DEVELOPMENT OF A SIMPLIFIED FRACTURE TOUGHNESS TOOL FOR POLYMERS

THESIS

Presented to the Graduate Council of the

University of North Texas in Partial

Fulfillment of the Requirements

For the Degree of

MASTER OF SCIENCE

By

Patrick J. Marnock, B.S.

Denton, Texas

August, 1997

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This thesis presents research toward the development of a simple inexpensive fracture toughness tool for polymeric materials. Experiments were conducted to test the specimen configuration and the fracture toughness tool against an established ASTM standard for polymer fracture toughness, D5045, and a commonly used four-point bend method. The materials used in this study were polycarbonate and high density polyethylene. Reductions in both the production time and the variability resulting from the preparation of the specimens were addressed through the use of specially designed fixtures. The effects from the razor cut depths used in the chevron notch were compared to the fracture toughness values obtained in order to determine the effect upon the validity of the fracture toughness.

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CHAPTER I

INTRODUCTION

Current methods used to determine a material's fracture toughness require sophisticated equipment not readily accessible to many companies because of costly equipment and skilled personnel needed to make the specimens and perform the tests. Progress has been made to reduce the specimen costs and difficulty in testing metals with the American Society for Testing and Materials (ASTM) standard E1304 and a new engineering tool developed by Stromswold and Quesnel, (1992) University of Rochester Materials Science Department that promises to reduce specimen preparation costs and test equipment costs. The elimination of the introduction of a crack in the specimens used with ASTM standard E1304 represents a major cost reduction. ASTM E1304 uses short rod or bar specimens with a chevron notch that creates a crack immediately when the load is applied. However, the machining of the notch and the testing of the specimens still requires expensive equipment. These problems are addressed by Stromswold and Quesnel who have created a simplified fracture toughness tool for metallic materials whose specimens utilize the chevron notch configuration. Stromswold and Quesnel's fracture toughness tool further reduces costs by using essentially a 4-point bend geometry that simplifies the preparation of the specimen. The result is a fracture toughness tool that

is a simple inexpensive device used in a test that can be performed by a non-skilled technician. However, the tool developed by Stromswold and Quesnel has been proven for metallic materials only. Testing the feasibility of using a similar design for polymeric materials is the objective of this thesis.

Fracture toughness of polymers used in engineering applications is becoming an important material property with the growing use of these materials. Therefore, a simple fracture toughness tool for polymers would have the same advantages of reduced cost in both specimen preparation and testing that the fracture toughness tool has with metallic materials. ASTM D5045 defines the current test method for determining the fracture toughness for polymeric materials. Adapting the fracture toughness tool to polymeric materials involved using key components outlined in the ASTM standard.

The major focus in adapting the fracture toughness tool to polymers is the specimen configuration. The specimens used in ASTM D5045 are dimensioned to insure that a plane strain condition exists around the crack tip in order to find a valid K_{Ic} value. The two specimen types defined by ASTM D5045 are the single edge notch bend and the compact tension (CT) specimen. The single edge notch (SEN) specimen is designed to be tested using a 3-point bend procedure (see Fig. 1.1). The compact tension specimen is tested by subjecting the specimen to tensile stresses (ASTM D5045-95, 1995). In both types of the specimens, the thickness needed to produce a plane strain condition in the specimen depends upon the toughness and ductility of the material and must satisfy the following equality given in ASTM D5045:

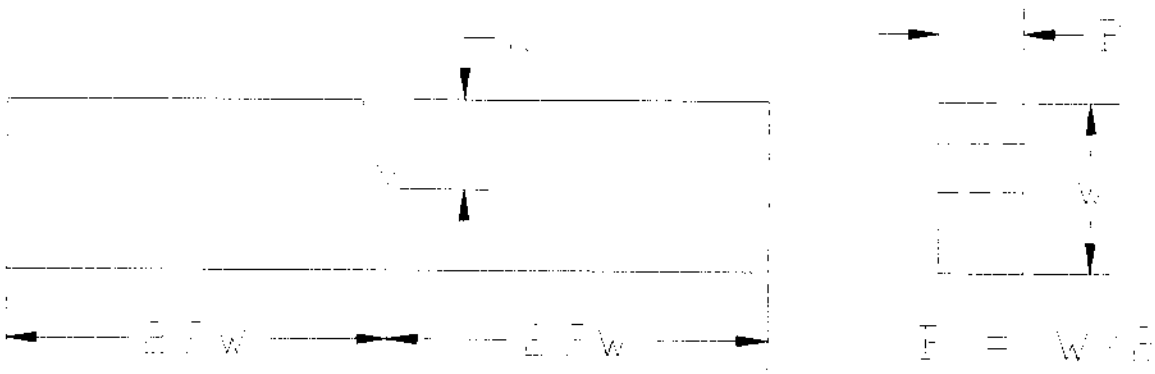

Fig. 1.1 ASTM SEN 3-point bend general dimension requirements.

$$B \geq 2.5\left(\frac{K_{Ic}}{\sigma_{ys}}\right)^2, \qquad (1\text{-}2)$$

where:

B = the thickness of the specimen,

K_{Ic} = the fracture toughness,

σ_{ys} = represents the yield strength (1991).

Since K_{Ic} is unknown, a load deflection curve is obtained to estimate this value for use in the above equation. This procedure is defined in the ASTM D5045 standard. Some researchers contend that K_{Ic} can also be estimated by using previous experience or by making the specimen as thick as possible (Edwards and Wanhill, 1991). The specimen's notch configuration and dimensions must satisfy the equation 1-2 in order to ensure that plane strain conditions exist at the crack tip allowing the use of linear elastic fracture mechanics (LEFM) in the calculation of the fracture toughness.

In order to apply LEFM to the hand held testing device, the behavior of the polymers must be controlled, especially the size and development of the plastic zone at the crack tip of the specimen. The presence of a sharp crack and limited plastic deformation are the two keys for polymers that allow the application of LEFM (Su, 1989). Also, the crack tip region has been shown to be a possible fracture criterion (Yehia, 1986). An initial crack is produced using a razor blade. The limited plastic deformation is also controlled by the geometry of the specimen including the width and notch configuration

(Zhang and Venugopalan, 1987). These two variables are reflected by the equation used to calculate K_Q, the conditional critical stress intensity factor for K_{Ic}, in ASTM D5045,

$$K_Q = \left(\frac{P_Q}{BW^{1/2}}\right) f(x), \tag{1-3}$$

where:

P_Q = the peak load,

B = the thickness,

W = the width,

a = crack length,

f(x) = a geometry dependent value of the specimen, x = a/W.

The simple hand held fracture toughness tester also uses an equation for K_Q reflecting the influence of these two variables,

$$K_Q = \frac{CM}{B^{2.5}}, \tag{1-4}$$

where:

C = the critical shape factor based upon the geometry of the notch and specimen,

M = the moment applied,

B = the specimen thickness.

Therefore, the dimensions of the specimen and the configuration of the notch play an important role in determining the fracture toughness value. However, the necessary dimensions required to produce the correct conditions demonstrates one of the difficulties that arises from using these specimen types.

The use of the SEN and the compact tension specimen poses certain difficulties in their preparation and testing. The thickness, B, can become very large depending upon the ductility of the material; another difficulty concerns specimen preparation. Fatiguing metallic specimens or pre-cracking, is required to produce a sharp crack. The notch placement is critical to valid results. Finally, the testing of the specimens requires expensive equipment.

The tool developed by Stromswold and Quesnel offers a very inexpensive method for determining the fracture toughness of metallic materials compared to other methods. The specimens are not as difficult to produce; notch placement is not a critical dimension. Stromswold and Quesnel explain this characteristic,

> Moreover, the required machining involved in preparing a chevron notch four point bend sample is less critical...the area surrounding the crack in a chevron notch bend sample is exposed to a constant bending moment. Therefore, it is not necessary to accurately position the chevron notched portion of the sample between the inner load points. As a result, the overall specimen length and chevron notch are not critical dimensions (1992, p. 309).

Also, the specimens do not require special equipment for production as the chevron notched rod and bar specimens do. Finally, the toughness tool apparatus is a simple testing device which does not require expensive testing equipment to measure pertinent parameters needed to determine the K_{Ic} value. The cost of this device allows access to fracture toughness testing for a greater number of companies that can not afford expensive testing procedures. Adapting this tool for polymeric materials has been the focus of

continuing research in the Department of Engineering Technology at the University of North Texas.

1.1 Purpose

The purpose of the research is to determine the feasibility of using a fracture toughness tool similar to Stromswold and Quesnel's for polymers. Three areas are of major concern in the development of the simplified fracture toughness tool. The first area is to reduce the variability from the preparation of the test specimens. This area concerns the fabrication of the notch. Using fixtures that will securely hold the specimen during machining and tools to apply the razor notch help to both reduce the variation and facilitate the preparation of the specimens. The second area is to reduce the amount of time needed to produce the specimens. New fixtures for machining multiple specimen blanks and applying the chevron notch are tested. These fixtures have been designed and created by Dr. Phillip R. Foster of the Engineering Technology Department at The University of North Texas. Also, the tool that allows for easy loading and unloading of razor blades reduces the amount of time needed to apply to razor notch. The third reason focuses on modifying the fracture toughness tool to give comparable results to the ASTM D5045 test method results. This modification involves making an adaptable toughness tool that will work for all polymeric materials at a reasonable price.

1.2 Statement of the problem

The problem addressed in this thesis is that there is not a simple inexpensive method to test for the fracture toughness of polymers used in structural engineering applications. Related to the problem statement, the objective of this thesis is to design a fracture toughness tool for viscoelastic polymeric materials similar to the fracture toughness tool developed by Stromswold and Quesnel for metallic materials. In order to accomplish this objective, variations in the specimen configuration are tested using a four point bend procedure an compared with the established ASTM standard D5045 for polymer fracture toughness. Also, the specimens tested using the fracture toughness tool are compared to a four point bend test procedure since the fracture toughness tool imitates the four point bend procedure in producing almost the same bending moments characteristic of a four point bend test. The results will determine whether the specimen configuration for the polymers tested produce valid fracture toughness results and whether the fracture toughness tool can produce values comparable to the established test methods.

1.3 Research Questions

There are four research questions addressed in this research. They are presented in terms of null (H_o) and alternative (H_a) hypothesis.

1. H_o: $\mu = \mu_o$

   H_a: $\mu_o \neq \mu$

where:

μ = the mean of the 4 point bend specimen group tested on the Sentec,

μ_o = the mean of the ASTM D5045 3 point bend specimen group.

2. H_o: $\mu = \mu_o$,

   H_a: $\mu \neq \mu_o$

   where:

   μ = the mean of the 4 point bend specimen group,

   μ_o = represents the specimen group tested using the hand held fracture toughness tester.

3. H_o: $\mu = \mu_o$

   H_a: $\mu \neq \mu_o$,

   where:

   μ = the mean of the specimen group tested on the hand held fracture toughness tester,

   μ_o =the mean of the ASTM D5045 3-point bend specimen group.

4. H_o: $\mu = \mu_i$

   H_a: $\mu \neq \mu_i$,

   where:

   μ = the mean of the 4-point bend specimen groups with varying depth of razor cuts, where i = (.080", .040", .020", no razor cut),

   μ_i = the mean of the ASTM D5045 3-point bend specimen group.

1.4 Assumptions

The following assumptions apply to the research performed in this thesis.

1. Variations in humidity encountered during the manufacturing and testing of specimens will not impact test results.
2. Variations in ambient temperature encountered during the manufacturing and testing of specimens will not impact test results.
3. Time span between fabrication of chevron notch and application of razor nick will not impact test results.
4. Time span between complete fabrication of specimens and testing will not impact test results.

1.5 Limitations

The following limitation will apply to this research.

1. The study will be limited to polycarbonate (PC) and high density polyethylene (HDPE), two time dependent viscoelastic materials.
2. The Dillon universal tensile test machine has an accuracy of +/- 25 pounds and has not been calibrated recently.
3. The specimen thickness dimension is determined by the nominal standard stock being used which comes in sheets with a standard thickness of 1/2 inches.
4. The depths of razor cuts in the specimen notch used in comparisons will be limited to .020", .040", and .080", and no razor cut.

1.6 Need statement

Catastrophic failure for materials used in structural applications has been a serious concern for designers To a large extent, these failures can be traced back to fractures. Fracture mechanics offers structural designers a tool to understanding how and why a fracture occurs in a given material based upon the properties of that material. While the theory of fracture mechanics has been applied mainly to metallic materials, the increasing use of engineering plastics requires more effort to understand the fracture behavior of polymers. However, the time dependent viscoelastic nature of polymers adds new factors that do not exist with metallic materials. ASTM D5045 presents a testing method that accounts for these variables by insuring that the test specimens behave in a quasi linearly elastic manner enabling determination of K_{ic}. Unfortunately, the ASTM method requires resources that are not available to all companies and an affordable testing method would allow more accessibility. Therefore, any testing method devised must be able to ensure that linear elastic behavior is being achieved. Stromswold and Quesnel developed a simple hand held device for metallic specimens that met the necessary conditions for the determination of the fracture toughness.

1.7 Research design and methodology

The areas covered in this section include: the variables encountered, the methods used to create the sample groups, and the method used for data analysis.

Variables pertaining to the research include dependent, independent, and extraneous variables. The dependent variable is the fracture toughness parameter that is

to be determined. The independent variables include the type of materials, the depth of razor notch, and the orientation of the specimens. Extraneous variables that may affect this research include time delays, temperature, humidity, and any affects from the machining of the specimens.

Sample groups will be selected from specimens made from standard stock of 1/2" thick sheets of both polycarbonate and HDPE. One hundred eighty specimens will be made to test the chevron notch design from Stromswold and Quesnel's research. Ten specimens of each material for the ASTM D5045 fracture toughness test for polymeric materials and a few samples of the remaining materials will be made to perform tensile tests to provide an accurate reading of the mechanical properties of the materials being used. The groups to be used for the 4-point bend specimens for each material will be divided into groups of thirty specimens each. The remaining material will be used to make the specimens for the fracture toughness tool; thirty specimens will be used for the HDPE and thirteen specimens will be used for the PC. The fracture toughness values from these sample groups will be determined and analyzed.

The fracture toughness results obtained from the chevron notch specimens will be compared to the results obtained from the ASTM group and each other. Fracture toughness values given by the 4-point bend procedure will be compared to the fracture toughness values given from the ASTM D5045 test group by comparing the means from each group. The data analysis will be accomplished through the use of a Student's t-test, hereafter called t-test. A t-test is used because of the small sample sizes and difference in

sample group sizes. The fracture toughness results will be listed in the appendix. Also, the 4-point bend sample group will be compared to the same specimen type tested using the hand held device. The magnitude and disparity in the group sizes dictate the analysis tool to be used.

Finally, recommendations and conclusions will be drawn from these results concerning future research directions. The recommendations will be based upon the conclusions about the data analysis focusing upon improving the design of the hand held fracture toughness tester. These improvements will be suggested with the goal of keeping the device simple to use and inexpensive. Also, the recommendations are centered upon increasing the adaptability of the device in order to be usable for as many polymers as possible.

1.8 Overview of the study

The following chapters of this thesis will discuss the importance of fracture mechanics and the methods used to perform the research. Chapter Two will discuss the concepts behind fracture mechanics and how fracture mechanics addresses the concept of fracture toughness in relation to polymeric materials. The development of the plastic zone at the crack tip has been shown to be an important factor in how a material behaves. Especially in polymeric materials, whether or not a material behaves linearly elastic manner depends upon the plastic zone development. The application of these principles to the hand held fracture toughness tester for polymers are discussed.

Chapter Three includes the preparation of the specimens and the testing procedures used. The different types of specimens used for this research include: specimens used for the ASTM method, the four point bend test specimen, the hand held test specimens, and the tensile specimens needed for each material. The preparations covered include the dimensions required for specimen blanks, the final specimen dimensions and notches, and the utilization of the different fixtures used for each step involved. Important precautions taken in order to improve the quality of the specimens are discussed. Also, procedures used in the testing and the methods used to take the necessary measurements are included. The data analysis and conclusions and recommendations are covered in chapters four and five, respectively.

CHAPTER II

REVIEW OF LITERATURE

Fracture mechanics is the area of study which concerns itself with structural failure because of crack propagation. The question that fracture mechanics attempts to answer focuses on how cracks form and propagate eventually causing catastrophic failure. Fracture mechanics, therefore, studies the theory behind the development and growth of cracks in materials. According to Huang, "Fracture is a crack-dominated failure mode. For a fracture to occur, a crack must somehow be created, then initiate, and finally propagate" (1996, p. 2270). Cracks can develop from internal or external flaws that all materials possess. These flaws could originate from processing or from the intended use of the part. Processing refers to the steps required to produce the final part, for example, welding, riveting, machining, heat treating, and other production steps necessary to achieve final shape and properties. Subjected to loads, the stress concentrations about these flaws cause them to grow. When cracks grow to a certain size, dependent upon the material, they will rapidly propagate throughout the material causing to failure. Griffith began the development of fracture mechanics by working with the fracture of glass (Griffith, 1920). His work showed that the stress needed to cause fracture was related to

the size of the flaws present in the glass. Additional studies done by Irwin. Orowan, and others has led to further applications to fracture mechanics to metallic and polymeric materials that are more ductile than glass; ductile materials under stress tend to deform more than brittle materials. The distribution of the energy required to fracture a non-brittle material is summarized as follows:

> In the fracture of non-brittle materials nearly all the energy consumed is made up of the energy dissipated in the plastic zone, and only a small fraction of it is spent in breaking bonds." (Zhang and Venugopalan, 1987, p. 913).

Since fracture mechanics can be applied to less brittle materials, the fracture toughness of these materials can be found. The concept of linear elastic fracture mechanics (LEFM) can be applied to brittle materials to determine the fracture toughness property. Fracture toughness (K_{Ic}) measures the resistance of a material to fracture when in a plane strain state of stress for the mode I testing configuration. There are three modes of loading used create stress in the vicinity of the crack in the specimen: opening, sliding, and tearing. Mode I, or opening mode, applies the load in a manner to pull apart the crack and applies to many practical situations. K_{Ic} is technically the plane strain mode I fracture toughness. It is the critical stress intensity factor (K_c) that determines when and how a crack will cause failure from fracture for a given material. Huang explained that a crack will propagate when the stress intensity value at the crack tip , K, exceeds the appropriate K_{Ic} value (1996). K_{Ic} is specimen geometry independent and thus, is a true material property.

Since, K_{Ic} is a material property, fracture mechanics can be used in structural and component design.

While the study of fracture mechanics has been applied extensively to metallic materials, the application of fracture mechanics to engineering polymeric materials is just beginning. One reason for this is that metals exhibit an elastic strain-stress relationship. Thus, the principles of LEFM can be readily applied to determine stress intensity factor and the material property, K_{Ic}. A linearly elastic stress-strain relationship is defined mathematically by Hooke's Law,

$$\sigma = E\varepsilon, \tag{2-1}$$

where:

σ = stress,

E = the Young's Modulus,

ε = strain.

The behavior of polymeric materials, however, is different from metallic materials. Polymeric materials are viscoelastic in behavior and tend to display a non-linear stress-strain response. The plastic zone development at the crack tip in a given polymeric material affects the properties of the material (Su, 1989) and can vary with time. Therefore, polymeric materials that behave in a quasi linear elastic manner at the crack tip must be used. When linear elastic behavior exists at the crack tip, the fracture toughness property, K_{Ic}, can be measured. The great variety of polymers adds to the difficulty in using polymers in design because establishing a single method to determine the K_{Ic} value

may not be valid for all polymers. In fact, LEFM probably only has validity when applied to a limited class of polymeric materials. Some other approach such as J-integral is probably of more general applicability.

Polymeric materials are viscoelastic in behavior and tend to display a non-linear stress-strain response. The plastic zone development at the crack tip in a given polymeric material affects the crack growth properties of the material (Su, 1989). Therefore, material must be chosen and the specimens prepared so that they will behave if at all possible in a linear elastic manner at the crack tip. When linear elastic behavior exists at the crack tip, the fracture toughness property, K_{ic}, can be obtained.

Fracture proceeds differently for each type of material depending upon its characteristics. Two requirements must be satisfied at the crack tip for any material before fracture can take place. First, there must be enough energy in the system. Second, the local stress at the crack tip must be greater than or equal the cohesive strength of the material. (Cayard, 1990). Griffith developed an energy balance equation dictating crack propagation based on the first law of thermodynamics that states that energy is conserved (Griffith, 1920). Given a through thickness crack (see Fig. 2.1) of length 2a subjected to a tensile uniform stress, σ, applying the first law of thermodynamics results in the following equation:

$$U = U_o + U_a + U_\gamma - F, \tag{2-2}$$

Fig. 2.1 Through thickness crack in a wide plate.

where,

U_o = elastic energy of the loaded non cracked plate (a constant),

U_a = change in the elastic energy caused by introducing the crack in the plate,

U_γ = change in the elastic surface energy caused by the formation of the crack surfaces,

F = work performed by external forces.

The terms U_a, U_o, and F in the total energy equation (2-1) are defined in more specific terms. For a given unit thickness, U_a is given by the following equation:

$$|U_a| = \frac{\pi\sigma^2 a^2}{E}, \tag{2-3}$$

where,

E = modulus of elasticity.

The elastic surface energy, U_γ, is given by the following equation:

$$U_\gamma = 2(2a\gamma_s), \tag{2-4}$$

where,

γ_s = specific surface energy.

Furthermore, for the case of zero external forces, called the fixed grip condition, F equals zero. Also, the elastic energy, U_a, becomes negative because as the load is applied, the elastic strain energy drops as the plate loses stiffness. Substituting in for the variables the total energy equation (2-1) becomes

$$U = U_o - \frac{\pi\sigma^2\gamma^2}{E} + 4a\gamma_s. \tag{2-5}$$

Differentiating equation (2-4) with respect to crack length, a, the equilibrium condition is found by setting the equation to zero and is given by the following equation:

$$2\gamma_s = \frac{\pi\sigma^2 a}{E}. \tag{2-6}$$

Taking the second derivative of equation (2-5) with respect to a results in a negative solution which means that the crack will always grow. Solving equation (2-5) for σ gives the following equation:

$$\sigma = \sqrt{\frac{2E\gamma_s}{\pi a}}. \tag{2-7}$$

Under plane strain conditions, the term $1/(1+\nu^2)$ is added to equation (2-6) enclosed by the radical. Here, ν represents the Poisson's ratio for the given material. Because this relationship is derived under the assumption of a very sharp crack, equation (2-6) becomes a necessary but not complete condition for fracture (Cayard, 1990). A second condition must be met.

The second condition of fracture requires that the local stresses at the crack tip be sufficient to overcome the cohesive strength of the material. Cayard (1990) defines the cohesive strength of a material as the following equation:

$$\sigma_c = \sqrt{\frac{E\gamma_s}{a_o}}, \tag{2-8}$$

where,

σ_c = cohesive strength of the material

a_o = interatomic spacing of the material.

This cohesive strength is compared to the fracture stress at the crack tip which is represented by the following equation:

$$\sigma_{max} = 2\sigma\sqrt{\frac{a}{\rho}}, \tag{2-9}$$

where,

ρ = the radius of curvature at the crack tip.

Therefore, it follows that for fracture to occur, the fracture stress, σ_{max}, must be greater than the cohesive strength or

$$\sigma_{max} > \sigma_c. \tag{2-10}$$

Substituting equation (2-8) and equation (2-9) into equation (2-10), the applied stress must satisfy the following inequality:

$$\sigma > \sqrt{\frac{E\gamma_s\rho}{4aa_o}}. \tag{2-11}$$

Comparing equation (2-11) to equation (2-7) gives a value for the radius of curvature. In terms of plane strain conditions ρ is expressed as

$$\rho = \frac{8a_o}{\pi\left(1-\nu^2\right)} \approx 3a_o. \tag{2-12}$$

Thus, the radius of curvature can be used to determine whether or not a crack is sharp enough to insure linear elastic conditions can be met. Along with the importance of the radius of curvature to LEFM, the energy spent to develop the plastic zone affects the

behavior of a material. The ductility of a material dictates the size of the specimen needed to ensure plane strain conditions.

The expansion of Griffith's approach to fracture mechanics for less brittle materials required a modification that allowed accounting for the energy spent plastically deforming the material. The energy representing a material's resistance to crack propagation includes the sum of the elastic surface energy and the plastic strain work (Orowan, 1950). Including this additional variable in equation (2-7), the fracture stress is denoted by

$$\sigma = \sqrt{\frac{2E\left(\gamma_s + \gamma_p\right)}{\pi a}}, \tag{2-13}$$

where,

γ_p = plastic strain work.

For relatively ductile materials, γ_p is much larger than γ_s and the surface energy can be neglected with little loss of validity. However, γ_p is not an easy term to determine for many practical applications (Edwards and Wanhill, 1991). As a consequence, Irwin developed a stress intensity factor approach to explain the fracture process (1958).

2.1 Stress intensity factor approach

The stress intensity approach developed by Irwin is based upon applying linear elastic theory to the stress concentrations about the crack tip. Irwin proved that the stresses about the crack tip are mathematically defined as

$$\sigma_{ij} = \frac{K}{\sqrt{2\pi r}} f_{ij}(\theta) + \ldots, \tag{2-14}$$

where,

σ_{ij} = individual stresses about the crack tip,

r, θ = polar coordinates with respect to the crack tip,

K = constant denoting the magnitude of the elastic stress field (stress intensity factor),

$f(\theta)$ = dimensionless value dependent upon the geometry of the specimen and the crack.

Further manipulation of equation (2-13) allows for the stress intensity factor, K, to be defined. K is linearly related to stress and the square root of a characteristic length, the crack length and is represented mathematically by

$$K = \sigma\sqrt{\pi a} * f\left(\frac{a}{W}\right), \tag{2-15}$$

where,

a = crack length,

W = width of the specimen (Edwards and Wanhill, 1991).

Further analysis done by Irwin showed that there is a critical stress intensity factor, K_c, which defines an amount of stress beyond which the crack will propagate (1958). Under plane strain conditions in the mode I case, the minimum K_c is referred to K_{Ic}. The K_{Ic} value provides a measurable quantity that relates the stress intensity factor, K, to a measurable material property.

Comparing the energy balance approach and the stress intensity factor approach allows for the stress intensity factor, K, to be defined in useable terms. Combining the Griffith's energy balance approach and Irwin's stress intensity factor approach yields the following expression:

$$K_c = \sqrt{\frac{EG}{\left(1+\nu^2\right)}}, \tag{2-16}$$

where,

G = energy release rate,

ν = Poisson's ratio,

K_c = critical stress intensity factor (also called fracture toughness).

The terms G, and ν are properties that can be determined through the use of standard tests.

2.2 Effect of plastic zones on fracture toughness

All materials will plastically deform when the yield stress of the material is exceeded. At high stress concentration points, such as the stress concentrations about internal flaws or cracks, the yield stress will be surpassed. Subsequently, an area of plastic deformation, or a plastic zone, will exist surrounding the crack tip. As mentioned previously, a ductile material will have a larger plastic zone than a brittle material. Because linear elastic fracture mechanics was defined for an ideally elastic material with a limited plastic zone size, the size of the plastic zone can affect the fracture toughness of a material. Thus, factors that affect the plastic zone development are important to consider

in understanding the development of the plastic zone. These factors include the radius of curvature at the crack tip and the dimensions of the specimen. Theoretical models attempt to explain how the plastic zone develops within a material. Controlling the plastic zone development within test specimens depends on the specimen dimensions and the formation of the crack in order to produce the necessary conditions to achieve valid fracture toughness values. The behavior at the crack tip dictates the necessary conditions for valid results.

The two widely known models for describing a plastic zone's size and shape are those by Irwin and Dugdale. These models take the approach of using a selected shape for the plastic zone (see Fig 2.1). Irwin assumes the plastic zone is circular in shape (while Dugdale assumes the plastic deformation in concentrated along a strip in front of the crack (see Fig 2.3). The defining relationships for the plastic zone size of Irwin's model are given by the following equations (Irwin, 1958):

$$2r_y = \frac{1}{\pi}\left(\frac{K_Q}{\sigma_{ys}}\right)^2 \text{, for the case of plane stress,} \qquad (2\text{-}17)$$

$$2r_y = \frac{1}{3\pi}\left(\frac{K_Q}{\sigma_{ys}}\right)^2 \text{, for the case of plane strain,} \qquad (2\text{-}18)$$

where,

$2r_y$ = diameter of the plastic zone,

K_Q = critical fracture stress,

σ_{ys} = yield stress.

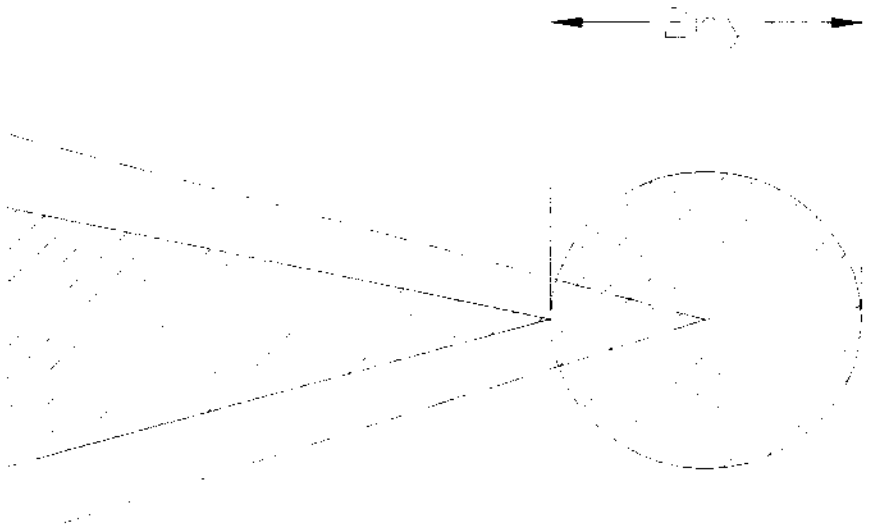

Fig. 2.2 Plastic zone according to Irwin's model.

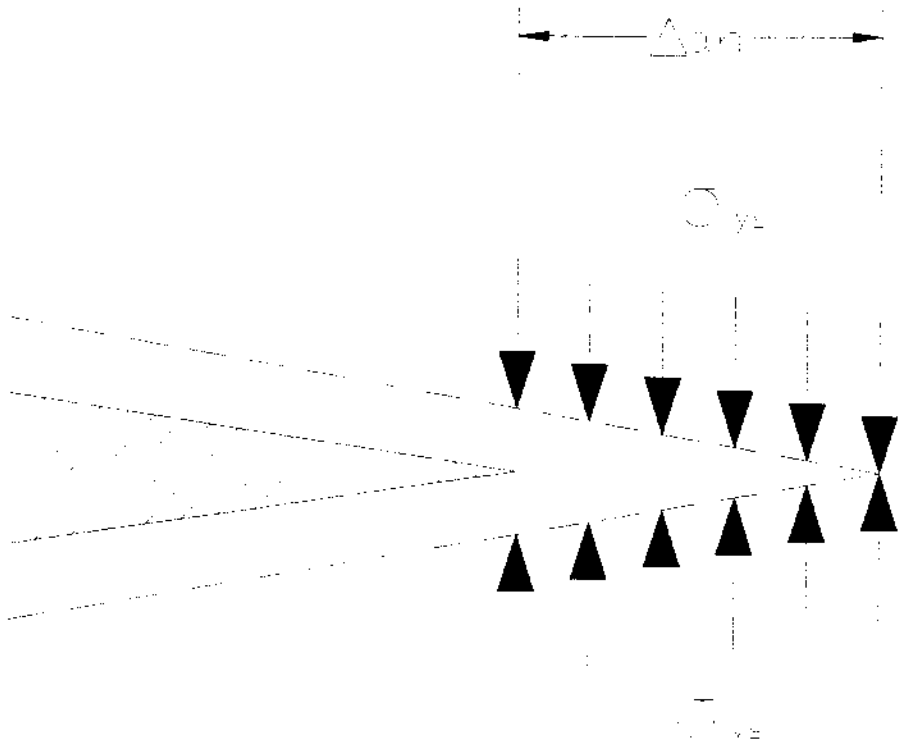

Fig. 2.2 Plastic zone according to Dugdale's model.

Dugdale's relationship defining the plastic zone size is given by the following equation (Edwards and Wanhill, 1991):

$$\Delta a_n = \frac{\pi}{8}\left(\frac{K_Q}{\sigma_{ys}}\right)^2, \tag{2-19}$$

where,

Δa_n = size of the plastic zone,

K_Q = conditional fracture toughness,

σ_{ys} = yield stress.

These models do not, however, give an accurate representation of the size and shape of the plastic zone because of the assumptions about the shape of the plastic zones. The state of stress at the crack tip contributes to the inaccuracy.

Also known as a factor, the state of stress, whether plane stress or plane strain, will alter the configuration of the plastic zone (Zhang and Venugopalan, 1987). The effect of the stress state is expressed in the differences in Irwin's model equations for the size of the plastic zone for both the plane stress and the plane strain case. However, these equations do not express the shape distortion that also occurs. The size of the plastic zone is affected more for the case of plane stress than for the case of plain strain at the same stress. Therefore, to determine K_{Ic}, plane strain conditions at the crack tip must exist in order to provide valid fracture toughness values for the material being tested. For polymeric materials which have the potential of substantial plastic zone development, controlling the plastic zone is crucial in attaining plane strain conditions. Plane strain

conditions at the crack tip can be achieved through the manipulation of the specimen dimensions.

2.3 Effect of specimen dimensions on fracture toughness

The dimensions that affect the size of the plastic zone are the width, the thickness, and the crack length of the specimen. According to Putatunda and Banerjee, the plastic zone decreases in size as the width of the crack increases (1984). As a consequence, the fracture toughness of a material is directly affected by the dimensions of the specimen. By establishing the necessary configuration for the specimens, plane strain conditions can be reasonably assured.

Although the thickness and the width of the specimen affect the stress state at the crack tip, there are limiting values for their effectiveness. These limits to the dimensions are dependent upon the material being examined. Above a certain value of thickness, K_c, the fracture toughness value, is independent of the thickness (Chan and Williams, 1981). K_c shows a strong dependence as the width of the specimen drops below the critical value. Linear elastic fracture mechanics, LEFM, becomes increasingly invalid as the width continues to decrease (Chan and Williams, 1981). The invalidity of LEFM results from the loss of plane strain conditions at the crack tip. The crack length for a given specimen can also influence the fracture toughness results for a given specimen configuration.

The crack length refers to the depth of the crack into the material. Above the critical thickness, K_c was found to be relatively independent of the crack length. According to ASTM D5045, the fracture toughness test standard for polymeric materials,

a sharp crack is required to ensure that a minimum value of toughness is achieved (ASTM D5045, 1995). The standard that the ASTM uses for determining the proper crack length is defined by the following inequality:

$$.45 < \frac{a}{W} < .55, \tag{2-20}$$

where,

a = crack length,

W = specimen width.

There are different ways of introducing the crack into the specimen.

The method used to introduce a crack into a specimen depends upon the configuration and the specimen material. For metallic materials, the cracks are usually introduced by fatiguing or pre-cracking the specimen. ASTM E1304 defines the use of rod and bar configurations that do not require pre-cracking (ASTM E1304, 1991). The notch in these specimens are sufficient to create a pop-in crack upon loading, eliminating the pre-cracking step. Stromswold and Quesnel have incorporated the idea of eliminating the pre-cracking method with their specimen design for metallic materials (1992). Polymeric materials require a different method for introducing cracks.

In order to introduce a sharp crack into a polymeric specimen, razor notching is recommended. The razor can either be drawn across the notch or pressed into the notch directly. Through the use of a razor edge, a crack can be made sufficiently sharp to produce valid K_{Ic} results. ASTM D5045 uses the following equation to determine if a conditional toughness value, K_Q, is a valid fracture toughness value, K_{Ic} (1995):

$$B,a,(W-a) > 2.5\left(\frac{K_Q}{\sigma_y}\right)^2, \qquad (2\text{-}21)$$

where,

B = specimen thickness,

a = crack length,

W = specimen width,

K_Q = conditional fracture toughness value,

σ_y = yield stress.

Equation 2-21 uses the yield stress of the material being tested to test the validity of the conditional fracture toughness value, K_Q. As can be seen from equation 2-21, the more ductile the material is, the larger the specimen needs to be, since a ductile material will have a lower yield stress value. These specimen requirements and data validity tests ensure that the fracture toughness values obtained are valid for the material being tested.

The discipline of fracture mechanics began with Griffith and his work on the fracture of glass. He developed an energy equation to explain the mechanics of fracture at an internal crack with an elastic material and the additional assumption of a sharp crack. Irwin and Orowan developed Griffith's energy equation to account for less brittle materials by including the energy required in plastically deforming the material. In addition, the material property , plane strain fracture toughness (K_{Ic})was defined in terms of readily obtainable measurements and material properties such as yield stress using linear elastic fracture mechanics. As a result, tests could be run to determine a material's

resistance to fracture called the fracture toughness. Further research has been conducted to include multiple test specimen configurations for metallic materials. ASTM D5045 defines the test standard for expanding fracture toughness to polymeric materials. The understanding of how a material behaves at the crack tip allows the development of a testing procedure for the fracture toughness of that material.

CHAPTER III

EXPERIMENTAL PROGRAM

The objective for this study was to examine the feasibility of using polymeric materials with the chevron notch configuration developed by Stromswold and Quesnel for metallic materials. The structure of the experimental program is divided into three major sections, the specimen preparation, the testing procedures, and the analysis of the results.

3.1 Specimen preparation

The specimens were made from Lexan sheet polycarbonate (PC) manufactured by General Electric (GE), and high density polyethylene (HDPE) from an unknown manufacturer. In general, the orientation of each specimen can affect the fracture toughness depending upon the direction of crack propagation. Typically, the L-T and the L-S are the most common orientations. Here, the L, T, and S designations refer to the orientation of how the specimen was extracted from the plate in relation to how the material was formed (see Fig. 3.1). In this research, the L-T orientation was used in each sample group for each material. Three specimen types were made from each material; a set of specimens was made according to the ASTM D5045 standard, a second set of specimens with dimensions given by the Stromswold and Quesnel research, and tensile specimens. According to ASTM D5045, the SEN 3-point bend specimens need to be

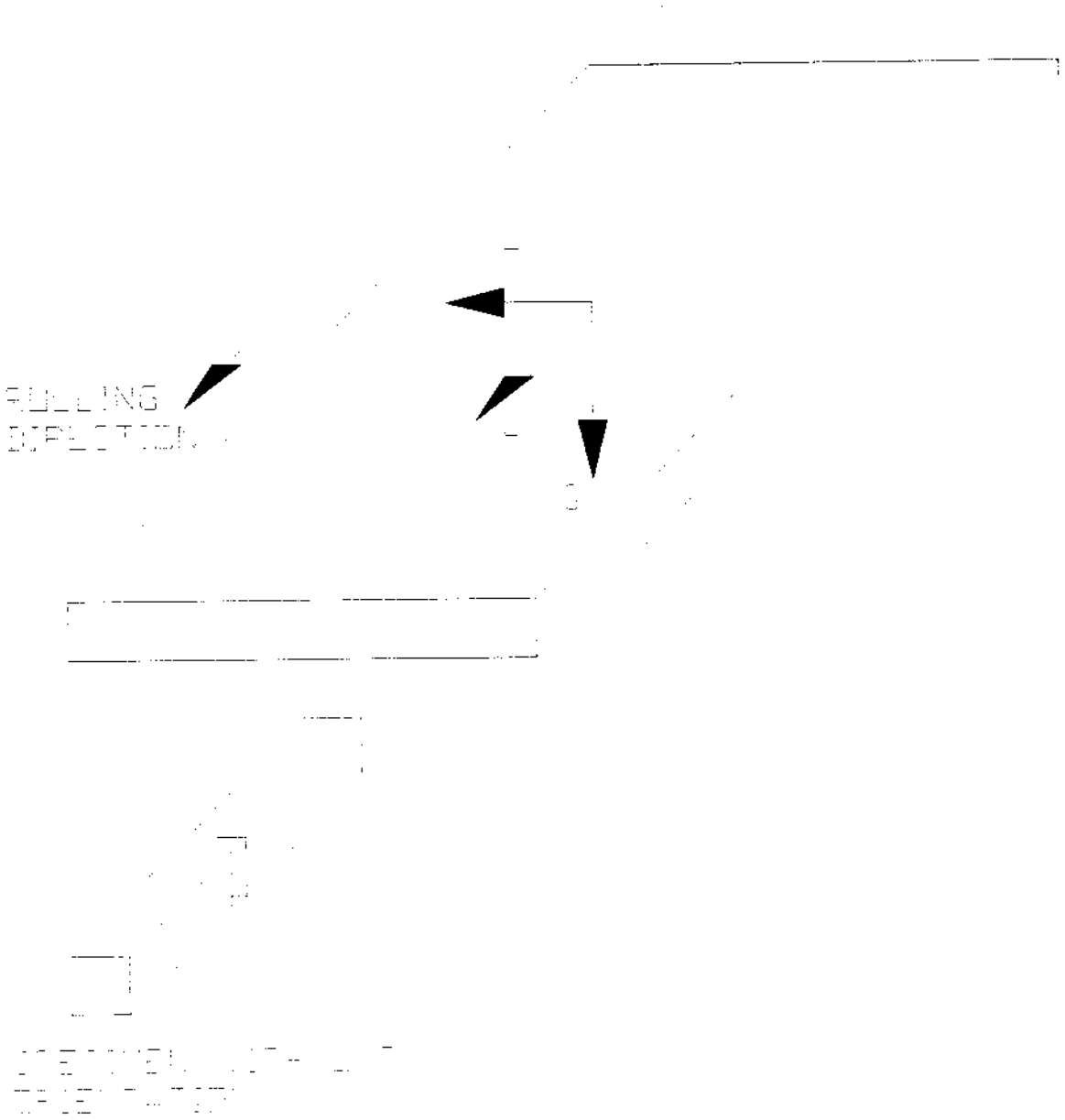

Fig. 3.1 Specimen and material orientations.

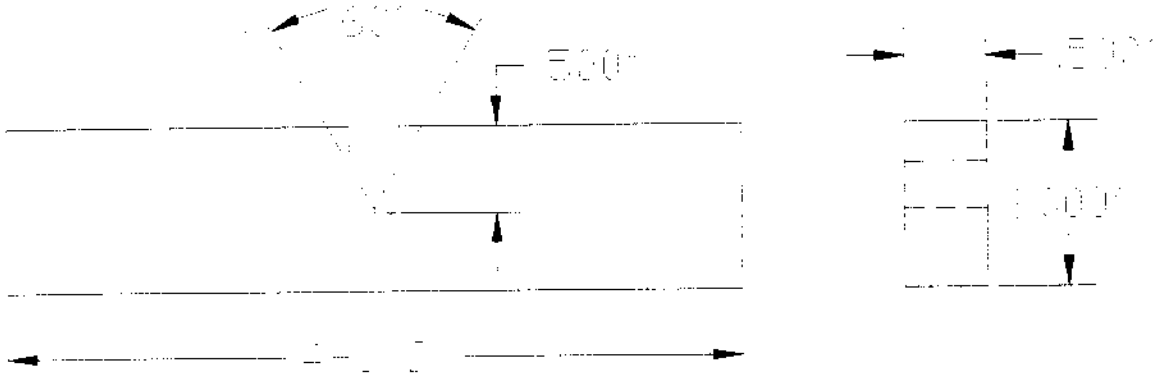

Fig. 3.2 ASTM SEN 3-point bend specimen.

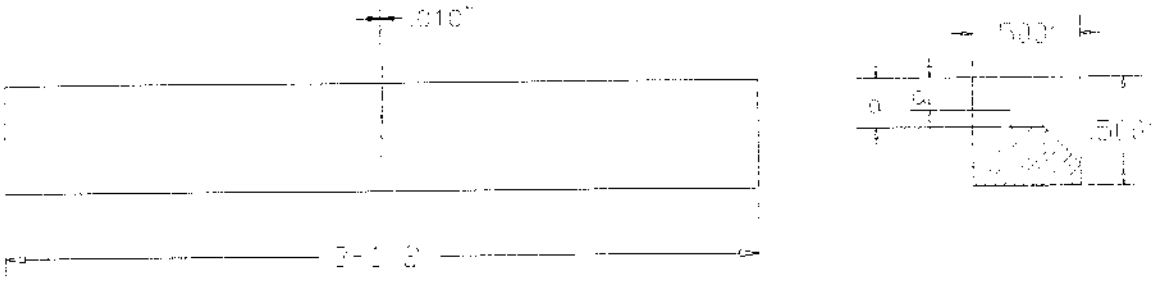

Fig. 3.3 Stromswold and Quesnel specimen configuration.

Fig. 3.4 Tensile specimen configuration.

thick enough to create plane strain conditions at the crack tip (see equation 2-21). The dimensions used for this study are for this study are 1/2" x 1" x 4-1/2" (see fig. 3.2). The specimen dimensions defined by Stromswold and Quesnel are 1/2" x 1/2" x 3-1/2" (see fig. 3.3). For the tensile specimens, the dimensions used were 1/2" x 1" x 3-1/2" (see fig. 3.4). To aid in the production and repeatability of the dimensions of the specimens, certain precautions were employed. The ASTM specimen configuration and the specimen configuration used by Stromswold and Quesnel were produced with the aid of fixtures. The tensile specimens did not require any special fixture. The specimens were made using the in-house equipment.

Specimens were manufactured on a Bridgeport horizontal spindle milling machine using a variety of different arbor setups and cutters. Three steps were used in the making the specimens: producing blanks, applying the notch, and applying the razor nick or cut. Creating blanks was the initial phase in manufacturing of the specimens. The dimensions of the blanks depended upon the specimen type and the fixture used to apply the notch. A 3/4" high speed steel (HSS) end mill was used to machine the blanks for all the specimens. For the preparation of the blanks used to create the 1/2" x 1/2" x3-1/2" specimens and the tensile specimens, the blanks were machined to 1/2" x 3" x 3-1/2" dimensions. From these blanks, a fixture was designed to allow the simultaneous cutting of five specimens. A gang milling setup with four saws mounted on the arbor enabled the simultaneous cutting. During the machining, compressed air was used to cool the saws and remove the chips from the saw. Compressed air was used in order to keep any contaminates from touching

the plastic. Keeping the saws cool prevented the plastics from melting. The fixture held two blanks allowing ten specimens to be machined with one pass. Once the individual specimen blanks were made, the notches were machined using additional fixtures.

In order to create the characteristic features of the different specimen types, specific fixtures were used to hold and position the specimen securely. For the ASTM SEN three point bend specimens, the blanks were held securely in a fixture mounted in a fixed vise on the table of the milling machine. A 16 tooth, 2.950" diameter saw was employed to create the notch. Once the machining setup was fixed, the specimens could be prepared without repositioning or movement until after each notch was finished. The chevron notch for the 1/2" x 1/2" x 3-1/2" specimens was created using a special fixture that allowed a ninety degree indexing of the specimen while providing secure clamping. The notch required two passes by a 72 tooth saw that was .010" thick and has a 2-3/4" diameter. Each tooth was ground to a 60 degree angle keeping with the design used by Stromswold and Quesnel in their research in order to produce a sharp notch. Because of the fragile nature of the thin saw, oversized spacers on the arbor were custom made to provide additional rigidity support while allowing clearance for the work piece. The indexing feature of the fixture allowed the notch to be machined without having to remove and reposition the specimen after the first pass. The specimens used for the tensile test were finished with the aid of a 2" HSS endmill. The specimens were held in a vise while the endmill was fed into the side of the blank producing the desired radius feature. No

fixture was required for these specimens. Once the features were created, the razor blade could be used to make the sharp crack.

The razor nick was applied using a razor blade holder with a depth guide. A new razor blade was used for each specimen. The holder was designed to allow easy removal and loading of the razor blades while providing the support needed to press the razor blade into the notch without breaking the blade. The holder also made the pressing of the blade easier.

3.2 Testing procedures

Experimental specimens were tested against ASTM approved specimens in order to test the validity of the simplified fracture toughness tester. The experimental specimens were tested in a 4-point bend fixture and with the aid of the fracture toughness tool. All specimens were tested on the universal Sentec machine to measure the peak load and obtain a load versus deflection curve if needed. The specimens were broken down into the different sample groups for the 4-point bend specimens and the fracture toughness tool with the depth of the razor cut being varied with the 4-point bend specimens groups.

The 4-point bend specimens were divided into four different groups with different razors cuts depths. The depths of the razor cuts were .020", .040", .080", and no razor cut. From these results and based upon the ASTM results, the remaining 4-point bend specimens for both the polycarbonate and the HDPE materials were tested at the depth that gave the most comparable results to the ASTM test. The razor cut depth was determined based upon t-test comparisons of the fracture toughness of the 4-point bend

sample groups and the ASTM group for both materials. Specimens designated for the fracture toughness tool used this depth of cut. Along with the peak loads obtained, the yield strength of the materials was obtained to use in determining the validity of the fracture toughness values.

The yield strength was determined for both the materials by using tensile specimens that were specifically designed for their ease of production. The specimens were tested using the Dillon universal tensile machine. From these results, the fracture toughness values obtained from the given peak loads could be checked for validity as required by the ASTM standard.

3.3 Analysis procedures

The analysis of the data included calculating fracture toughness means and standard deviations, comparisons among the ASTM standard results, the 4-point bend specimens and the fracture toughness tool specimens, as determining the validity of obtained fracture toughness values based upon the material properties. A t-test with a confidence interval of .95 was used to compare the results by sample group to determine if the fracture toughness values can be assumed to be from the same population independent of the type of specimen geometry and test used.

The fracture toughness results from the ASTM standard were used as the benchmark for the other tests. The 4-point bend specimens were used to compare the new notch configuration to the ASTM results using a common test method. Since the samples determined by razor cut depth were in groups of ten, a t-test was an ideal analysis tool

since a normal distribution cannot be guaranteed. A t-test assumes a normal distribution. The remaining 4-point bend specimens were tested at the determined razor cut depth and compared to the fracture toughness tool specimens that had the same configuration as the four point bend specimens. Both materials were tested in the same way, but the fracture behavior of PC required additional analysis within the PC samples.

Additional analysis was done on the fracture modes occurring within the PC samples. It is well known that fracture in PC is a combination of both shear yielding and crazing. Therefore, analysis was done on the individual specimens within the PC groups depending upon a visual inspection of the failure surfaces. The division of the PC specimens into two groups, depending upon their fracture face, determined if the specimens were failing as a result of either one or the other mechanism. Thus, the variation of the fracture toughness values was seen as a consequence of the multiple fracture mechanisms.

The experimental program for this research focuses on providing a testing method for the fracture toughness of polymeric materials that is comparable to the established ASTM standard. Preparing the specimens with as little variation as possible allowed the analysis to exhibit a relatively small standard deviation within sample groups. Thus, decisions on the direction of future research will be made on the most reliable data given the limitations of the study.

CHAPTER IV

DATA ANALYSIS AND RESULTS

Chapter three discussed the experimental design followed in this thesis. This chapter presents the results and comparisons obtained in the analysis of these results. The controlled variables are displayed and their effects on the outcome of the research are discussed. This chapter begins with the tensile tests, followed by the fracture toughness values obtained from the individual samples. Next, the comparison results from analyzing the effects of varying depths of razor cuts applied in the chevron notch, the different tests, and the fracture mechanisms apparent in the PC sample groups.

4.1 Tensile tests

The validity of the fracture toughness values obtained from the individual specimens was dependent upon the having plane strain conditions in the region around the crack tip. Equation 2-21 defines an inequality derived from the specimen dimensions, the yield strength of the specimen material, and the conditional fracture toughness value. Valid K_{Ic} values satisfy the inequality. However, accurate yield strength for both the materials used in this research were required. The yield strength for extruded PC sheet (Lexan) is 9000 psi while, HDPE extruded sheet yield strength values range from 3500 psi to 4500 psi. The large range for the HDPE is a result of the variation in the material

properties of polymeric materials. The tensile tests gave a more accurate yield strength value to use in the validity calculations.

Yield strength values were calculated from the peak loads obtained from the tensile tests. The yield strength is given by the following equation:

$$\sigma_y = \frac{P}{A}, \tag{4-1}$$

where,

P = peak load,

A = .25 in^2, the cross sectional area,

σ_y = yield strength.

The cross sectional area, A, is given from the specimen geometry. Table 4.1 lists the calculated yield strengths. The validity of the fracture toughness values were checked using the yield strengths obtained from these tests.

4.2 ASTM results

Results from the ASTM groups were used as a benchmark to compare the results from the other tests. The conditional fracture toughness values were calculated from the following equation given by the ASTM standard D5045:

$$K_Q = \left(\frac{P_Q}{BW^{1/2}}\right) f(x), \tag{4-2}$$

MATERIAL	RANGE (PSI)	OBTAINED σ_y
PC	9000	9000
HDPE	3500-4500	4200

Table 4.1 Yield strength values for PC and HDPE materials.

where,

K_Q = conditional fracture toughness value,

P_Q = peak load,

B = .500", thickness,

W = .500", width,

f(x) = geometry derived value (1991).

The conditional fracture toughness values for the ASTM groups are listed in table 4.2. The table also includes the validity check results for the fracture toughness values (see equation 1-2).

The borderline HDPE K_Q values result from the specimen configuration, material yield strength, and the test equipment. Failure to meet the inequality requirements implies the specimen configuration is not thick enough to guarantee plain strain conditions at the crack tip for such a low strength, high ductility material. However, the accuracy of the Dillon tensile test equipment can be questioned; loads applied during the loading of the specimen, the calibration of the machine, and the accuracy of the readout were the three areas in question. Thus, in keeping with the assumptions of the research, the ductile nature of the HDPE was taken to be a non factor in the validity of the calculated fracture toughness values. Therefore, the results of the HDPE sample groups were used in the original objective of the research; namely, to test the feasibility of the fracture toughness tool in convention with polymeric materials.

Material	Mean Fracture Toughness Value (PSI$\sqrt{in}$)	Standard Deviation	VALIDITY CHECK (< .5)
PC	3086.80	61.36	VALID (.29 < .5)
HDPE	1958.11	65.93	NON-VALID (.54 > .5)

Table 4.2 ASTM fracture toughness values.

4.3 Fracture toughness versus razor cut depth

As part of the objective to develop an universal fracture toughness tool for polymers, a common notch configuration was desired. Four point bend (4-point) specimens were razor notched to various depths to determine the depth of cut that would give the best fit for the fracture toughness values in relation to the ASTM results. Fracture toughness values were calculated for four samples each with a different depth of razor cut: .020", .040", .080", and no razor cut (see table 4.3 and figure 4.1). In addition, the effect from the competing fracture mechanisms characteristic of PC was displayed by dividing the original groups by their respective fracture surface appearance. The samples were composed of ten specimens each and tested using a 4-point bend fixture. A t-test with a confidence interval of .95 was performed comparing the groups with the varying razor cut depths to the ASTM results. The depth for the razor notch was chosen based on these results.

Comparing the fracture toughness of the different groups to the fracture toughness value obtained according to the ASTM standard allowed the selection of a common razor cut depth for both materials. For PC, the only razor cut depth of .020" gave fracture toughness results that did not reject the null hypothesis (see table 4.4) as stated:

H_o: $\mu = \mu_o$

H_a: $\mu \neq \mu_o$

Depth of Cut	Mean Fracture Toughness Value (PSI√in)	Standard Deviation
PC	ASTM = 3086.80	ASTM = 65.93
.020"	**3045.72**	**281.50**
(Smooth Fracture Surface)	2750.67	180.61
(Rough Fracture Surface)	3172.16	214.04
.040"	**2706.90**	**315.04**
(Smooth Fracture Surface)	2546.93	169.20
(Rough Fracture Surface)	3080.16	249.38
.080"	**2519.01**	**88.65**
(Smooth Fracture Surface)	2434.03	54.12
(Rough Fracture Surface)	2575.67	52.52
No RC	**3694.23**	**693.59**
(Smooth Fracture Surface)	2840.28	284.46
(Rough Fracture Surface)	4060.21	416.84
HDPE	ASTM = 1958.11	ASTM = 61.36
.020"	1680.65	52.07
.040"	1711.17	107.06
.080"	1530.84	75.54
None	2010.50	77.60

Table 4.3 Fracture toughness values at different razor notch depths.

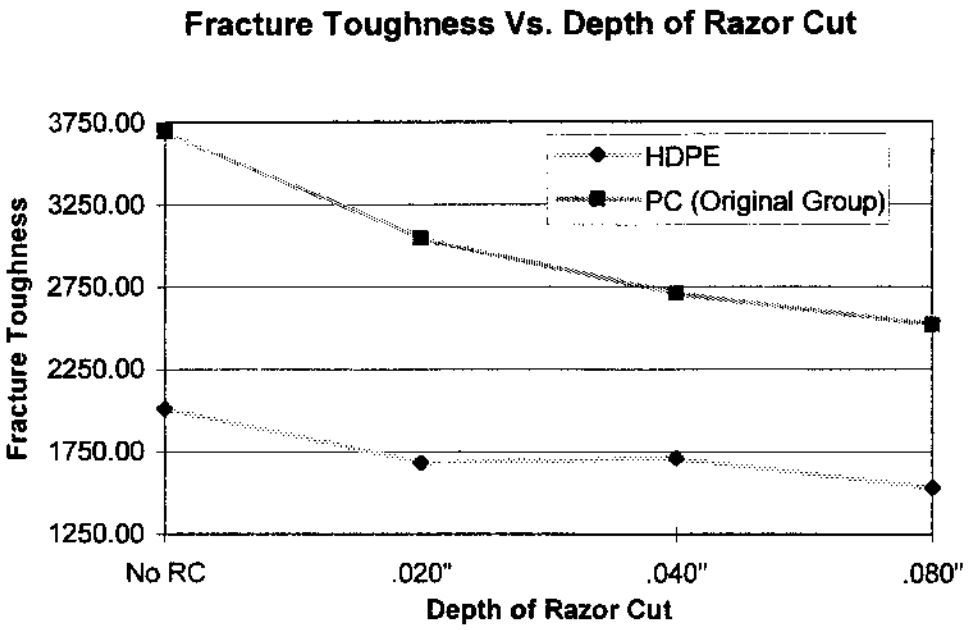

Figure 4.1 Fracture toughness versus depth of razor notch.

PC	t-statistic	t-critical	Accept/Reject
.020"	1.98	2.024	Accept
.040"	-2.757	-2.1	Reject
.080"	16.25	2.1	Reject
No RC	-2.57	2.1	Reject
HDPE	**t-statistic**	**t-critical**	**Accept/Reject**
.020"	3.69	-2.024	Reject
.040"	6.32	2.1	Reject
.080"	13.88	2.1	Reject
No RC	-1.67	-2.1	Accept

Table 4.4 t-test comparisons of the effects of varying depths of razor cut.

where,

μ = the mean of the sample group with a .020" razor cut,

μ_o = the ASTM fracture toughness mean.

For this comparison, the t-statistic, 1.98, was less than the t-critical value, 2.024, and therefore, the null was accepted. For HDPE, only the sample group with no razor cut satisfied the null hypothesis, the same as stated for the PC sample, where the t-statistic, -1.67, was greater than the t-critical value, -2.1. A depth of .020" was chosen for the depth of the razor cut based upon the PC samples because the HDPE material produced only borderline valid fracture toughness results with the ASTM standard.

The remaining four point bend chevron specimens were tested with the .020" razor notch giving a larger sample size of thirty specimens each for both materials (see table 4.5). These specimens were tested using the 4-point bend fixture and the fracture toughness tool. The K_Q values were calculated from the peak loads obtained during the tests using the equation for the specimen configuration (see equation 1-4). Both tests were performed with the Sentec. The load was applied to the arm of the toughness tool which was mounted in a vise. From the specimens tested using the four point bend fixture, the HDPE had a mean fracture toughness value of 1799.47 psi$\sqrt{in}$ with a standard deviation of 130.09. While the mean fracture toughness increased, the standard deviation more than doubled which can be partially attributed to the time delays between the application of the razor cut and the testing of the specimens. In an attempt to reduce the variability obtained here, a razor cut depth of .080" was used for the fracture toughness

Material	Mean Fracture Toughness Value (psi√in)	Standard Deviation
PC	ASTM = 3086.80	65.93
4-pt Bend Fixture	2754.03	524.60
Fracture Toughness Tool	2956.95	253.44
HDPE	ASTM = 1958.11	61.36
4-pt Bend Fixture	1799.47	130.09
Fracture Toughness Tool (.080" RC)	1436.66	95.54

Table 4.5 Fracture toughness values for expanded sample groups.

tool. A standard deviation of 95.54 was obtained using the increased razor cut depth. The results form the .080" deep razor cut were then compared to the sample tested with the 4-point bend fixture with the same razor cut depth in order to test the compatibility of the notch. Analysis performed using the t-test showed significant effects from the type of fracture toughness test used.

The next analysis done was to determine if the four point bend test and the fracture toughness tool gave fracture toughness results that were not significantly different from the results given from the ASTM standard and to each other. The HDPE showed that there was a significant difference between all the test methods (see table 4.6).

The null hypothesis comparisons for HDPE are listed as follows:

1. H_o: $\mu = \mu_o$

   H_a: $\mu \neq \mu_o$

   where,

   μ = the sample mean with the 4-point bend fixture,

   μ_o = the sample mean with the fracture toughness tool.

For this comparison, the t-statistic, -12.31, was less than the t-critical value, -2.000, and therefore, the null was rejected.

2. H_o: $\mu = \mu_o$

   H_a: $\mu \neq \mu_o$

where,

μ = the sample mean with the 4-point bend fixture,

μ_o = the ASTM sample mean.

For this comparison, the t-statistic, -2.82, was less than the t-critical value, -2.024, and therefore, the null was rejected.

3. H_o: $\mu = \mu_o$

H_a: $\mu \neq \mu_o$

where,

μ = the sample mean with the fracture toughness tool,

μ_o = the ASTM sample mean.

For this comparison, the t-statistic, 3.7, was greater than the t-critical value, 2.024, and therefore, the null was rejected.

The analysis of the HDPE sample groups showed that there was a significant difference between the different test methods. Each comparison rejected the hypothesis that there is no significant difference between the fracture toughness values calculated by the different test methods. In general, these results show that the fracture toughness tool may not be re-usable more ductile materials.

The PC samples showed significant indications of competing fracture mechanisms. The mean fracture toughness value of the original pre-divided group tested with the 4-point bend fixture was 2754.03 psi$\sqrt{in}$ with a standard deviation of 524.60. A mean fracture toughness value of 2956.95 psi$\sqrt{in}$ with a standard deviation of 253.44 was

HDPE	T-Statistic	T-Critical	Accept/Reject Null
4-Point Bend vs. Fracture toughness tool	-12.31	2.00	Reject
4-Point Bend vs. ASTM	3.7	2.024	Reject
Fracture toughness tool vs. ASTM	-2.82	2.024	Reject

Table 4.6 t-test comparisons between test methods for HDPE.

obtained with the toughness tool. Both tests showed decreases in the mean fracture toughness and increases in the standard deviation. The substantial changes in the mean fracture toughness values and standard deviations of the PC can be associated with the competing fracture mechanisms.

Dividing the PC samples according to their fracture surface, either rough or smooth, appearance resulted in two significantly different sample groups using a t-test comparison (see table 4.7). The groups with a rough fracture surface had mean fracture toughness values comparable to the fracture toughness of the ASTM sample with decreased variability. Compared to the ASTM method, both test methods were shown to satisfy the null hypothesis stating the there is no significant difference between the test methods (see table 4.8). The null hypothesis comparing the test methods is stated as:

H_o: $\mu = \mu_o$

H_a: $\mu \neq \mu_o$

where,

μ = the mean of the 4-point bend fixture or toughness tool,

μ_o = the mean of the ASTM.

For the comparison of the 4-point bend fixture with the ASTM standard, the t-statistic, 1.98, was less than the t-critical value, 2.024, and therefore, the null was accepted. The t-statistic, 1.57, of the fracture toughness tool was less than the t-critical value, 2.07, and was accepted.

PC/TEST	Average Fracture Toughness Value (PSI√in)	Standard Deviation
4-Point Bend		
Smooth fracture Surface	2340.36	357.60
Rough fracture Surface	3167.71	294.03
Fracture Toughness Tool		
Smooth fracture Surface	2732.94	176.96
Rough fracture Surface	3148.96	141

Table 4.7 Fracture toughness values for divided PC sample by fracture surface.

PC	T-Statistic	T-Critical	Accept/Reject Null
4-Point Bend vs. Fracture toughness tool	1.37	2.02	Accept
4-Point Bend vs. ASTM			
Original group	1.98	2.024	Accept
Smooth fracture Surface	-6.49	-2.07	Reject
Rough fracture Surface	-.9	-2.07	Accept
Fracture toughness tool vs. ASTM			
Original group	1.57	2.07	Accept
Smooth fracture Surface	5.9	2.14	Reject
Rough fracture Surface	-1.23	-2.13	Accept

Table 4.8 t-test comparisons between test methods for PC.

As can be seen by the comparisons, the depth of the razor notch does have a significant effect on the fracture toughness values obtained from a specimen. For PC, the results suggest that there is a critical depth for the razor cut beyond which there is no longer a significant effect on the fracture toughness as displayed by the acceptance of the null hypothesis with the groups with the .040" and the .080" razor cut depths. Similarly, the HDPE results suggest that there is a critical depth above which there is no significant effect on the fracture toughness as shown with the acceptance of the null hypothesis between the groups with a .020" and a .040" razor cut depth.

The null hypothesis comparisons for PC are listed as follows:

1. H_o: $\mu = \mu_o$

   H_a: $\mu \neq \mu_o$

   where,

   μ = the sample mean with the four point bend fixture,

   μ_o = the sample mean with the fracture toughness tool.

For this comparison, the t-statistic, 1.37, was less than the t-critical value, 2.02, and therefore, the null was accepted.

2. H_o: $\mu = \mu_o$

   H_a: $\mu \neq \mu_o$

   where,

   μ = the pre-divided sample mean with the four point bend fixture,

   μ_o = the ASTM sample mean.

For this comparison, the t-statistic, 1.98, was less than the t-critical value, 2.024, and therefore, the null was accepted.

3. H_o: $\mu = \mu_o$

   H_a: $\mu \neq \mu_o$

   where,

   μ = the smooth fracture surface sample mean with the four point bend fixture,

   μ_o = the ASTM sample mean.

For this comparison, the t-statistic, -6.49, was less than the t-critical value, -2.07, and therefore, the null was rejected.

4. H_o: $\mu = \mu_o$

   H_a: $\mu \neq \mu_o$

   where,

   μ = the rough fracture surface sample mean with the four point bend fixture,

   μ_o = the ASTM sample mean.

For this comparison, the t-statistic, -.9, was greater than the t-critical value, -2.07, and therefore, the null was accepted.

5. H_o: $\mu = \mu_o$

   H_a: $\mu \neq \mu_o$

where,

μ = the pre-divided sample mean with the fracture toughness tool,

μ_o = the ASTM sample mean.

For this comparison, the t-statistic, 1.37, was less than the t-critical value, 2.02, and therefore, the null was accepted.

6. H_o: $\mu = \mu_o$

H_a: $\mu \neq \mu_o$

where,

μ = the smooth fracture surface sample mean with the fracture toughness tool,

μ_o = the ASTM sample mean.

For this comparison, the t-statistic, 5.9, was greater than the t-critical value, 2.14, and therefore, the null was rejected.

1. H_o: $\mu = \mu_o$

H_a: $\mu \neq \mu_o$

where,

μ = the sample mean with the four point bend fixture,

μ_o = the sample mean with the fracture toughness tool.

For this comparison, the t-statistic, -1.23, was greater than the t-critical value, -2.02, and therefore, the null was accepted.

4.5 Comparisons of the various razor cut depths

Analysis of the specimens with respect to the depth of the razor notch, indicated there was a significant effect on the fracture toughness values (see table 4.9).

The null hypothesis comparisons for PC are listed as follows:

1. H_o: $\mu = \mu_o$

   H_a: $\mu \neq \mu_o$

   where,

   μ = the mean of the sample group with a .020" razor cut,

   μ_o = the mean with a .040" razor cut.

For this comparison, the t-statistic, 2.53, was greater than the t-critical value, 2.024, and therefore, the null was rejected.

2. H_o: $\mu = \mu_o$

   H_a: $\mu \neq \mu_o$

   where,

   μ = the mean of the sample group with a .020" razor cut,

   μ_o = the mean with a .080" razor cut.

For this comparison, the t-statistic, 5.64, was greater than the t-critical value, 2.024, and therefore, the null was rejected.

3. H_o: $\mu = \mu_o$

   H_a: $\mu \neq \mu_o$

where,

μ = the mean of the sample group with a .020" razor cut,

μ_o = the mean with no razor cut.

For this comparison, the t-statistic, -2.73, was less than the t-critical value, -2.024, and therefore, the null was rejected.

4. H_o: $\mu = \mu_o$

H_a: $\mu \neq \mu_o$

where,

μ = the mean of the sample group with a .040" razor cut,

μ_o = the mean with a .080" razor cut.

For this comparison, the t-statistic, 1.85, was less than the t-critical value, 2.1, and therefore, the null was accepted.

5. H_o: $\mu = \mu_o$

H_a: $\mu \neq \mu_o$

where,

μ = the mean of the sample group with a .040" razor cut,

μ_o = the mean with no razor cut.

For this comparison, the t-statistic, -4.1, was less than the t-critical value, -2.1, and therefore, the null was rejected.

6. H_o: $\mu = \mu_o$

H_a: $\mu \neq \mu_o$

where,

μ = the mean of the sample group with a .040" razor cut,

μ_o = the mean with no razor cut.

For this comparison, the t-statistic, -5.315, was less than the t-critical value, -2.1. and therefore, the null was rejected.

The null hypothesis comparisons for the PC samples are listed as follows:

1. H_o: $\mu = \mu_o$

   H_a: $\mu \neq \mu_o$

   where,

   μ = the mean of the sample group with a .020" razor cut,

   μ_o = the mean with a .040" razor cut.

For this comparison, the t-statistic, 1.934, was less than the t-critical value, 2.024, and therefore, the null was accepted.

2. H_o: $\mu = \mu_o$

   H_a: $\mu \neq \mu_o$

   where,

   μ = the mean of the sample group with a .020" razor cut,

   μ_o = the mean with a .080" razor cut.

For this comparison, the t-statistic, 6.16, was greater than the t-critical value, 2.024, and therefore, the null was rejected.

3. H_o: $\mu = \mu_o$

   H_a: $\mu \neq \mu_o$

   where,

   μ = the mean of the sample group with a .020" razor cut,

   μ_o = the mean with no razor cut.

For this comparison, the t-statistic, -4.826, was less than the t-critical value, -2.024, and therefore, the null was rejected.

4. H_o: $\mu = \mu_o$

   H_a: $\mu \neq \mu_o$

   where,

   μ = the mean of the sample group with a .040" razor cut,

   μ_o = the mean with a .080" razor cut.

For this comparison, the t-statistic, 4.352, was greater than the t-critical value, 2.1, and therefore, the null was rejected.

5. H_o: $\mu = \mu_o$

   H_a: $\mu \neq \mu_o$

   where,

   μ = the mean of the sample group with a .040" razor cut,

   μ_o = the mean with no razor cut.

For this comparison, the t-statistic, -7.16, was less than the t-critical value, -2.1, and therefore, the null was rejected.

6. H_o: $\mu = \mu_o$

H_a: $\mu \neq \mu_o$

where,

μ = the mean of the sample group with a .080" razor cut,

μ_o = the mean with no razor cut.

For this comparison, the t-statistic, -14.007, was less than the t-critical value, -2.1, and therefore, the null was rejected.

Analyzing the validity of the specimens required comparing the results from the different tests in this research against the results given from the ASTM standard. The analysis of the four point bend sample groups and the specimens tested with the fracture toughness tool had a razor notch of .020". In addition to the total sample group, the groups formed based on the fracture characteristic were analyzed. The results from the analysis showed positive results for polycarbonate; however, HDPE did not give encouraging results.

In conclusion, the data shows that the type of material and the depth of the razor cut are both important factors in whether the fracture toughness tool will provide accurate results for all types of polymeric materials. In particular, the more ductile materials are more likely to provide inaccurate fracture toughness values. It is also important to note that the geometry determinate constant, C, used in the fracture toughness equation 1-4 may not be material specific. Thus, the K_{Ic} values obtained from equation 1-4 may not be accurate. Also, for the materials used in this research, the analysis suggests that there is a

critical depth for the razor notch beyond which further changes in the depth have no significant effect on the fracture toughness. The analysis showed the competing fracture mechanisms in the PC specimens produced two separate groups from one original group that were significantly different from each other. Chapter five summarizes the conclusions from the research and lists the recommendations.

PC/Depth of RC	T-Statistic	T-Critical	Accept/Reject Null
.020:" vs. .040"	2.53	2.024	Reject
.020" vs. .080"	5.64	2.024	Reject
.020" vs. No RC	-2.73	-2.024	Reject
.040" vs. .080"	1.85	2.1	Accept
.040" vs. No RC	-4.1	-2.1	Reject
.080" vs. No RC	-5.315	-2.1	Reject
HDPE/Depth of RC	T-Statistic	T-Critical	Accept/Reject Null
.020:" vs. .040"	1.934	2.024	Accept
.020" vs. .080"	6.16	2.024	Reject
.020" vs. No RC	-4.826	-2.024	Reject
.040" vs. .080"	4.352	2.1	Reject
.040" vs. No RC	-7.16	-2.1	Reject
.080" vs. No RC	-14.007	-2.1	Reject

Table 4.9 t-test analysis of depth of razor cuts.

CHAPTER V

CONCLUSIONS AND RECOMMENDATIONS

The objective of this research was to adapt to polymeric materials the fracture toughness tool Stromswold and Quesnel developed to determine the fracture toughness of metallic materials. The specimens used with the tool were tested on a 4-point bend apparatus and with the fracture toughness tool. The fracture toughness values were compared to each other and to the results obtained with an ASTM approved standard test. Conclusions and recommendations were made.

5.1 Conclusions

The effect of the razor notch and the effect of the variation of material properties from polymer to polymer impacted the fracture toughness values obtained. The nature of polymeric material suitable for fracture toughness testing was an important outcome of the research. Similarly, the impact of the depth of the razor notch for each material was found to be important in the configuration of the specimen. Conclusions follow:

1. PC was shown to provide accurate K_{Ic} values that were independent of the type of test method used.

2. HDPE was shown to provide inaccurate K_{Ic} values that were dependent on the type of test method used.
3. The more brittle materials can be anticipated to provide more accurate K_{Ic} values.
4. The more ductile materials can be anticipated to provide inaccurate or invalid K_{Ic} values of lesser accuracy.
5. The depth of the razor notch was shown to have a significant effect on the fracture toughness of a material using the specimen configuration for the fracture toughness tool.
6. There appeared to be a critical razor cut depth beyond which any further changes do not make a significant difference.

5.2 Recommendations

Recommendations for future research are listed as follows:

1. The research should be extended to include other thermoplastics, thermosets, and eventually composites.
2. Specimen pretest conditioning should be explored. PC has been shown to exhibit a significant decline in fracture toughness when subjected to aging pretest conditioning (Jones, 1990).
3. The effects of humidity on fracture toughness should be researched for different polymers.

4. The effects of temperature on fracture toughness should be researched for different polymers.
5. The effects from razor notch depth should be researched for different polymers
6. This study should be replicated to verify the results obtained from this research.

APPENDIX

SPECIMEN	HDPE	PC
1	4200	9000
2	4200	
3	4200	
4	4100	
5	4200	
Average Yield Strength σ (psi)	4180	9000

Fig. A.1 Yield strength values for PC and HDPE from tensile specimens.

ASTM FRACTURE TOUGHNESS VALUES (PSI√IN)		
SPECIMEN	HDPE	PC
1	2029.89	3026.73
2	2032.02	3160.92
3	2004.33	3197.13
4	1997.94	3050.16
5	1974.51	3069.33
6	1872.27	3177.96
7	1857.36	3035.25
8	1925.52	3041.64
9	1931.91	3077.85
10	1955.34	3030.99
AVERAGE	1958.11	3086.80

Fig. A.2 ASTM fracture toughness values.

HDPE FRACTURE TOUGHNESS RESULTS BY RAZOR NOTCH DEPTH (PSI√IN)				
Specimen	.080"	.040"	.020"	No Razor Cut
1	1528.88	1780.89	1710.89	2044.10
2	1621.28	1831.29	1674.49	2035.70
3	1470.07	1696.89	1573.68	1934.90
4	1607.28	1632.48	1694.09	2024.50
5	1559.68	1926.50	1688.49	1990.90
6	1472.88	1579.28	1705.29	1912.50
7	1506.48	1705.29	1666.08	1884.50
8	1624.08	1677.29	1761.29	2108.51
9	1388.87	1604.48	1710.89	2080.51
10	1528.88	1677.29	1621.28	2088.91
Average	1530.84	1711.17	1680.65	2010.50

Fig. A.3 HDPE fracture toughness results by razor cut depth.

PC FRACTURE TOUGHNESS RESULTS BY RAZOR NOTCH DEPTH (PSI√IN)				
Specimen	.080"	.040"	.020"	No Razor Cut
1	2620.93	2797.34	2931.75	4396.22
2	2438.92	2410.92	3203.36	3642.99
3	2511.73	2730.14	2570.53	2906.55
4	2651.74	2447.32	2886.95	3584.18
5	2556.53	2615.33	2749.74	2528.53
6	2536.93	2472.53	3483.38	3085.76
7	2483.73	3354.57	3144.56	3701.79
8	2576.13	2354.92	3413.56	4326.22
9	2357.72	2867.35	3043.76	4141.1
10	2455.73	3018.55	3029.75	4328.64
Average	2519.01	2706.90	3045.72	3694.23

Fig. A.4 PC fracture toughness results by razor cut depth.

Fracture Toughness Values at Selected RC Depth (PSI√IN)				
	HDPE		PC	
Specimen	4-pt fixture (.020")	Fracture Toughness Tool (.080")	4-pt fixture (.020")	Fracture Toughness Tool (.020")
1	1710.89	1612.88	2931.75	2956.95
2	1674.49	1344.07	3203.36	3046.56
3	1573.68	1344.07	2570.53	2688.14
4	1694.09	1433.67	2886.95	2419.32
5	1688.49	1344.07	2749.74	2956.95
6	1705.29	1523.28	3483.38	3225.76
7	1666.08	1612.88	3144.56	3136.16
8	1761.29	1344.07	3413.56	3315.37
9	1710.89	1523.28	3043.76	3315.37
10	1621.28	1523.28	3029.75	2867.35
11	1985.30	1344.07	2718.94	2867.35
12	1996.50	1433.67	3141.76	3315.37
13	1948.90	1344.07	3152.96	2688.14
14	1856.49	1523.28	1979.70	2867.35
15	1741.69	1523.28	2886.95	3046.56
16	1943.30	1433.67	3169.76	
17	1682.89	1433.67	2144.91	
18	1722.09	1523.28	2710.54	
19	1831.29	1433.67	2828.14	
20	1943.30	1433.67	1677.29	
21	1677.29	1523.28	2296.12	
22	1660.48	1344.07	2301.72	
23	1859.29	1523.28	2100.11	
24	1797.69	1612.88	2206.51	
25	1906.90	1344.07	3315.37	
26	1856.49	1344.07	3883.80	
27	2032.90	1344.07	2805.74	
28	2004.90	1344.07	2088.91	
29	1904.10	1344.07	2774.94	
30	1825.69	1344.07	1979.70	
Average	1799.47	1436.66	2754.03	2956.95

Fig. A.5 Fracture toughness values, with 4-pt bend fixture and toughness tool.

Split PC Sample by Fracture Surface (PSI√IN)				
	4-point fixture		Toughness tool	
	Smooth	Rough	Smooth	Rough
	2931.75	3203.36	2688.14	2956.95
	2570.53	2886.95	2419.32	3046.56
	2749.74	3483.38	2867.35	3225.76
	2718.94	3144.56	2867.35	3136.16
	1979.70	3413.37	2688.14	3315.37
	2144.91	3043.76	2867.35	3315.37
	1677.29	3029.75		3046.56
	2296.12	3141.76		
	2301.72	3152.96		
	2100.11	2886.95		
	2206.51	3169.76		
	2805.74	2710.54		
	2088.91	2828.14		
	2774.94	3315.37		
	1979.70	3883.80		
Average	2355.11	3152.96	2732.94	3148.96

Fig. A.6 Fracture toughness values by fracture surface, .020" RC.

Split PC Samples by Fracture Surface (PSI√IN)							
.080"		.040"		.020"		No Razor Cut	
S	R	S	R	S	R	S	R
2438.92	2620.93	2797.34	3354.57	2931.75	3203.36	2906.55	4396.22
2483.73	2511.73	2410.92	2867.35	2570.53	2886.95	2528.53	3642.99
2357.72	2651.74	2730.14	3018.55	2749.74	3483.38	3085.76	3584.18
2455.73	2556.53	2447.32			3144.56		3701.79
	2536.93	2615.33			3413.37		4326.22
	2576.13	2354.92			3043.76		4141.41
		2472.53			3029.75		4628.64

Fig. A.7 Fracture toughness values by fracture surface, varying RC depths.

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