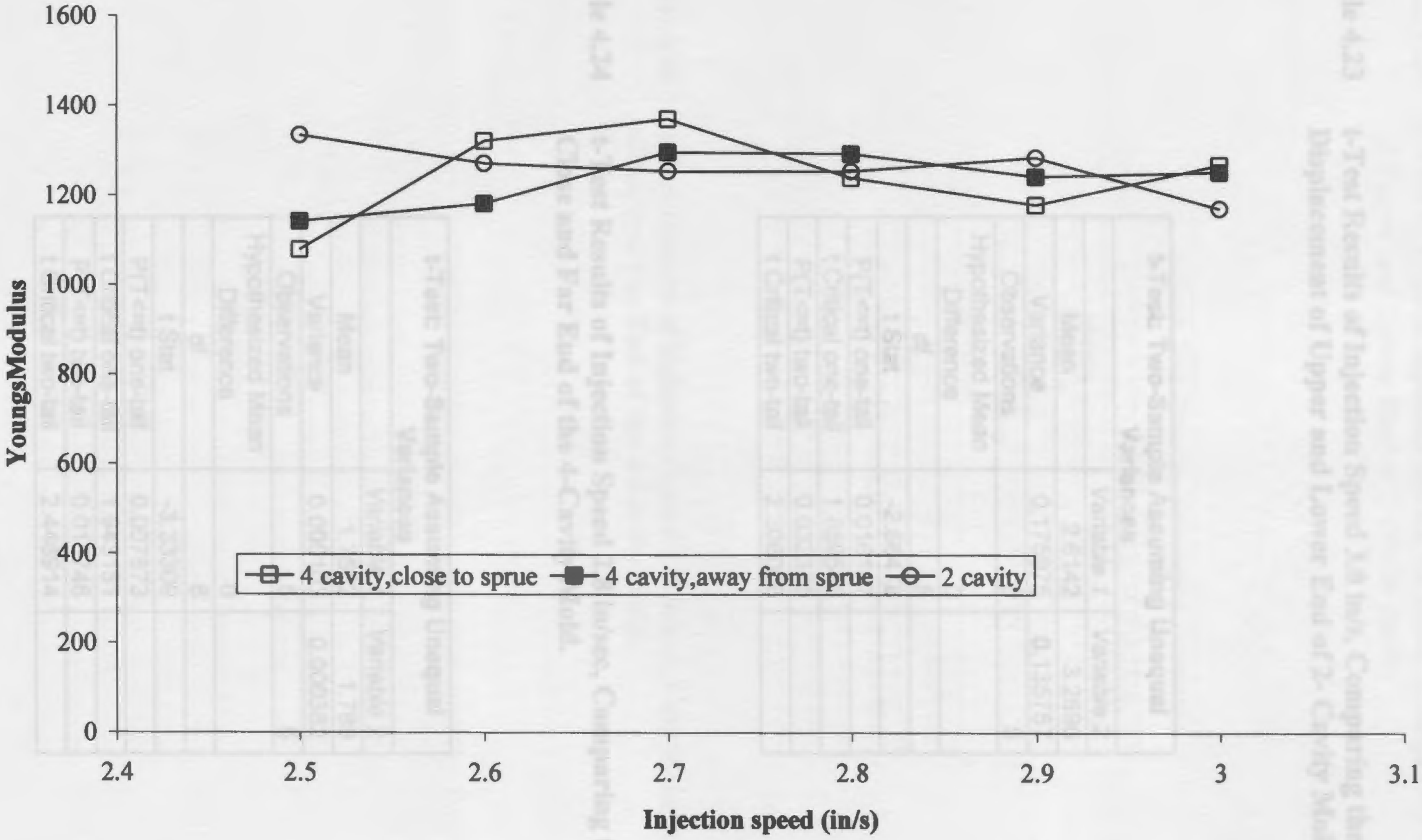


Figure 4.58 Young's Modulus for Close, Away from Sprue in 4-Cavity and 2-Cavity Mold as the Injection Speed Increases from 2.5 to 3.0 in/sec

Table 4.23 **t-Test Results of Injection Speed 3.0 in/s, Comparing the Displacement of Upper and Lower End of 2- Cavity Mold.**

t-Test: Two-Sample Assuming Unequal Variances		
	Variable 1	*Variable 2*
Mean	2.6142	3.2596
Variance	0.175975	0.135757
Observations	5	5
Hypothesized Mean Difference	0	
df	8	
t Stat	-2.58478	
P(T<=t) one-tail	0.016187	
t Critical one-tail	1.859548	
P(T<=t) two-tail	0.032375	
t Critical two-tail	2.306006	

Table 4.24 **t-Test Results of Injection Speed 2.8 in/sec, Comparing the Load of Close and Far End of the 4-Cavity Mold.**

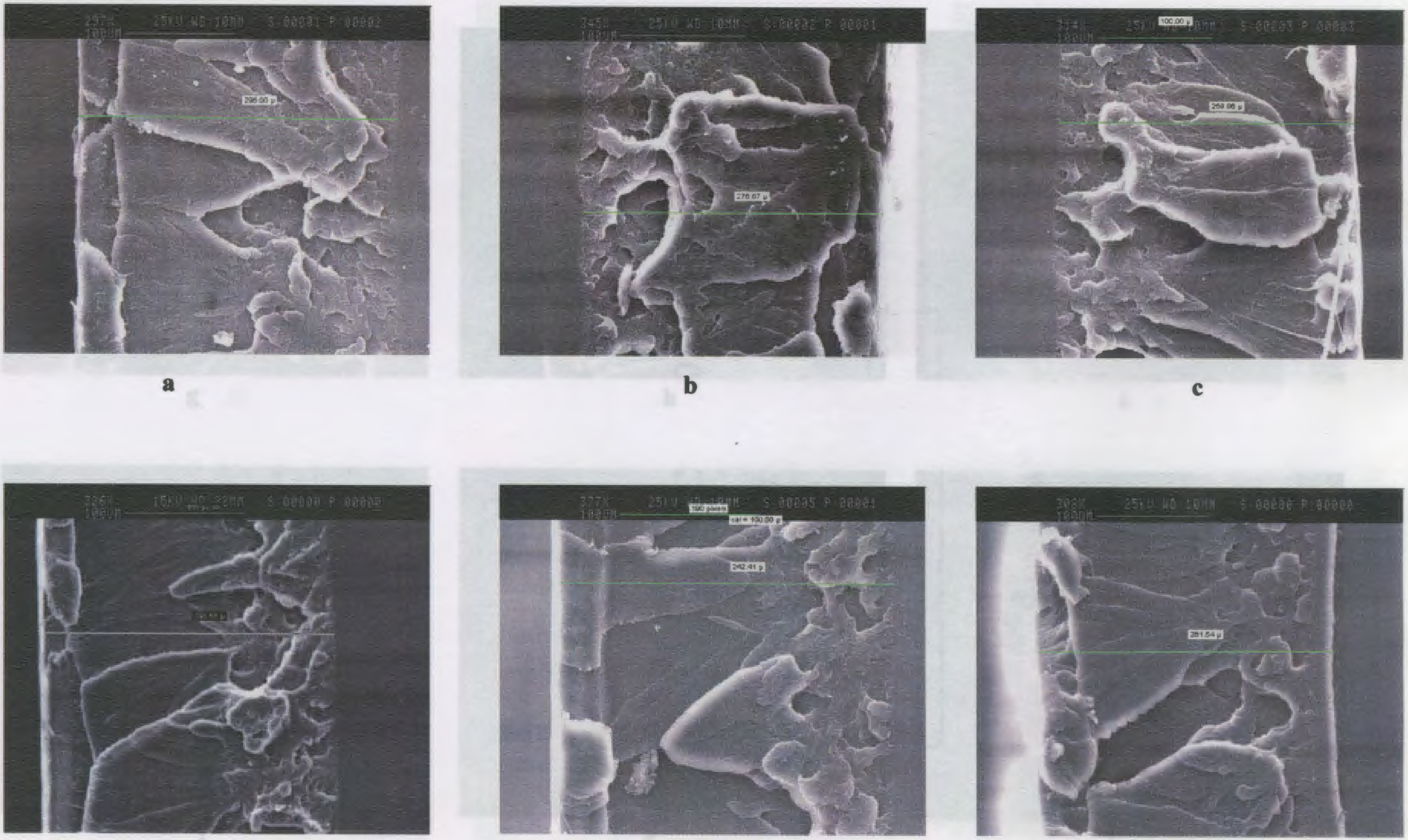
t-Test: Two-Sample Assuming Unequal Variances		
	Variable 1	*Variable 2*
Mean	1.7562	1.789
Variance	0.000103	0.000382
Observations	5	5
Hypothesized Mean Difference	0	
df	6	
t Stat	-3.33309	
P(T<=t) one-tail	0.007873	
t Critical one-tail	1.943181	
P(T<=t) two-tail	0.015746	
t Critical two-tail	2.446914	

Table 4.25 **t-Test Results of Injection Speed 3.0 in/sec, Comparing the Strain % of Upper and Lower End of 2-Cavity Mold.**

t-Test: Two-Sample Assuming Unequal Variances		
	Variable 1	*Variable 2*
Mean	5.3724	6.5188
Variance	0.559414	0.54262
Observations	5	5
Hypothesized Mean Difference	0	
df	8	
t Stat	-2.44188	
P(T<=t) one-tail	0.020223	
t Critical one-tail	1.859548	
P(T<=t) two-tail	0.040446	
t Critical two-tail	2.306006	

Table 4.26 **t-Test Results of Injection Speed 2.8 in/sec, Comparing the Stress of Close and Far End of the 4-Cavity Mold.**

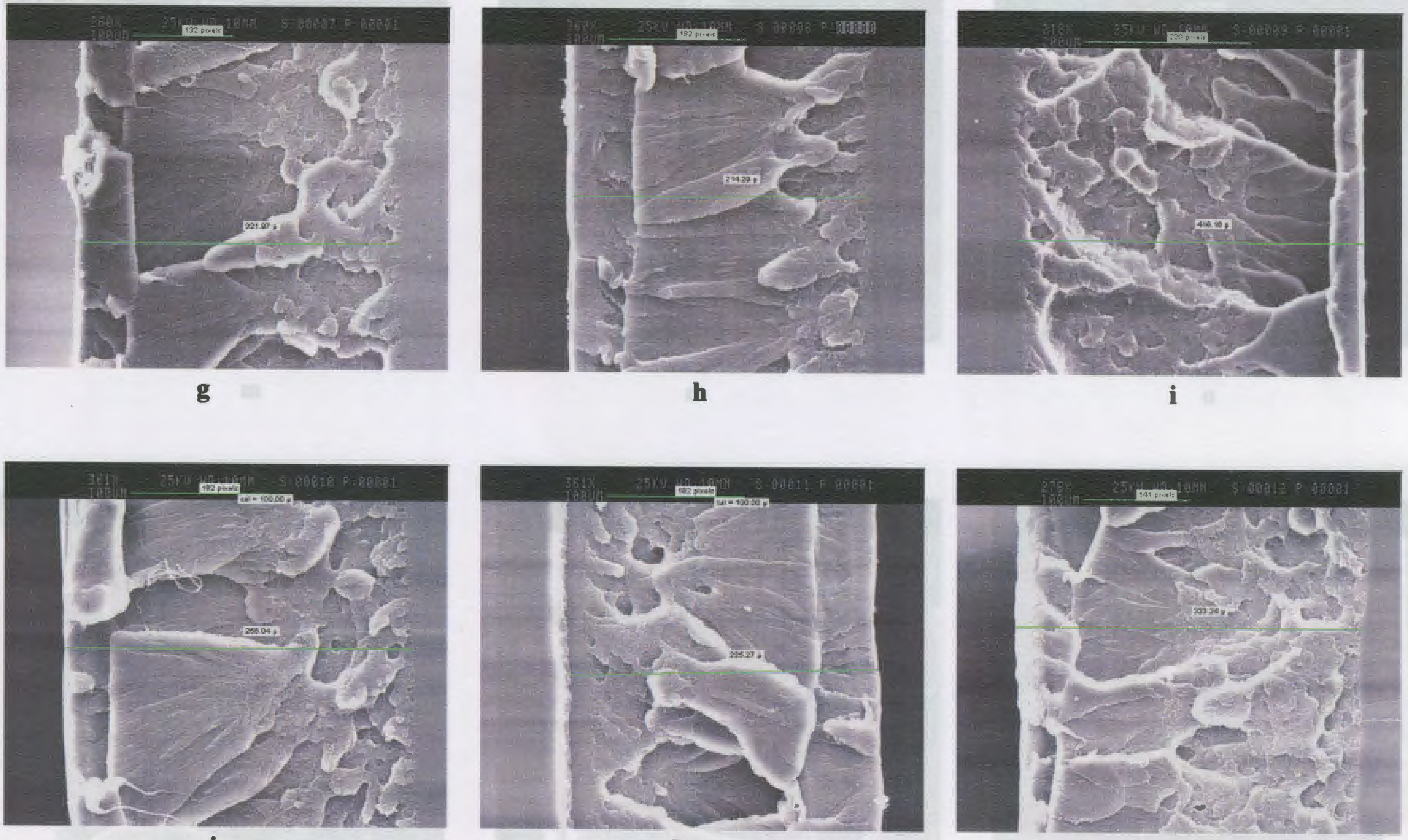
t-Test: Two-Sample Assuming Unequal Variances		
	Variable 1	*Variable 2*
Mean	45.0276	45.8706
Variance	0.065315	0.248405
Observations	5	5
Hypothesized Mean Difference	0	
df	6	
t Stat	-3.36544	
P(T<=t) one-tail	0.007564	
t Critical one-tail	1.943181	
P(T<=t) two-tail	0.015128	
t Critical two-tail	2.446914	



a b c

d e f

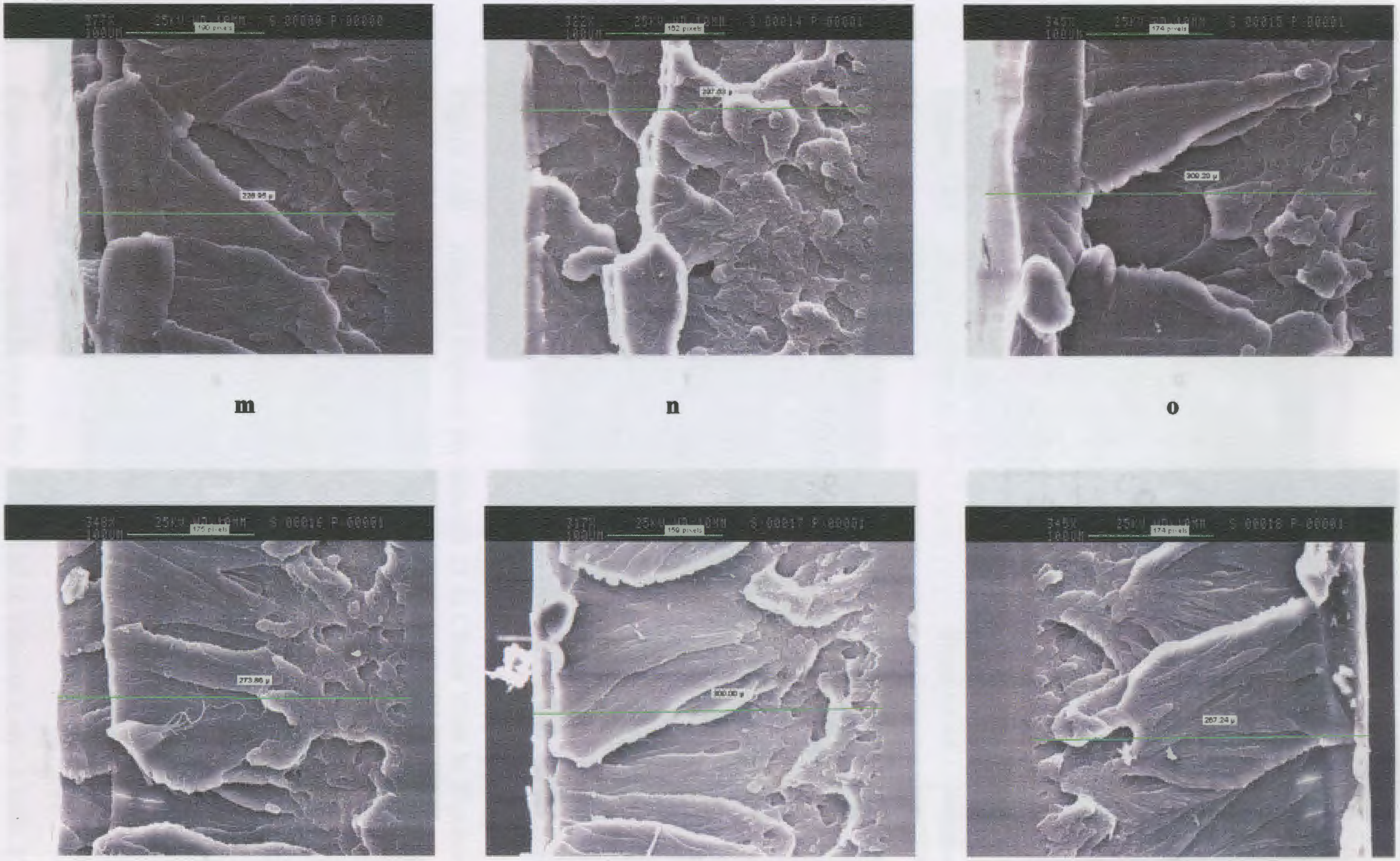
Figure 4.59 Average Thickness Along the Borders for Samples 1, 2, 3, 4, 5 and 6 Corresponding to Figures a, b, c, d, e and f, Respectively



g h i

j k l

Figure 4.60 Average Thickness Along the Borders for Samples 7, 8, 9, 10, 11 and 12 Corresponding to Figures g, h, i, j, k and l Respectively



m n o

p q r

Figure 4.61 Average Thickness Along the Borders for Samples 13, 14, 15, 16, 17 and 18 Corresponding to Figures m, n, o, p, q and r, Respectively

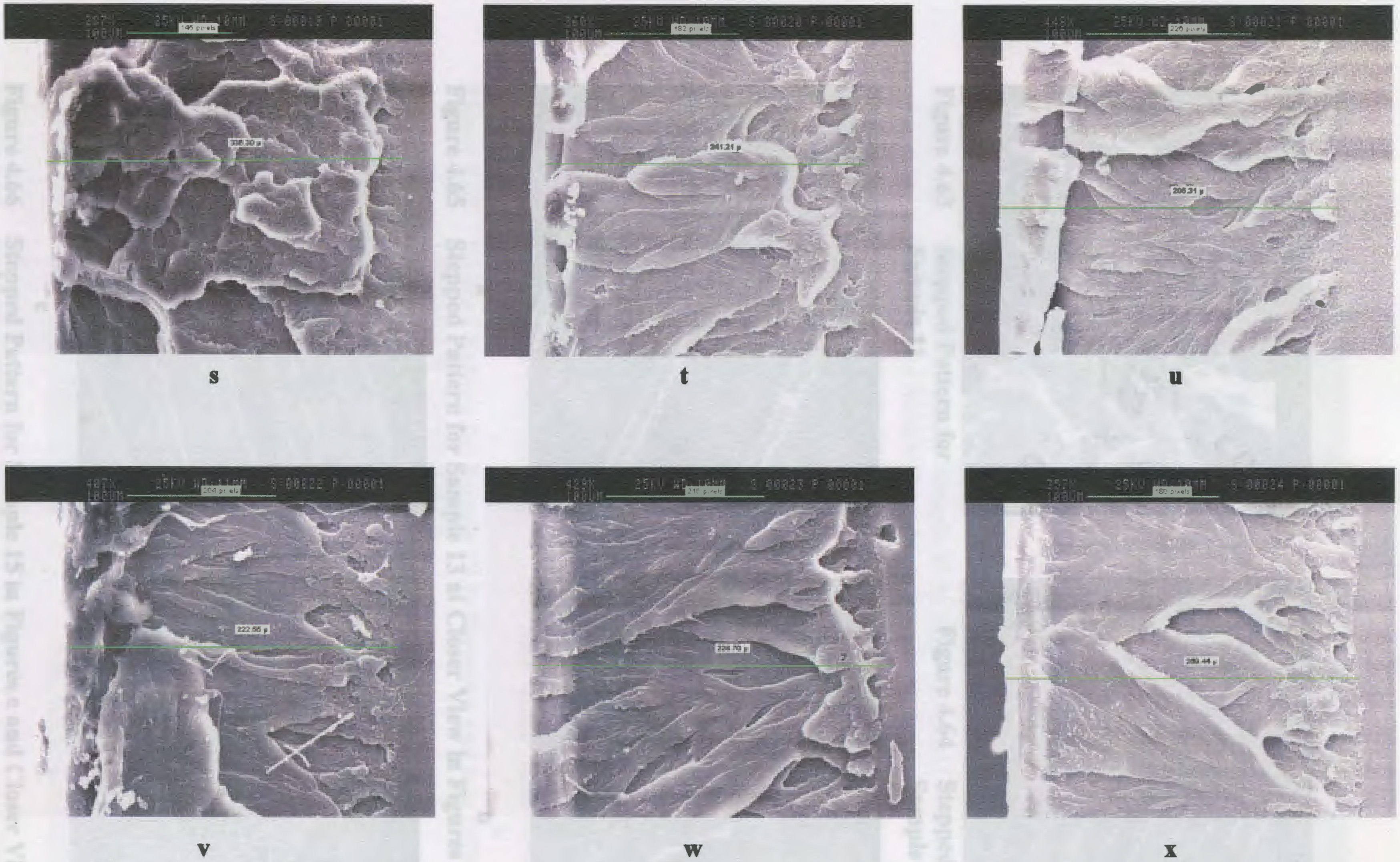


Figure 4.62 Average Thickness Along the Borders for Samples 19, 20, 21, 22, 23 and 24 Corresponding to Figures s, t, u, v, w and x Respectively

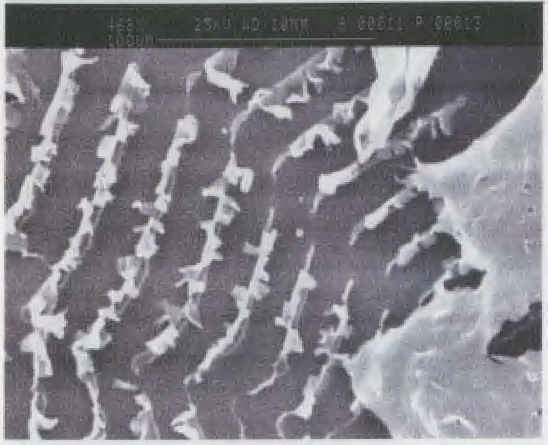


Figure 4.63 Stepped Pattern for Sample 11

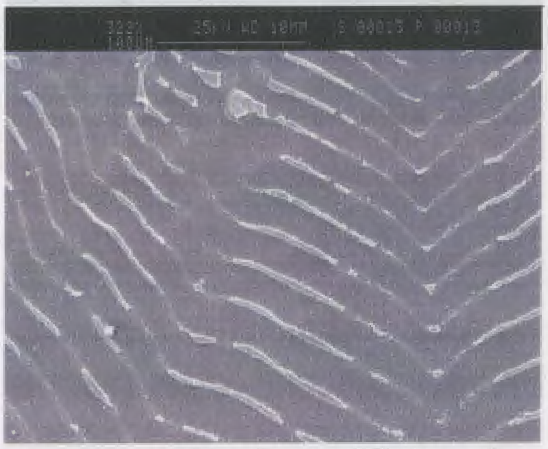
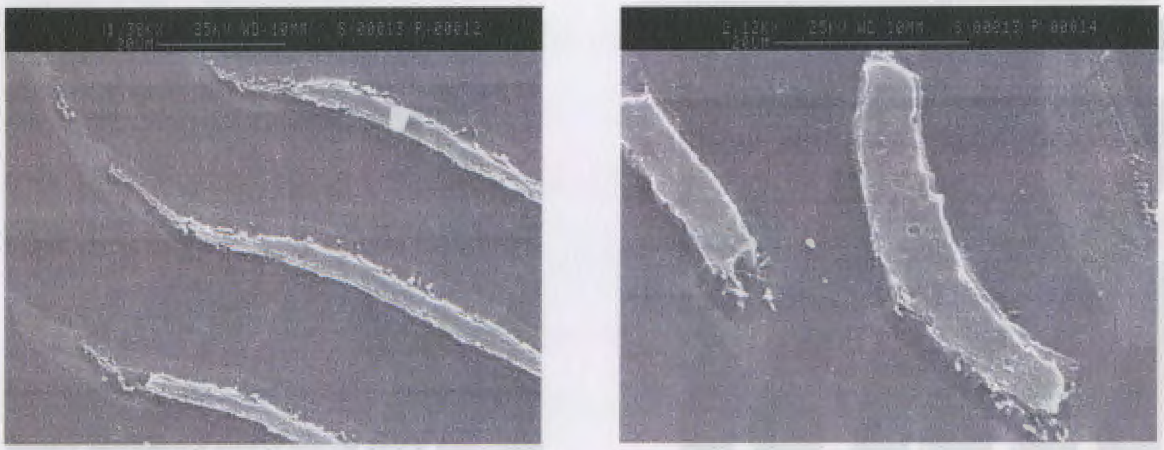


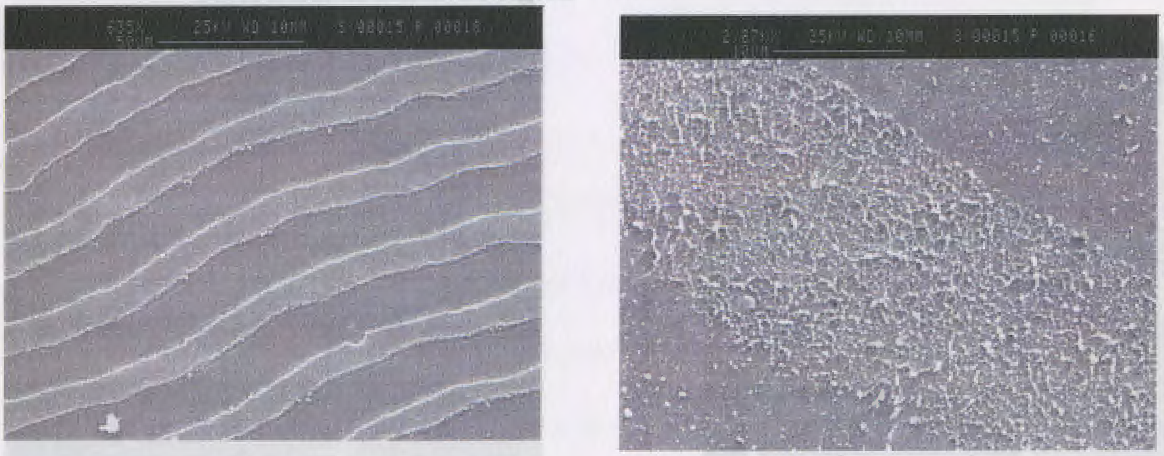
Figure 4.64 Stepped Pattern for Sample 13



a

b

Figure 4.65 Stepped Pattern for Sample 13 at Closer View in Figures a and b



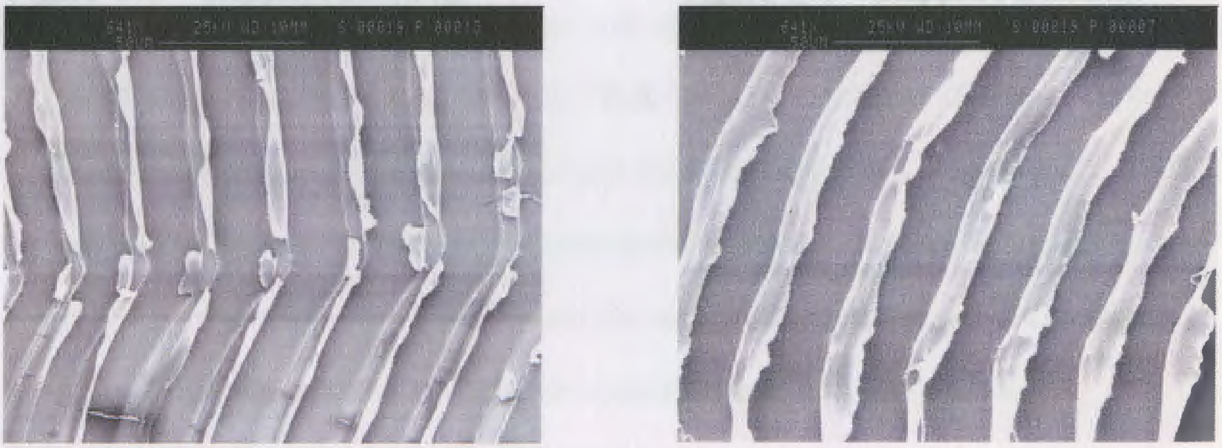
c

d

Figure 4.66 Stepped Pattern for Sample 15 in Figures c and Closer View for Sample 15 in Figure d

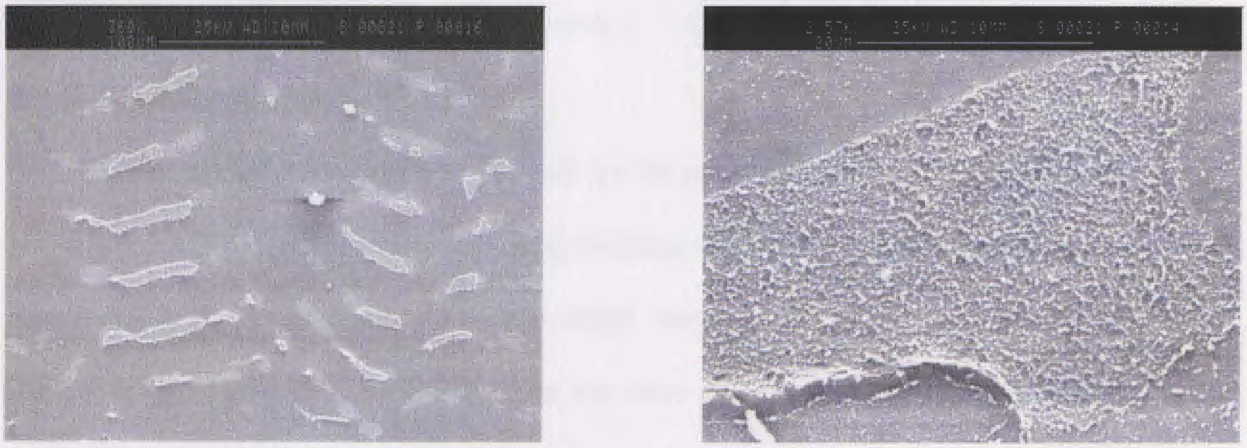
e f

Figure 4.67 Stepped Pattern for Sample 18 in Figures e and f at Different Locations in Hackle Region



g h

Figure 4.68 Stepped Pattern for Sample 19 in Figures g and h at Different Locations in Hackle Region



i j

Figure 4.69 Stepped Pattern for Sample 21 in Figure i and Closer View at the Mackeral Band for Sample 21 in Figure j

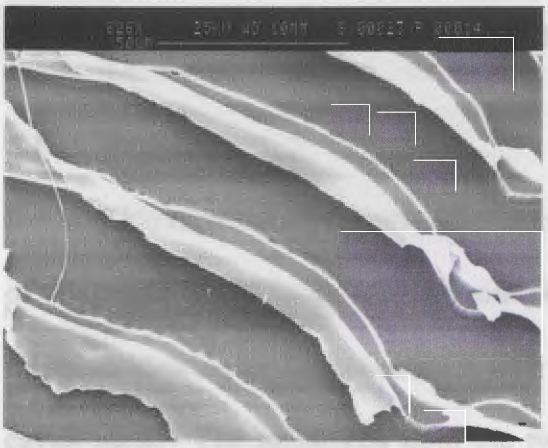


Figure 4.70 Stepped Pattern for Sample 23

Figure 4.71 Stepped Pattern for Sample 24

CHAPTER 5

SUMMARY AND RECOMMENDATIONS

5.1 Summary

This research investigated the effect of processing conditions on the development of structural hierarchy in injection-molded GPPS. A single-stage reciprocating screw injection molding machine was used with two different mold designs; a 2-cavity and a 4-cavity mold. The specimens from the two molds were produced with injection speeds ranging from 3.0 in/second to 2.5 in/second with same processing variables and the load, strain, Young's modulus were calculated. There was no significant difference in the stress and strain % for the specimens close and away from sprue in a 4-cavity mold. By comparing the two mold designs it was concluded that the specimens at an injection speed of 2.5 in/second from a 2-cavity mold are stronger compared to samples produced in an asymmetric 4-cavity mold at the same injection speed.

By using the micrographs obtained, this research concludes that by using a symmetric mold at slow injection speeds, the intensity of crazes can be decreased and thus improve the mechanical tensile properties

5.2 Recommendations

This research opens up a wide study for the micromorphology of general purpose polystyrene by using an injection molding machine. This research only investigated the specimens at different injection speeds while keeping the other variables constant. Further study should be done by changing the other process variables and observing the micromorphology before and after the tensile testing. By using injection molding other types of polymeric materials can be investigated in blends at different ratios.

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