Crack prediction of plastic housing subjected to impact loading

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Crack Prediction of Plastic Housing Subjected to Impact Loading

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**SCHOOL OF MECHANICAL AND PRODUCTION
ENGINEERING**

**NANYANG TECHNOLOGICAL UNIVERSITY
2004**

Crack Prediction of Plastic Housing Subjected to Impact Loading

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School of Mechanical and Production Engineering

A thesis submitted to the Nanyang Technological University
in fulfilment of the requirement for the Degree of
Master of Engineering

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Crack Prediction of Plastic Housing Subjected to Impact Loading

ABSTRACT

This report establishes a procedure or methodology to model and predict potential plastic crack on plastic housing at impact. A test rig is designed and fabricated to deliver tensile impact load to plastic tensile bar specimens and the final displacement on the plastic specimens at fracture are obtained. These values are used in the finite element analysis (FEA) simulation to establish thresholds to predict failure of product housing when impact loaded. Various notch sizes are introduced on the tensile specimens to study the effect of notch-induced crack. Similarly, the fracture displacements are also used in the FE modelling to obtain threshold. Dynatup drop dart test is also employed to study cracks on a multi-axial stress state. The critical height where specimen begins to puncture is extracted and modeled in FEA software. The thresholds at peak load are obtained. These thresholds are tabulated as failure criteria to predict surface and fillet cracks on plastic housing. The prediction is carried out by modeling actual plastic housing subjected to impact load. The analysis generates a contour plot of stress and strain distributions on the finite element (FE) model. Those regions that satisfy failure criteria are identified as potential crack regions and are verified by observing physical failure on product housing. Polycarbonate/acrylonitrile-butadiene-styrene (PC/ABS) is selected for the study. The simulation performed on plastic housing shows good correlation with experiments. The concluding results show accurate prediction of crack on plastic housing.

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SUMMARY

This report establishes a procedure or methodology to model and predict potential plastic crack on plastic housing at impact. A test rig is designed and fabricated to deliver uniaxial tensile impact load to plastic tensile bar specimens and the final displacement on the plastic specimens at fracture are obtained. These values are used in the finite element analysis simulation to establish failure thresholds to predict failure of product housing when impact loaded. Also, failure thresholds are obtained from specimen with various notch sizes and Dynatup drop dart test as to study cracks on a multi-axial stress state. These thresholds are tabulated as failure criteria to predict surface and fillet cracks on plastic housing at impact loading using finite element analysis. Verification studies are conducted to determine the dependability of the criteria. Polycarbonate/acrylonitrile-butadiene-styrene (PC/ABS) thermoplastics is selected for the study. The concluding results show accurate prediction of crack on plastic housing.

Chapter One

INTRODUCTION

1.1 Background

Plastic is widely used in housings for many portable electronics products such as notebook computer, pagers, cellular phones and personal digital assistants etc, and it is not uncommon that these handheld devices are dropped accidentally onto hard ground or knocked against hard object. The consequences of these impact collisions may range from a minimal aesthetic defect to a complicated malfunction of the device. The latter case may lead to a possible loss of valuable data or an unexpected terminal downtime, and may also cause inconveniences associated with repairing and replacing the device. It is known that the reliability of a product is very much dependent on its drop survivability and its continual functionality after collisions [1]. Hence, design considerations of portable devices among manufacturers have rapidly developed into producing rugged and high impact resistant handheld products in need of attracting consumers to remain loyal to their brands.

The improvement of impact resistant housing through design modifications has been the subject of many studies. Design considerations in injection moulding from mould filling, weld lines, shrinkage and warpage, to part ejection were studied [2] [3] [4] [5]. Improvement of impact toughness in materials through blending of rubber particles into polymer was used. The results from these design studies combines with the development in material toughness properties have led to the understanding of building better and higher impact resistant housings.

Usually, plastic parts are built, tested, altered and retested to ensure they fulfilled performance requirements. Alternatively, engineering analysis such as finite element analysis (FEA) can be used to provide answers to effectiveness in design before parts are fabricated. With the analysis, the mechanical behaviours of plastic housings under actual functional test can be modeled. FEA is increasingly

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being applied to practical engineering problems to reduce long and tedious experiments and to lower cost required to achieve an effective part [6]. The result of the analysis is used to predict experimental results and to establish correlations.

However, it is not easy to capture experimentally the fracture behaviour of an extremely fast deformation at large plastic strain. That is to some extent why tests on polymer conducted at impact are always more complex than those at static. In the past, many tests such as Charpy, Izod, ball drop impact tests etc were used to measure the energy absorbed by the specimen to resist fracture. However the fracture behaviour of specimen under tensile impact test has been rarely studied. The initial portion of the research therefore aims at gaining an insight into the stresses and fracture displacements of polycarbonate/acrylonitrile-butadiene-styrene (PC/ABS) under tensile impact and in addition, effect of melt flow indices on fracture behaviour of PC/ABS. The remaining key portion will focus on making use of the experimental results obtained from PC/ABS studies, to predict potential cracks in plastics housing under impact collision.

1.2 Objective

The objective is to establish suitable methodology and failure criteria using finite element method to predict potential cracks on plastic housing under impact load

1.3 Scope

The research explores a test method to measure mechanical properties of plastics specimen under uniaxial static and impact loading. The testing is also extended to multi-axial impact testing. It includes design and fabrication of a tensile impact test rig. The experiments lead to an understanding of fundamental mechanics and failure of plastic materials in relation to notch effect as well. The investigation also extends to using finite element modeling and analysis software, ABAQUS® CAE/Standard/Explicit, to model the subject of interest. Verification methods for FEM prediction are also explored.

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1.4 Methodology

The methodology consists of three stages as shown in Figure 1.1. Stage 1 will conduct experiments and investigate its failure characteristic so as to obtain critical material test data for finite element analysis (FEA). Stage 2 models specimens undergo testing using finite element method (FEM) of analysis utilising the material test data in stage 1. From the analysis results, threshold parameters that determine failure will be obtained and used as failure criteria. Regions on a plastic housing that satisfied the failure criteria would be identified as potential crack regions. Stage 3 consists of verifying criteria in stage 2 by conducting impact collision test on plastic housings. Crack formation on housings after impact collision test will be observed and correlated with FEM modeling of actual plastic housing. The following paragraphs will explain in greater details of each stage in the methodology.

In stage 1, tensile test specimens are injection-moulded and used in uniaxial quasi-static and impact test. In quasi-static test, Instron Universal Machine is used to measure the amount of test specimen deformation as load is applied at a constant speed. The impact test uses an Impact Test Rig that is able to deliver similar uniaxial tensile load as in quasi-static test to fracture the specimen, but at a higher loading rate. Notches on the specimen are also introduced to determine the effect of notch diameters on both tests. All the displacements at point of fracture for both tests are recorded. Subsequently, Dynatup drop dart test is also carried out to study the material in multiaxial stress state. The critical or the optimum drop height that punctured the specimen is recorded. This information on displacement and critical height from experiments served as important data inputs in FEA simulations. The one-dimensional stress-strain curve obtained from quasi-static test will be used to input into finite element material model to predict plastic housing undergo three-dimensional impact loading.

Stage 2 utilizes material data and fracture information from stage 1 to perform finite element analysis to model all tests conducted. In these FEM models, 5 different stress and strain threshold parameters at point of fracture are obtained. These 5 selected parameters are *max principal engineering stress*, *von mises engineering stress*, *max principal engineering strain*, *max principal*

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logarithmic strain and *equivalent plastic true strain*. These thresholds once established will function as failure criteria for crack prediction.

In previous stage, we have successfully created the failure criteria. Stage 3 will concentrate on developing verification methods to prove the dependability of the criteria. The purpose of this phase is to identify crack formation on actual plastic housing and correlate test results with FEA analyses. Regions on the phone housing that satisfy failure criteria will be deemed as potential crack regions. A steel impactor drop test will be used on plastic housing for the verification stage.

METHODOLOGY

Chapter Two

LITERATURE REVIEW

2.1 Polycarbonate (PC) and polycarbonate/acrylonitrile-butadiene-styrene (PC/ABS)

Many investigations in polymers aim at improving the toughness and examine the mechanism by which such improvement can be made [7]. The toughness of a material is described as the ability to resist fracture by absorbing energy and is an important material property [8].

Polycarbonate (PC) is well known for its toughness and is an important engineering plastic that is widely used since mid 1950s. Its main features are transparency, toughness and high temperature stability, and its usage includes helmets, vehicle's headlamps, mobile phone's housings, medical syringes, electric shaver's housings, etc. However, PC has several drawbacks which may hinder its field of application. The material has a high melt viscosity, and this may pose a problem in injection moulding of thin-walled products. In thick-walled applications, PC loses its tough characteristic and exhibit brittle failure. Another problem is that PC also becomes brittle when a small flaw or a hairline crack is present in the material. Such cracks can form when the material is exposed to the environment [7].

To help overcome drawbacks to these conditions, PC is often blended with acrylonitrile-butadiene-styrene (ABS). This can only be done in applications where the transparency character of PC is less critical. PC/ABS is one of the most successful commercial polymer blends. This blend combines the good mechanical and thermal properties of PC and the ease of processibility, notched impact resistance and the lower price of ABS. Its usage includes portable laptops, handheld meters and mobile phone housings as well.

2.1.1 Polymer Microstructure

Many properties of polymeric materials depend on the microscopic arrangement of their molecules. Polymers can have an amorphous or semi-crystalline (partially crystalline) structure (see figure 2.1).

Figure 2.1: (a) Amorphous polymer (observe the entanglements among the polymer chains) and (b) semi-crystalline polymer [9].

Amorphous polymers consist of polymer molecules having no regular conformation. Upon heating amorphous polymers, the tangled polymer chains become active and begin moving past each other to disentangle themselves. This results in softening of the polymer and, ultimately, to polymer flow. As molecular activity increases, the material becomes more fluid. After polymer flow is achieved, the molten polymer is fabricated or shaped into a defined plastic part. Upon cooling, rigidity returns to the polymer and molecular movement decreases. Many engineering thermoplastics such as polycarbonate, polycarbonate/ABS blends and polystyrene are amorphous polymers.

In semi-crystalline polymers, because of their stereo-regularity, ordered molecular configurations are built into the chain structure. These ordered areas are crystals that form when the polymer is cooled from its molten state. When the polymer is heated once again, the crystal domains remain unchanged until the polymer reaches its melting point. This point is referred to as the crystalline melting point of the polymer.

Once these materials reach the melting point, the polymer behaves like an amorphous polymer in that the molecular configurations become random. Another factor, the degree of crystallinity, is not only affected by the chemical structure, but by the process conditions used to manufacture the plastic part. The rate of cooling is the process variable having the greatest effect on the degree of crystallinity. Examples of semi-crystalline polymer are polypropylene, polyethylene and nylon. Table 2.1 provides a comparison of mechanical properties of both semi-crystalline and amorphous polymers.

Mechanical Property	Semi-crystalline Polymer	Amorphous Polymer
	Examples: Polypropylene, Polyethylene, Nylon, PBT, PET	Examples: Polycarbonate, PC Blends, ABS, Polystyrene, TPU, SAN, PPO
Chemical Resistance	Higher	Lower
Shrinkage	Higher	Lower
Warpage	Higher	Lower
Tensile Strength	Higher	Lower
Tensile Modulus	Higher	Lower
Elongation	Lower	Higher
Creep Resistance	Higher	Lower
Flow	Higher	Lower
<i>Maximum Exposure Temperature</i>	Higher	Lower
Density	Higher	Lower

Source: Rosato, Donald V. and Dominick V., Injection Molding Handbook, 1995.

Table 2.1: Comparison of properties of both semi-crystalline and amorphous polymers [10].

High crystallinity improved chemical resistance in comparison to amorphous polymers. Therefore, semi-crystalline polymers can be exposed to a

wide variety of agents without failure in comparison to amorphous polymers. Part shrinkage for semi-crystalline polymers is higher than that for amorphous polymers. This is due to better packing of the molecular chains in the crystalline regions. Differences in cooling lead to differences in crystallinity and thus differences in shrinkage. Therefore, controlling process variables, such as mould temperature and cooling time, plays a major role in determining mould shrinkage for semi-crystalline materials.

In semi-crystalline polymers, crystals will form more completely in areas where they are the most densely packed. A crystallized area is rigid and strong, where an amorphous area is tougher and more flexible. This results in better creep, heat, and stress crack resistance, as well as increased shrinkage for semi-crystalline polymers in comparison to amorphous polymers. However, since amorphous areas are tougher and more flexible, the low temperature resistance properties are improved for amorphous polymers in comparison to semi-crystalline polymers.

2.1.2 Viscoelasticity

A material is elastic, if upon an applied force, its deformation is instantaneous and constant, and upon the removal of the force, its recovery is instantaneous and complete (i.e. the material will return to its original shape). Fluids show a characteristic resistance to movement (flow), which is called viscosity. Viscosity results in a frictional energy loss, which dissipates in the fluid as heat. Polymeric materials behave both as viscous fluids and elastic solids. They are viscoelastic materials. The most important characteristic of viscoelastic materials is that their mechanical properties depend on time.

Figure 2.2: Mechanical response (deformation) of a material subjected to a constant load for a finite time interval (a) Load application; (b) solid – elastic behaviour (c) liquid – viscous flow behaviour (d) polymer – viscoelastic behaviour [9].

The deformation of a material over time due to the application of a constant load is called creep. A purely elastic material responds instantaneously to the load and the deformation remains the same as shown in figure 2.2b, in addition, it will recover its initial shape upon the removal of the load. On the contrary, a viscous liquid will deform as long as the load continues to be applied as shown in figure 2.2c. Upon the removal of the load, the fluid does not return to its initial position. The response of a viscoelastic material is intermediate between the solid and the liquid (see figure 2.2d). A combination of springs (linear elastic behaviour) and dashpots (linear viscous behaviour) can be used in order to quantify the mechanical behaviour of polymeric materials.

Figure 2.3: Voigt-Kelvin element.

In figure 2.3 the Voigt-Kelvin element is shown. This is a parallel combination of a spring and a dashpot which gives a reasonable model of the response of polymer at creep. It is expressed as:

$$\sigma = E\varepsilon + \eta\dot{\varepsilon} \quad (2.1)$$

where σ is the total stress distributed between the spring and dashpot, E is the Young's modulus, the strain ε which is defined as the elongation divided by the initial length, η is the viscosity constant and $\dot{\varepsilon}$ is the strain rate.

2.1.3 Viscoplasticity

Plastic yielding occurs when stress and deformation in materials loaded beyond the elastic limit. If the materials experiences significant deformation-rate dependency after the plastic state has been reach, they are known to display plastic and viscous properties. The study of such materials is called rate-sensitive plasticity or simply viscoplasticity. Such studies involve dependency on the path of loading (the plasticity aspect) plus dependency on the rate of loading (the viscous aspect). These studies are quite complex and still in a formative stage [11].

A viscoplastic mechanical model consisting of a nonlinear Kelvin element arranged in parallel with a Saint-Venant element and both are in series with a linear spring is considered [11]. It is an example of a linear elastic, nonlinear viscoplastic mechanical model as shown in figure 2.4.

Figure 2.4: Example of a Linear Elastic, Nonlinear Viscoplastic Mechanical Model [11].

This model gives a reasonable representation of the behaviour of plastic deformation for various tensile stress and stress rate. It is express as [11]:

$$\dot{\epsilon} = \begin{cases} \frac{\dot{\sigma}}{E} & \text{for } \sigma < \sigma_{\text{yield}} \\ \frac{\dot{\sigma}}{E} + \frac{1}{t_e} \left[\left(\frac{\sigma - \sigma_{\text{yield}}}{\mu_p} \right)^n - \epsilon + \frac{\sigma}{E} \right] & \text{for } \sigma \geq \sigma_{\text{yield}} \end{cases} \quad (2.2)$$

where $\dot{\epsilon}$ is the strain rate, $\dot{\sigma}$ is the stress rate, E is the Elastic Modulus, t_e is the strain retardation time, n and μ_p are plastic material constants, σ is the stress variable, σ_{yield} is the yield stress and ϵ is the strain variable [11].

Figure 2.5 shows a sketch of stress versus strain for some loading cases. The curves show that the plastic zone “lifts” as the loading rate and strain rate increase. Viscoplasticity is a very extensive study and more information can be obtained from external reading [11].

Figure 2.5: Linear Elastic, Viscoplastic Curves for Various Loading Rates [11].

2.1.4 Failure Threshold

In practice, nearly all thermoplastic mouldings are frequently subjected to impact loads. They are generally well suited for this type of loading since they have a relatively high toughness, deformability and mechanical damping. However, in some cases of normally very ductile thermoplastics, a glass like brittle fracture with small elongation can occur at certain conditions. This type of failure can occur at low temperatures or at high deformation rates. It is particularly concerned that in such cases the failure occurs without much plastic deformation or virtually without warning. Hence, it has become important to perform works on thermoplastic materials under impact loading and to establish material failure threshold that are suitable for design calculation.

In most cases the permissible loading of plastic before fracture should be determined to ensure that there is a safety margin to the failure threshold. Thermoplastics examined under impact loading, generally, have pronounced decrease in elongation at break. The types of failure occurring on impact loading can be divided into four types [12]:

1. Failure with necking. There is a distinct yield point, and when exceeded, the stress drops appreciably. In this case, the yield stress and yield strain have been given as the characteristic failure data. If strain hardening behaviour of thermoplastics has caused stress to exceed yield point, the ultimate or rupture point will be given as failure threshold. See figure 2.6.

Figure 2.6: Typical stress-strain curve of a polymeric material. A is the proportional point, B the yield point and C the rupture (break) point. The point where the linear elastic behaviour starts to be non-linear is called the proportional limit or point [9].

2. Failure with a weakly defined yield point. There is neither a drop in the stress nor any necking. In this case, the stress at break and the respective elongation have been taken as the characteristic failure data.
3. Failure without yield point with simple fracture. Fracture is perpendicular to direction of loading. As usual, the tensile stress and the elongation at break (strain at maximum force) were determined.
4. Multiple splinter failure. A primary break generally forms perpendicular to the direction of loading, fracturing the material into tiny splinters within a break zone. Beside this, several secondary fractures often occur, which can run in any direction through the test

specimen and have a smooth, glass-like appearance. The failure data for this are given as with 3.

2.2 Types of Impact Test

In standard testing, such as tensile and flexural testing, the material absorbs energy slowly. In real life, materials often absorb applied forces very quickly: falling objects, blows, collisions, drops, etc. The purpose of impact testing is to simulate these conditions. Izod and Charpy methods are used to investigate the behaviour of specified specimens under specified impact stresses, and to estimate the brittleness or toughness of specimens. The results obtained can be used as a source of material selection criteria but are not advisable to be used as data for design calculations on components. Information on the typical behaviour of a material can be obtained by testing different types of test specimens prepared under different conditions, varying notch radius and test temperatures. Both Izod and Charpy tests are performed on a pendulum impact machine. The specimen is clamped in a vice. The pendulum hammer attached with a hardened steel striking edge with specified radius, is released from a predefined height, causing the specimen to shear from the sudden load. The residual energy in the pendulum hammer carries it upwards: the difference in the drop height and return height represents the energy to break the test bar. The test can be carried out at room temperature, or at lower temperatures to test cold-temperature embrittlement. Test bars can vary in type and in dimensions of the notches. The test results of falling-weight impact, such as Gardner Impact and Dynatup drop dart tests, are dependent on the geometry of both the falling weight and support. They are advisable to be used for relative rankings of materials. Impact values from these test results are useful when the industry usage of the material conforms to the equipment and specimen parameters when it was laboratory tested [13].

An impact test can be used to assess a material's fracture resistance. The two most common laboratory test configurations, the pendulum machine type and the falling weight type, will be discussed.

2.2.1 Pendulum Type Impact Tests

The specimen is broken by the impact of a heavy pendulum hammer as shown in figure 2.7 [14], falling through a fixed distance to strike the specimen. The hammer is released by striking the holding lever. The ductile to brittle transition is obtained by measuring the toughness over a range of temperatures. The impact energy is measured from the height through which the hammer swings after the impact. The results are reported in terms of energy absorbed per unit of specimen width, or more specifically, the energy absorbed in breaking the specimen which is equal to the difference between the potential energy at the moment of impact and the residual energy.

Figure 2.7: Pendulum Machine [14].

i) Charpy Impact Test

In the Charpy test procedures, a hammer is mounted on a very nearly frictionless pendulum. It is released from a specified height, h , and strikes the sample to be evaluated at the bottom of its arc. When it does so, the material is subjected to a high strain rate, which favors fracture. Moreover, the notch on the specimen on the side of the bar subjected to impact loading also tends to promote fracture. Thus, an impact test is associated with a high strain rate and high stress concentration at the notch, and as such it is a rather severe test of a material's toughness. Additionally, the sample test temperature can be varied, thereby

allowing the determination of the temperature variation of the toughness. Subsequent to striking and then breaking the sample, the hammer rises to a height, h , which is less than that from which it was released. The difference in potential energy, $= mg(h - h')$, is the energy expended in fracturing the sample. This test is actually the modification of the Izod test. Charpy modified the test by orientating the specimen in a horizontal position (see figure 2.8) [14] instead of the vertical position as in the Izod test. Values determined by Charpy impact testing are sometimes used in place of Izod impact test results as material selection criteria. In the Charpy test set up, the specimen is simply supported at both ends, and the test measures the amount of energy needed to break a specimen fixed between supporting ends. Figure 2.9 shows a typical curve of Charpy notched impact strength of PC/ABS with the effect of temperature [15]. It is noted that toughness of PC/ABS increases with temperature.

Figure 2.8: Charpy's Specimen Set Up [14].

Figure 2.9: Charpy notched impact strength of PC/ABS at 4mm thickness vs. effect of temperature [15].

ii) Izod Impact Test

The Izod impact strength of a material is the amount of energy necessary for a swinging pendulum to break a notched specimen that is secured at one end as shown in figure 2.10 [14]. The notch in the specimen acts as a stress concentrator or crack growth site. While the test gives a good indication of a material's notch sensitivity, the values may have little validity for the behaviour of unnotched parts in actual service. If the Izod impact strength of a particular resin increases as the notch radius increases, the resin is said to be notch-sensitive. For such resins, sharp corners should be eliminated from product designs whenever possible. Figure 2.11 shows a typical curve of Izod notched impact strength of PC/ABS vs. the effect of temperature [15]. The curve indicates a gradual increase in toughness with increasing temperature.

Figure 2.10: Izod's Clamping Set Up [14].

Figure 2.11: Izod notched impact strength of PC/ABS at 4mm thickness vs. Effect of Temperature [15].

iii) Tensile Impact Test

The tensile impact test, measures the energy required to rapidly stretch a specimen to failure. The energy utilised in this method is delivered by a single swing of a tensile impact tester. The energy to fracture is determined by the kinetic energy extracted from the pendulum in the process of breaking the specimen. The specimen is impacted at the bottom of the swing of the pendulum. The specimen is horizontal at rupture. One end of the specimen, at impact, is held either by the frame or the pendulum crosshead as shown in figure 2.12 [16]. The crosshead may be either mounted stationary on the support frame or carried downward together with the pendulum. Corrected tensile impact energy is calculated as scale reading of energy minus a friction correction plus the bounce correction factor. As in the case with other impact tests, tensile impact does vary with temperature, the rate at which the test force is applied, and the polymer's MFI. Figure 2.13 shows a typical curve of tensile impact strength of polycarbonate vs. effect of temperature [17]. The general material data specifications does not provide PC/ABS blend data, hence, only generic polycarbonate data is displayed. It is noted that tensile impact strength peaks at temperature at around 27°C.

Figure 2.12: Tensile Impact Test With Specimen Held at Crosshead [16].

Figure 2.13: Tensile impact strength of polycarbonate vs. effect of temperature [17].

2.2.2 Drop weight Type Impact Test

i) Gardner Impact Test

Gardner impact, is a traditional method for evaluating the impact strength or toughness of a plastic material. The test is often used to specify appropriate materials for applications involving impact or to evaluate the effect of secondary finishing operations or other environmental factors on plastic impact properties. The test sample rests on a base plate over an opening of specified diameter. An "impactor" sits on top of the test sample with a nose of specified radius in contact with the centre of the test sample. A weight is raised inside a guide tube to a predetermined height, then released to drop onto the top of the impactor, forcing the nose through the test sample. The drop height, drop weight, and the test result (pass / fail) are recorded. Figure 2.14 shows a Gardner impact tester [18]. Figure 2.15 shows a typical curve of falling weight impact strength of polycarbonate vs. effect of temperature [19]. The general material data specifications does not provide PC/ABS blend data, hence, only generic polycarbonate data is displayed. The curve indicates an increase in impact strength with increasing temperature.

Figure 2.14: Gardner Impact Tester [18].

Figure 2.15: Falling weight impact strength of polycarbonate vs. effect of temperature [19].

ii) Dynatup™ Drop Dart Test

Dynatup™ drop dart impact system can be used for puncture testing as well as flexural testing. A flat circular disc or a square specimen is securely clamped over a clamping ring and a falling dart is activated by a releasing mechanism to deliver impact load onto the specimen at a predetermined height. The drop height and the mass of drop dart determine the impact energy of the fall. It is different from Gardner impact test because Dynatup drop dart test is an instrumented puncture test. Force-deflection and absorbed energy-deflection data are registered during the impact event. Gardner impact test only records pass or fail outcome of test specimens. Figure 2.16 shows a typical set up of a drop dart system [20]. Figure 2.17 shows an example of fracture appearance of polycarbonate specimen compared with a data plot [21]. The general material data specifications does not provide PC/ABS blend data, hence, only generic polycarbonate data is displayed.

Figure 2.16: Typical Set Up of A Drop Dart System [20].

Figure 2.17: Fracture Appearance Of Polycarbonate Specimen Compared With a Data Plot [21].

2.2.3 Comparison Of Several Impact Test Methods

An evaluation of the impact test methods is necessary to determine the range of applicability. The comparison is based on the stress state and failure modes for the various impact tests. Table 2.2 [22] shows the evaluation of test methods for most of the impact tests mentioned in this chapter.

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No.	Test Method (ASTM Standard)	Test Velocity (m/s)	Stress State	Failure Criterion	Measured Characteristic
1	Izod Notched (D256-81 Method A)	3.45	In-plane Bending	Break	Total energy
2	Izod reverse notched (D256-81 Method E)	3.45	In-plane Bending	Break	Total energy
3	Charpy (D 256-81 Method B)	3.45	In-plane Bending	Break	Total energy
4	Tensile (D 1822M-83 Modified)	3.45	Uniaxial Tension	Break	Tensile Strength, Tensile Elongation
5	Falling Weight (D 3029-84 Method B)	3.60	Multi-axial Bending/ Tension	Cracking	Yield Energy
6	Gardner Standard	Variable	Normal Shear	Cracking	Yield Energy
7	Gardner 1.25in. Ring	Variable	Multi-axial Bending	Cracking	Yield Energy
8	Gardner Anvil	Variable	Normal Compression	Cracking	Yield Energy
9	Dynatup	3.60	Multi-axial Tension	Cracking	Ultimate Force and Deflection, Total Energy
10	Driven Dart	3.60	Multi-axial Bending	Yield-break	Ultimate Force, Total Energy

Table 2.2: Comparison of impact test methods [22].

From the comparison table 2.2, tensile impact method is a more preferable method in terms of applicability. Apart from delivering uniaxial tensile load, the test method satisfies the requirements of measuring direct tensile force and tensile elongation of test specimens at impact. The recorded load and elongation data can be used to determine the ultimate stress and strain values of the material tested whereas, other methods mostly register total energy of the material at impact. These stress and strain values will be useful for comparison with finite element analysis (FEA) results in later stages of the research.

For ease in data capturing, a slight modification of the tensile impact test method is made and is necessary to incorporate with measurement set up. A detailed working principle of the impact test rig is mentioned in chapter 3.

2.3 Fracture Behaviour in Plastics

When speaking in terms of mechanical failure, fracture is the ultimate failure for a material. Fracture can be generally characterized into 2 categories, which is ductile fracture and brittle fracture. Brittle materials require less energy

to fracture (e.g. glass and polystyrene) but ductile materials require a lot of energy to induce fracture (e.g. rubber). This is because ductile materials are not prone to crack propagation and would absorb a significant total of energy before fracture. Yet, some ductile materials can actually fracture abruptly under some given circumstances. This means that there is a transition from ductile to brittle fracture as crack propagation takes precedence over plastic deformation.

There are a few factors that bring about this transition from ductile to brittle fracture occurring in some materials and they are as listed below:-

- a. when the temperature is lowered
- b. when the rate of straining is increased
- c. when a stress raiser is introduced into the material (e.g. a notch)

2.3.1 Brittle and Ductile Fractures

There are two kinds of fractures, which is ductile fracture and brittle fracture. With ductile fracture, there is a large plastic region where plastic deformation occurs during crack propagation. The fracture process occurs slowly as the crack propagates. This crack is considered stable as it resists further propagation with an increase in applied stress. Conversely, cracks propagate rapidly in brittle fracture with very small plastic region. The crack also propagates continuously and spontaneously without an increase in applied stress.

i) Ductile Fracture

As mentioned before, ductile fracture has a large plastic region. The evidence of this is the necking that occurs before fracture. If a material yields with about 100% area reduction, this material is a highly ductile material. For tensile fracture in a ductile material, the fracture process normally has several stages.

At first, necking will occur as in (A) in figure 2.18 [23]. Then small cavities, also known as void, will form in the cross section where the necking had occurred as in (B). As stress is increased and plastic deformation continues, the voids also increase in size and merge to form a crack. This can be seen in (C). The long axis of this crack is perpendicular to the direction of applied stress. The crack continues to propagate parallel to its major axis as in (D) until fracture occurs, (E). The fracture occurs due to rapid crack propagation around the outer perimeter of

the neck by a shear deformation of close to 45° to the tensile axis (which is the angle whereby the shear stress is maximum). As can be seen, ductile fracture has a rough surface where the fracture occurs. The region of the surface has an irregular and fibrous appearance, which indicates plastic deformation.

Figure 2.18: Ductile Fracture [23].

ii) Brittle Fracture

Brittle fracture occurs with little or no plastic region. This is because the crack propagation is rapid in brittle fracture. The direction of crack is almost perpendicular to the direction of applied tensile stress as shown in figure 2.19 [23], so the fracture surface is quite flat and smooth.

Figure 2.19: Brittle Fracture [23].

For most brittle crystalline materials, the crack propagation in an atomic level corresponds to spontaneous and successive breaking of atomic bonds along

specific crystallographic planes. This process is known as cleavage. This type of fracture is intragranular since the fracture passes through grains. The flat fracture surface often appears grainy/granular due to changes in orientation of the cleavage planes from grain to grain. Crack can also propagate at the grain boundaries in some alloys. This type of fracture is termed intergranular fracture. Brittle fracture that occurs in amorphous materials (e.g. ceramic glass) results in shiny and smooth fracture surfaces.

One damage mechanism that is in relation to brittle failure in thermoplastic materials is the appearance of crazes. Amorphous thermoplastic polymers and to some extent semi-crystalline thermoplastic, display a phenomenon known as crazing during the process of failure [6]. Although similar to a crack at some aspects, the detailed structure of a craze is significantly different. Specifically, the morphology of a craze includes fibrils of highly oriented material stretched between free or open surfaces. These fibrils provide load-carrying ability between the crack surfaces. Crazing is affected by numerous factors such as the presence of solvents, moulding conditions, annealed state and stress states. It is also a time dependent and temperature dependent process [6].

2.3.2 Temperature Effects on Plastics Fracture

Many thermoplastics experience a dramatic drop in its ductility and resistance to crack propagation (also known as toughness) when temperature is lowered. The impact strength of thermoplastics is affected by temperature. This effect is seen most clearly in the way the specimen fails. At temperatures above a certain level, a test bar moulded from the resin breaks via ductile fracture; that is, it stretches until failure. At lower temperatures, the break occurs by brittle fracture, with little deformation occurring during failure. The temperature at which the behaviour of the material changes is called the ductile-brittle transition temperature. See figure 2.20 for ductile-brittle transition curve [24].

Figure 2.20: Ductile-Brittle Transition Curve [24].

In many tests, impact testing studies the dependence of notch toughness or impact energy on the temperature. The tests conducted are functions of temperature of a specific blend. The ductile-brittle transition temperature is related to the dependence of impact energy. At high temperatures, the impact energy is relatively high. Conversely, at low temperatures, the impact energy is relatively low with a small, constant impact energy (a trademark of brittle fracture). The impact energy falls dramatically over a relatively small temperature range when it is lowered from a high temperature. The range of temperature over which this transition occurs is of particular interest and is important to identify. Figure 2.21 [25] shows approximate transition temperature of polycarbonate from ductile to brittle failure for several different geometries upon loading. Different geometries and loading conditions may yield different stress state on test specimens and hence may result in different transition temperature range. In a particular notched beam test performs beyond ductile-brittle transition zone, it is noted that temperatures at ductile zone alter notch-brittleness characteristics of thermoplastics at failure. Figure 2.22 [21] shows failure characteristics of thermoplastics as a function of temperature during a typical notched beam test.

Figure 2.21: Approximate transition temperatures (T_{DB}) of polycarbonate from ductile to brittle failure for several different geometries upon loading: (a) tensile bar, (b) puncture disk, (c) grooved tensile bar, and (d) notched beam [21].

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	Temperature								
	-20	-10	0	10	20	30	40	50 °C	
	-4	14	32	50	68	86	104	122 °F	
Polystyrene	A	A	A	A	A	A	A	A	
Polymethyl methacrylate	A	A	A	A	A	A	A	A	
Glass-filled nylon (dry)	A	A	A	A	A	A	A	B	
Polypropylene	A	A	A	A	B	B	B	B	
Polyethylene terephthalate (PET)	B	B	B	B	B	B	B	B	
Acetal	B	B	B	B	B	B	B	B	
Nylon (dry)	B	B	B	B	B	B	B	B	
Polysulphone	B	B	B	B	B	B	B	B	
High-density polyethylene (HDPE)	B	B	B	B	B	B	B	B	
Rigid polyvinyl chloride (PVC)	B	B	B	B	B	B	C	C	
Polyphenylene oxide	B	B	B	B	B	B	C	C	
Acrylonitrile-butadiene-styrene (ABS)	B	B	B	B	B	B	C	C	
Polycarbonate	B	B	B	B	C	C	C	C	
Nylon (wet)	B	B	B	C	C	C	C	C	
Polytetrafluoroethylene (PTFE)	B	C	C	C	C	C	C	C	
Low-density polyethylene (LDPE)	C	C	C	C	C	C	C	C	

*A: Brittle even when unnotched; B: notch brittle; C: tough; specimens do not break completely even when sharply notched.

Figure 2.22: Failure characteristics of thermoplastics as a function of temperature during a typical notched beam test [21].

2.3.3 Strain Rate Effects on Plastic Fracture

The experimentally observed yield behaviour depends on the deformation rate of the thermoplastic undergoing test. Although the quasi-static stress-strain curve is often treated as an inherent property of a material, it is a valid description of the material only at the strain rate at which the test was conducted. As higher strain rates are encountered, the stress-strain properties may change, and alternate testing techniques have to be employed. Constant strain rate test can be performed with specialised testing apparatus as shown in figure 2.23 [26]. At strain rates of the order of 10^{-6} /s to 10^{-5} /s, the creep behaviour of a material is the primary consideration. At higher strain rates of 10^{-4} /s to 10^{-3} /s, the uniaxial tension, compression or quasi –static stress strain curve obtained from constant strain rate test is used to describe the material behaviour. The range of strain rates from 10^{-1} /s to 10^2 /s is generally referred to as the intermediate or medium strain rates regime. Strain rates of 10^3 /s or higher are generally treated as the range of high strain rate response, although there are no precise definitions as to strain rate

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regimes and care must be taken in evaluating data to note the actual strain rates rather than the terminology [26].

Figure 2.23: Dynamic Aspects of Mechanical Testing [26].

Figure 2.24 [27] is obtained by conducting quasi-static tests on Polycarbonate with different strain rates. It shows that when strain rate increases, the stress-strain plot moves vertically upwards, displaying higher yield stress. It is also noted that with increasing strain rates, the “shape” of the stress-strain curves are maintained.

Figure 2.24: Stress-strain Data For Polycarbonate Under Different Strain Rates [27].

2.4 Types of Strain Measurements

Non-optical methods of experimental strain analysis such as extensometer and strain gauge, and optical methods such as holography, photoelasticity, grid method, speckle interferometry and moiré interferometry techniques, have effectively been employed to analyse a variety of engineering problems. In this chapter, techniques such as strain gauge, speckle interferometry, moiré interferometry and grid method are discussed.

2.4.1 Strain Gauge Technique

The concept of using a strain gauge or an element that changes resistance as the surface below it deflects is well established. By having a strain gauge securely bonded on to the surface of the region of interest, the change in electrical resistance will be observed and converted into values of physical displacement at that region. It is normally used for strain not more than 20% [28]. Figure 2.25 shows a strain gauge [29]. The gauge selection process consists of determining the particular operating conditions. And the operating constraints are generally expressed in the form of requirements such as accuracy, test duration, stability, temperature, ease of installation, elongation and environment.

Figure 2.25: Strain Gauge [29].

2.4.2 Speckle-Interferometry

The principle of speckle-interferometry uses the ability of laser light for interference. The object to be analyzed is entirely illuminated with laser light. The

image of the object is recorded by a video camera. The lightwaves which are reflected by single points on the object's surface, interfere and produce a so called speckle pattern (See figure 2.26 for speckle patterns) [30]. This represents the microstructure of the object's surface in combined form. This speckle pattern is superimposed by reference light. The interference between the reference light and the speckle pattern produces a new speckle pattern which defines a position of interest on the object's surface. This speckle pattern is stored in the image processing computer as reference image. When the object is moving, the speckle pattern is changing. By comparison with the reference pattern, correlation fringes are produced which represent the displacement of the object's surface in the measuring direction which is shown in figure 2.27 [30]. Software is employed to analyze and counts these correlation fringes, and transforms them automatically into a quantitative set of deformations or strain data.

Figure 2.26: Speckle Patterns [30].

Figure 2.27: Schematic Diagram of Speckle Interferometry System [30].

2.4.3 Moiré interferometry

Moiré interferometry allows for the detailed measurement of in-plane displacements on a surface. It does this by interrogating an extremely fine diffraction grating attached to a specimen surface with two beams of coherent laser light. The resulting interference pattern is proportional to in-plane displacements. Until recently, these patterns were photographically recorded and analyzed by hand. This typically resulted in information at a few points along lines of interest. Within the last few years, sophisticated digital techniques have been employed that allow for digital analysis of the whole field of recorded data. Techniques using phase-shifting and 2-D Fourier transforms have resulted in enhanced sensitivity as well as full field digital information [31]. Moiré is the generic term for full field measurement techniques, which utilise the interference effect between some form of specimen grating and reference grating to magnify the surface deformations and create a contour map which is related to surface displacement - a moiré fringe pattern or interferogram. For relatively large displacements, mechanical moiré uses the interference of lined gratings to achieve sensitivity of measurement of up to 10 microns. Optical moiré, in which a diffraction grating is illuminated by laser light, increases the sensitivity to sub-micron level, enabling measurement of elastic strains in engineering materials. Figure 2.28 shows an optical moiré interferometry system [32].

Figure 2.28: Schematic Diagram of Moiré Interferometry System [32].

The interferometer is based on four-beam arrangement consisting basically a system of three adjustable mirrors, a light source (Helium Neon laser), beam collimating and imaging optics. After passing through a spatial filter, light from the laser is expanded and collimated using a lens. A crossed-line diffraction grating of frequency 1200 lines/mm is replicated on the specimen and it deforms together with the specimen. To obtain the u -displacement field, half the incident beam B1 impinges directly on the specimen surface while the other half B2 impinges on the mirror M3 and then reflects to the specimen in a symmetrical direction to form a virtual (reference) grating. This virtual grating of frequency twice of the specimen grating, interacts with the vertical set of lines of the specimen grating to form a moiré fringe pattern which is recorded using a CCD camera. Similarly, the virtual grating formed by the mirrors M1 and M2 interacts with the horizontal set of lines of specimen grating to form a fringe pattern from which v -displacement field is depicted.

The displacement maps are obtained using an automated fringe analysis by temporal phase stepping technique which requires five fringe patterns from each field with a constant phase shift. The phase shift is introduced by placing an optical flat into the path of the half of the beam as shown in the figure 2.28. By rotating the optical flat about the diametrical axis of the beam, the path length of the beam travelling through the optical flat can be changed uniformly and thus giving a constant phase shift to the interferogram.

2.4.4 Grid Method

With the grid method, grid line markings are transferred on to the surface of a component and their relative displacements under loading makes the deformation observable. It is a straightforward non-contact optical method for in-plane strain measurements using high-speed camera to view and inspect deformation of plastics. The images captured can be immobilised frame by frame to track the deformation of the material under study. It is extremely useful for measuring deformation under dynamic load. The method includes utilising image-enhancing software to digitise and enhanced the image to measure relative displacement as well as angle of displacement. The method also allows viewing of materials propagating towards fracture, a very vital benefit, in comparison with other optical methods, for differentiating types of failure. Also, for large strain deformation greater than 1mm/mm in most plastics, the grid method can be more attractive than speckle and moiré interferometry methods [33]. Figure 2.29 shows the grid method system.

Figure 2.29: Typical Set Up of Grid Method System.

2.4.5 Comparison of Strain Measurement Techniques

Techniques	It requires laser light for operation.	It measures large strain deformation at 1mm/mm with ease.	It allows viewing of deformation images.	It allows easy set up.	It allows very high accuracy in measurement.	It allows dynamic measurement with ease.
Strain Gauge Method	No	No	No	No	No	No
Speckle Interferometry	Yes	No	No	No	Yes	No
Moiré Interferometry	Yes	No	No	No	Yes	No
Grid Method	No	Yes	Yes	Yes	Acceptable	Yes

Table 2.3: Comparison of Strain Measurement Techniques.

From the comparison study in table 2.3, grid method is the most favourable technique for our application in terms of its ability to measure large strain deformation and dynamic measurement with ease. It is easy to set up and is able to display deformation sequence of the tested specimen. It does not require the use of Laser light which may incur additional costs.

2.5 Types of Load Measurements

Force transducers are devices used for changing force into analog or digital signal suitable for recording or monitoring. The types of force transducers available are spring driven, strain gauges and piezoelectric. Strain gauges type force transducers are the most common. In this chapter, only strain gauge and piezoelectric types are discussed and piezoelectric force transducer will be used in the research.

In recent years, development of fiber optic load cells are gaining attention because of their immunity to electromagnetic and radio frequency interference (EMI/RFI), suitability for use at elevated temperatures, and intrinsically safe nature. One example is measuring forces using the Fiber Bragg Grating (FBG) effect. However, these optical load sensors are still undergoing field trials and it is less suitable for destructive testing. The reason is it requires a fiber optics sensor to be bonded on or embedded in to the subject of study.

2.5.1 Load cell using Strain Gauge Technology

A wide variety of force measurement applications and devices of one kind or another are based on the conventional strain gauge technology that has been the standard for force measurement and control for many years. The concept of using a strain gauge or an element that changes resistance as the surface below it deflects is well established. Figure 2.30 shows a tension type load cell [34].

Figure 2.30: Tension Load Cell [34].

Strain-gage load cells convert the load acting on them into electrical signals. The gauges themselves are bonded onto a beam or structural member that deforms when weight is applied. In most cases, four strain gages are used to obtain maximum sensitivity and temperature compensation. Two of the gauges are usually in tension, and two in compression, and are wired with compensation adjustments. When weight is applied, the strain changes the electrical resistance of the gauges in proportion to the load. But these discrete components have been excluded from many high-accuracy sensors and systems because of limited reliability and repeatability, and difficulty of installation.

Advantages are:

1. It is able to measure static loads
2. It is inexpensive
3. It is built into wide variety of devices
4. It is portable

Disadvantages are:

1. It needs calibration
2. It has limited range
3. It is easily damaged
4. It is sensitive to temperature and pressure

2.5.2 Load cell using Piezoelectric Principle

When small amounts of pressure are applied to a quartz crystal, a piezoelectric substance, a small voltage is produced from the changing charge

created by the moving electrons. The load cell, as shown in figure 2.31 [35], uses quartz that yields an electrical charge when mechanically loaded. In contrast to transducer using strain gauges, no flexing spring element is required. The mechanical stress induced in the quartz measuring element, which can be either tensile or compressive produces the output signal with only minimal mechanical deflection. A very important factor when measuring slow and quasi-static forces. The high rigidity is also important when measuring dynamic forces as it provides for a high natural frequency thus allowing the measurements of very fast force pulse.

Advantages are:

1. It has high rigidity. Very small deflection under high load.
2. It has high natural frequency which allows measurement of forces lasting only microseconds
3. It is tolerant of high overloads
4. It has very fast response time
5. It is small in size
6. It is more accurate
7. It has wide sensitivity range (1 N/V to 10 kN/V)

Disadvantages are:

1. It has voltage drift during static measurements
2. It is expensive and cannot be custom-built
3. It needs a charge amplifier

Figure 2.31: Piezoelectric Load Cell [35].

2.5.3 Comparison of Load Cells

Load Cells	It allows fast response force measurement up to microseconds.	It is miniature in size.	It is able to measures static load.	It is inexpensive.	It allows high accuracy in measurement.	It requires amplifier for data output.
Strain Gauge Type	No	No	Yes	Yes	No	Yes
Piezoelectric Type	Yes	Yes	No	No	Yes	Yes

Table 2.4: Comparison of Load Cells.

From the comparison study in table 2.4, apart from cost and its ability to measure static load, piezoelectric type load cell has more superior characteristics than strain gauge type load cell. Its high response time makes it very appropriate for impact measurement. It is also miniature in size and highly accurate. Hence, piezoelectric type load cell is a more favourable choice.

2.6 Melt Flow Index (MFI)

The testing of the Melt Flow Index (MFI) or Melt Flow Rate (MFR) is the most common quality control flow measurement in the polymer industry. Melt Flow Index measures the mass flow rate of extrusion of thermoplastics through an orifice at a prescribed temperature and load. An Extrusion Plastometer, as shown in figure 2.32 [36], is used. MFI provides a means of measuring flow of a melted material which can be used to differentiate grades, or determine the extent of degradation of the plastic as a result of moulding. Degraded materials would generally flow more as a result of reduced molecular weight, and could exhibit reduced physical properties [37]. Melt flow index can be easily calculated when both melt flow rate of raw resin and shredded moulded part is determined. Typically, a percentage difference is calculated.

The calculation for MFI (%):

$$\text{MFI (\%)} = \frac{\dot{m}_{\text{part}} - \dot{m}_{\text{raw}}}{\dot{m}_{\text{raw}}} \times 100\% \quad (2.1)$$

where $\dot{m}_{\text{part}}$ = melt flow rate of moulded part and $\dot{m}_{\text{raw}}$ = melt flow rate of the raw resin.

Figure 2.32: Schematic Diagram of an Extrusion Plastometer [36].

2.6.1 Test Procedures for MFI

For the measurement of the MFI value, the instrument is pre-heated to a defined temperature. The test sample is filled into the pre-heated measuring chamber, which has a defined inner diameter. The end of the chamber is closed with a standardized nozzle or capillary of 2 mm. The test sample is pre-heated for several minutes, to allow the material to melt. During this period the test chamber is closed with a piston, which gives low pressure on the test material to compress the material and to make sure the test material is air bubble-free during the measurement. After several minutes pre-conditioning, a defined standardized weight is located on top of the piston, to press the test sample through the nozzle at the bottom of the test chamber. The Melt Flow Rate (MFR) describes the amount of test material in grams, which is pressed within 10 minutes through the standardized nozzle. The unit of MFR is grams/10minutes [38]. The process is carried out for both raw resin and moulded part of thermoplastic material and MFI is determined.

2.7 Stress Wave Propagation Under Impact Loading Condition

It is noted that stress wave may contribute to premature failure of material under impact load. The magnitude of stress from the applied load can increase drastically due to the effect of stress wave propagation, thus produce unexpected early failure. The following section will cover the basic principle of stress wave propagation.

Figure 2.33: A uniformly distributed impact load P on an elastic bar [39].

If a uniform elastic bar as shown in figure 2.33 [39] is subjected to a suddenly applied load P distributed uniformly over the free end of the bar, a very thin segment of the bar under the load P is set to motion. The remainder of the bar, remote from the loading, remains undisturbed for some length of finite time. As

time passes, the deformation produced directly under P propagates along the bar in the axial direction in the form of an elastic deformation wave. Behind the wave front the bar is deformed and the particles are in motion. Ahead of the wave front the bar remains undisturbed and at rest. If the length of the bar is relatively large, the time required for the elastic deformation wave front to propagate its full length becomes significant and must be considered.

A one dimensional constant wave propagation velocity c is [39]

$$c = \sqrt{\frac{E}{\rho}} \quad (2.2)$$

where E is the Young's Elastic Modulus and ρ is the density of material.

It should also be noted that when the load P is suddenly applied to the end of the bar, the particles in the thin affected layer will be set into motion with a particle velocity, v , in the direction of the applied force. It is important to recognise that the particle velocity v is different and distinct from the wave propagation velocity c . To illustrate, it may be observed that instead of the suddenly applied compressive load shown in figure 2.33 above, one could have applied a sudden tensile load. In doing so the propagation of a tensile wave front would be initiated and the tensile wave front would propagate along the bar towards the fixed end with velocity c , just as the compressive wave does. However, the particle velocity in the stressed zone for the tensile case is directed away from the fixed end instead of towards the fixed end as in the compressive case. Thus, one may observed that for the case of a compressive stress wave the particle velocity v and wave propagation velocity c are in the same direction, whereas for a tensile stress wave the particle velocity is in the opposite direction to the wave propagation velocity. The particle velocity is expressed as [39],

$$\begin{aligned} v &= \frac{c\sigma}{E} \\ &= \frac{\sigma}{\sqrt{E\rho}} \end{aligned} \quad (2.3)$$

where c is wave propagation velocity, σ is the compressive or tensile stress, E is Young's Elastic Modulus and ρ is the density of the material.

2.7.1 Stress wave behaviour of a bar with one free and fixed end

The bar shown in figure 2.33, which is fixed at one end and subjected to a suddenly applied axial force at the free end, may be analysed in terms of stress wave propagation, as shown in figure 2.34. When the force is first applied, it initiates a compressive stress wave of magnitude $-\sigma$, which propagates along the bar with wave front propagation velocity c towards the fixed end in figure 2.34a. The particle velocity in the compressed zone is v towards the fixed end. The event continues in this way until the compressive wave front strikes the first end at time $t = l/c$ when it reflects from the fixed end as a similar compressive wave of magnitude $-\sigma$ travelling back towards the free end, as shown in figure 2.34c. Thus, in the zone behind the reflected wave front the stress level is -2σ and the particle velocity is zero. When the reflected wave front reaches the free end at time $t = 2l/c$, it is reflected from the free end as a tension wave of magnitude σ leaving a net compressive stress of $-\sigma$ in its wake as it travels again toward the fixed end at $t = 3l/c$, it is reflected as a similar tension wave, as shown in figure 2.34g. At this time the stress magnitude and particle velocity behind the wave front are both zero. When the wave front again reaches the free end at $t = 4l/c$, the whole bar is unstressed and at rest, just as it was prior to the impact. Since the tensile wave front next reflects as a compressive wave of magnitude $-\sigma$ propagating toward the fixed end, the whole cycle is ready to repeat, which it does indefinitely if we have assumed no internal friction damping or energy dissipation in the material. This assumption is, of course, incorrect for any real material [39]. Hence, the higher number of repeated cycles would have smaller effect on the overall stress magnitude in the bar.

For impact test experiments in this research, care has been taken to ensure stress wave does not affect the result of the experiments. Data collection should avoid the early cycles of the wave propagation when at its peak.

Figure 2.34: Propagation and interaction of stress waves in a bar fixed at one end and subjected to an impact load at the free end [39].

Chapter Three

EXPERIMENTAL SET UP

3.1 Impact Test Experiment and Equipment

Tensile impact tests are conducted to investigate if a relationship exists in plastic fracture. To conduct an impact experiment on plastic specimens, a test rig is required to perform a series of tensile tests that is reliable and repeatable. At present, drop test technique is widely used for conducting destructive impact testing on end products. A test rig is built using similar principle and designed and successfully fabricated as shown in figure 3.1. Parts and assembly drawings of test rig are shown in Appendix A.

Figure 3.1: Impact Test Rig.

3.1.1 Working Principle of Impact Test Rig

By manually releasing a sliding load at predetermined height along a rigidly mounted shaft on the structure allowing the load to collide onto an end

clamping plate. The end clamping plate shown in figure 3.2 will transfer the tensile force onto the test specimen until it ruptures. Important considerations in the designing phase include determining the amount of impact force to fracture specimens and ensuring the specimens does not slip of the clamps before fracture. A drop load of 1.5 kg is used at a drop height of 0.4 metres. The impact force calculations are given in Appendix B. The calculated impact velocity is 2.8m/s. Another consideration of the design is that the test rig should include several drop heights for varying the impact velocity. The drop height of the fixed load may contribute to the rate of elongation of the test specimens, which is believed to be a critical factor in deriving failure criterion. The varying height also provides flexibility to fracture other plastics with different fracture toughness. A range of drop heights from 0.3 metres to 0.7 metres can be used. Several advantages of the test rig are that it is specifically designed to cater for mounting of piezoelectric load cell and is able to convey uniaxial load and record specimen information during impact with ease.

Figure 3.2: A Close-up View of the Clamping Set up

A piezoelectric load cell for measuring dynamic tensile force is attached on to the impact test rig for load measurement. The quartz element in the sensor yields an electric charge which is proportional to the force. The charge signal is

fed via a screened cable to a charge amplifier, which converts it into a proportional output voltage. An additional output cable is connected from the charge amplifier to a digital oscilloscope. The oscilloscope displays a full sequence of the impact load behaviour on time domain. The set up is shown in figure 3.3. A typical result of load vs time response curve which is registered by the digital oscilloscope is shown in figure 3.4. Take note that the piezoelectric load cell registers tensile forces as negative signal, compressive forces as positive signal. Thus, the scope registers an inverted load vs time curve. The x-axis represents time at 4×10^{-3} second per division while the y-axis represents load at 50 N per division.

Figure 3.3: Load Measurement Set Up

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Figure 3.4: A Typical Result of Impact Load vs. Time.

The load vs. time response curve can be interpreted as material yields at point of maximum load, starts to deform plastically at the plastic zone and fails at point of fracture load. The response after the fracture event is caused by responses of test specimen and test rig structure after fracture occurred. When the tensile bar specimen underwent tensile fracture, it will exhibit a sudden strain recovery upon snapping (similar to snapping a rubber band). The snapping action will cause a significantly large compressive force (positive signal) to be registered by the load cell and displayed in the oscilloscope. Concurrently, the end clamping plate shown in figure 3.2 will be released from the test rig causing a drop in weight register by the load cell. When the clamping plate hit the bottom platform of the test rig, it will also exhibit small amount of response. Hence, this chain of actions causes oscilloscope to display a damped oscillatory response.

A non-contact optical method, Grid Method, is used to inspect fracture strain of plastics. The method utilises high-speed camera to capture images of the specimen undergoing impact load. Images are then digitised by image capturing and enhancing software, Image-Pro Express, as shown in figure 3.5. The digital images are employed to monitor displacements of the grid lines marked on the

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surface of the specimen. The software enables tracking of relative displacements of the grid lines during impact loading with an option of immobilising at the required frame, allowing measurements of length. The time of occurrence is extremely short. The high-speed camera uses up to a remarkable filming rate of 24.7 nanoseconds per frame to produce a full sequential fracture occurrence of 10 milliseconds, assuming instantaneous velocity before impact is at 2.8m/s. The camera settings were fixed on a resolution at 256 X 64 pixels and a filming rate at 55.5 nanoseconds per frame, satisfying acceptable resolution at high speed. Figure 3.6 shows the set up for strain measurement.

Figure 3.5: Image-Pro Express Software

Figure 3.6: Strain Measurement Set Up.

The impact velocity of the sliding load determined the strain rate of the test specimen. The impact velocity is obtained by observing time taken for the sliding load to travel a distance just before impact. The amount of time is recorded by high-speed camera over a distance of 5.0 mm. In every test, impact velocity is consistently monitored to maintain reliability of the results.

Chapter Four

MATERIAL TESTING ON PC/ABS SPECIMENS

4.1 Test Specimens

Experiments will be conducted on tensile bar specimens.

4.1.1 Preparation of test specimens

PC/ABS is selected for material testing. The dimensions of the test specimen are shown in figure 4.1. They are injection-moulded to 1mm thickness to represent the thickness of most plastic housing. It should be large enough to be adequately held in the clamps.

Figure 4.1: Dimension of Test Specimen with and without notch.

All specimens were moulded with a single gating. Figure 4.2 shows the ejected finished part with single gating which represent a standard test piece.

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Figure 4.2: Specimen with a Single Gating.

4.1.2 Grid Markings on Test Specimen

Grid patterns are marked on to the specimens to monitor displacement when plastic deformed. Figure 4.3 shows the schematic drawing of the test specimen for marking. Figure 4.4 shows lines pattern replicated onto specimen. These stick-on grid lines are evenly spaced at 1mm within the gauge length. Only grid lines of 0.5mm will be used. The figure also shows specimen with various notch diameters. Figures 4.5 shows a typical fracture sequence of a specimen.

Figure 4.3: Test Specimen Markings

Figure 4.4: Specimen with and without notches.

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Figure 4.5: Specimen (a) Before Impact, (b) Just Before Fracture and (c) Fractured.

4.1.3 Number of Test Specimens

In accordance with American National Standard ASTM D638 [40], a minimum of five specimens shall be tested. If the dependence of the measured values on temperature, relative humidity or other parameters is to be determined, five specimens per measurement point are generally sufficient. The test specimens are conditioned in a room maintained at $23 \pm 2^\circ\text{C}$, and 50% relative humidity [40].

4.2 Impact Testing Procedures

At least ten test specimens were used to conduct tensile impact test per measurement point. Each specimen was securely clamped on the test rig and care was taken not to puncture the specimen at the grip before the test was conducted. All devices such as high-speed camera, oscilloscope and charge amplifier, used to capture strain or load data, were either calibrated or conditioned. The strain and impact load data were recorded and tabulated. The impact velocity was monitored to ensure reliability of results. The test was repeated for all specimens.

4.3 Procedures for Determining Strains and Stresses

Usually, when nominal material properties are specified, engineering strain and engineering stress are employed.

Engineering strain [41],

$$\mathcal{E} = \frac{\Delta l}{l_0} \quad (4.1)$$

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where ε is engineering strain, Δl is the change in gauge length under load, and l_o is the original gauge length prior to application of the load.

Engineering stress [41],

$$\sigma = \frac{F}{A_o} \quad (4.2)$$

where σ is engineering stress, F is the applied load, and A_o is the original cross-section area normal to F in a simple tensile test.

4.4 Material testing

In this portion, works were focused on material fracture behaviors. Experiments were conducted on PC/ABS, commonly used in handheld consumer products. PC/ABS, as mentioned in the literature review, has good mechanical and thermal properties such as good impact toughness and ease of processibility. To study PC/ABS fracture behavior, quasi-static test and impact test are carried out to define its characteristics.

4.4.1 Stress Wave Calculation

By using one dimensional constant stress wave propagation velocity formula (2.2) in chapter 2.7, the velocity, c , for PC/ABS thermoplastics is 1291m/s with Young's Modulus at 2×10^9 Pa and density at 1200 kg/m³. From preliminary trial test on impact test rig conducted at impact velocity of 2.8 m/s, the typical time taken for the specimen to fracture was about 0.01sec. At the time of 0.01sec, the stress wave front will have traveled a distance of 12.91m or approximately 50 repeated cycles ($1 \text{ cycle} = 4l$) along the specimen length ($l=0.065\text{m}$) without causing any significant premature failure on specimen. Hence, it shows that stress wave effect does not contribute significantly to the failure of the PC/ABS specimen.

4.4.2 Experimental Observation

In quasi-static test, a rapid local contraction at gauge length was noticed when the specimen reached an initial maximum or yield point. The yield point defined the onset of irreversible plastic deformation. A drop in load is noted directly after yield. Also, local shear banding near the specimen edges began to develop, the cross section of the material rapidly began to thin and exhibit strain localization, quite similar to necking process occurred in metals. The necking process eventually terminated and the local deformation process stabilized. Once the localization stabilized, thinning initiated at the boundaries of the necked area and the area began to grow towards the tensile specimen grips. This process was referred as neck propagation process in the thermoplastics which had differentiated its behaviour from common structural metals. The load continued to rise with larger displacement on the specimen due to strain hardening effect in the thermoplastics until fracture had occurred. Another maximum point, usually higher than yield load was produced and it was known as fracture point. Crazes were noticed at the fracture surfaces. For specimen with notches, the yield behaviour began at the notch tip. The rest of the observation was similar to no-notch specimen. (See appendix D for load-displacement plots for specimens with and without notches.)

In impact test, the observation was conducted with the help of images captured by the high-speed camera. The initial fracture behaviours were similar to quasi-static test except that after the neck propagation process, the load began to decline gradually until fracture. The clamping condition may affect the test and the reasons maybe due to possible losses in the hinge of the clamp and friction between grip and specimen. For specimen with notches, the fracture response noticed was abrupt. The load reaches a peak and decline sharply upon fracture. The yield behaviour initiated at the notch tip and rapid thinning process was noted at the necked area, similar to specimen at quasi-static load. (See appendix D for load-time plots for specimens with and without notches.)

4.4.3 Comparison Between Quasi-static and Impact Tests Results

To begin, a general comparison of PC/ABS between quasi-static and high strain rate uniaxial tests were conducted. For quasi-static test, a universal tensile test machine (Instron Universal Machine) was used to conduct constant strain rate tension on specimen. The velocity was fixed at 1mm/min (approximate strain rate at 0.0014/s) as recommended by ASTM. This test was extremely reliable and effective for capturing load-displacement data and material comparison studies. In our case, the load-displacement data were collected and processed for study of MFI effect on mechanical properties and also for comparison study with impact test. MFI represents the relative amount of degradation of re-melted molded parts from raw resins melt of similar plastics materials via their rate of melt flow. In industry, it is assumed that large MFI percentage denotes larger degradation of plastic from original raw resins.

An impact test rig were designed and fabricated to exhibit similar means of fracture by Instron Universal Machine but at a higher strain rate. It delivers uniaxial load by manually releasing a sliding drop weight along a rigid shaft at a predetermined height. The drop load will transfer impact energy onto one end of tensile bar specimen (the other end is mobilised) causing it to rupture. The impact velocity was set at 2.8m/s, released at an adjustable drop height of 0.4 meters, with a drop load of 1.5kg. These test parameters were calculated in consideration of breaking the specimen in one impact sequence hence it was deliberately overloaded. Details of the setup are mentioned in chapter 3. The strain rate produced depends very much on the response of the material and specimen geometries to be tested.

A series of graphs for quasi-static test and impact test are compiled and displayed in the figures. Information on yield displacement/strain, yield stress, ultimate stress, and fracture displacement/strain, etc is plotted with MFI percentage variation. All data used in this chapter are engineering stress and strain unless specified. A yield point represents the first peak point of the load response curve. It indicates the turning point where material begins to soften after yielding take place. This point is easily extracted for comparison but sometimes, during

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impact testing, yield point is not easily identify. The yield point can be an indication of crazing where visibly a physical color change at the yielded region is observed. An ultimate point refers to the next peak point in the plastic region, usually higher than yield point of the load response curve. It normally took place just before fracture occurs.

A number of 10 specimens were conducted for each MFI value and in each type of test. Specimens with inconsistent or extreme behavior were discarded. A broad range of MFI percentage between 0% and 200% was chosen so as to study the effect of large MFI value towards industry accepted practice of MFI not more than 20%. The reason to select a broad range is to study at what level of MFI the plastic is still acceptable.

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Figure 4.6: Effect of MFI on PCABS at quasi-static and impact tests.

The results from quasi-static test as well as impact test in figure 4.6 did not show any clear distinct pattern of MFI effect on PCABS plastic. However, there are some interesting observations.

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At yield, a slight downward trend is spotted at yield strains of quasi-static test except for MFI at 205%. The high strain rate at impact test reflected higher yield stresses compared to quasi-static test. The yield stresses for both loadings have revealed a slight upward trend with higher MFI values except for MFI at 205%.

The ultimate stress and fracture strain did not reveal any consistent trend. But it has reflected smaller strains for fracture at impact. These suggest premature or more brittle failure when PCABS undergoes high rate of deformation.

The following figure 4.7 will show effects of MFI when results of plastic specimen with MFI at 19.54% are taken as a reference for comparison. An index is used to denote the variation.

$$Index = \frac{P}{P_{MFI19.54\%}} \text{ or } \frac{\delta}{\delta_{MFI19.54\%}}$$

where $P_{MFI19.54\%}$ and $E_{MFI19.54\%}$ are reference load and elongation values at MFI 19.54% respectively, P and δ are load and elongation values at various MFI respectively. The elongation or displacement at MFI 19.54% will be crucial in later stages of work in finite element simulation.

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Figure 4.7: Yield, ultimate and fracture indices.

At yield point, the yield indices for quasi-static and impact are consistently greater than 1. It implies that these yield loads are always higher if MFI exceed reference MFI 19.54%. An increasing trend is noticed on the yield indices with higher MFI except for MFI at 205%. As for yield displacement, the indices for quasi-static are always lower than 1. It shows that yield displacement is lower if the MFI exceeds reference MFI. A decreasing trend is observed with higher MFI values except for 205%.

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The ultimate indices for displacement and load did not reveal any trend in quasi-static test. As for impact test, more displacement at fracture is noticed with higher MFI values. This is an interesting phenomenon that has reversed the effect of MFI at yield.

4.4.4 Notch Effect on Quasi-static and Impact Tests

In fracture mechanics, it is known that presence of notch in plastic specimens would contribute significantly to early failure of plastics when subjected to loading. A small crack or void in plastics would cause severe stress concentration, results in crack propagation and eventually failure. In our case, notches were introduced on PCABS specimens so as to localize the point of fracture during loading. It has allowed a more predictable and a more uniform MFI deformation region. Without notches, specimens may fail at weakest chain or at a defect along the gauge length which may circumvent the true effect of MFI on mechanical properties.

A number of 10 specimens were conducted for each MFI value and in each type of test. Similarly, specimens with inconsistent and extreme behavior were discarded. A range of notch diameter between 1.5mm and 5mm was milled onto the specimens before testing. A cross-section area of 2mm^2 is maintained at the milled region for all notched specimens to maintain consistency and to facilitate comparison. A drop height of 0.1 meter was sufficient to break notched specimens at impact test. Figure 4.8 shows the effect of MFI on yield displacement at quasi-static test for notched specimen.

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Figure 4.8: Effect of MFI on yield displacement at quasi-static test for notched specimen.

In quasi-static tests, for specimen with no notch, a decreasing trend is noticed except for MFI at 205%. The displacement for notch diameters at 2mm and 5mm also share the same behaviour with no notch specimen except for MFI at

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205%. The rest of the notch diameters do not share the same trend. No significant trend can be concluded.

Figure 4.9: Effect of MFI on yield stress at quasi-static test for notched specimen.

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In figure 4.9, the effect of MFI on yield stress at quasi-static test for various notch diameters were plotted. For specimen with no notch, an upward trend is noticed with increasing MFI values. A similar behaviour is reflected in notch diameters of 1.5mm, 3mm and 5mm in exception of MFI at 205%. The rest of the graphs display a different trend. No observable trend is noticed.

Figure 4.10: Effect of MFI on ultimate stress at quasi-static test for notched specimen.

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Figure 4.10 shows the effect of MFI on ultimate stress at quasi-static test. When specimen reaches plasticity region, the ultimate stresses recorded for all specimens did not reveal any significant trend. They appeared very inconsistent and highly unpredictable.

Figure 4.11: Effect of MFI on fracture displacement at quasi-static test for notched specimen.

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In figure 4.11, similarly for fracture displacement, the results for all specimens did not present any trend as they reach plasticity region.

Figure 4.12: Effect of MFI on yield stress at impact test for notched specimen.

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Figure 4.12 shows the effect of MFI on yield stress at impact test. As for impact test study, an increasing trend is noticed for specimen with no notch with the exception of MFI at 205%. The yield stresses at 3mm notched specimens did reveal a small upward trend. The mean results for notch diameter of 5mm also display a similar trend except for MFI 205%. The rest of the graphs did not follow any trend. However, majority of notched specimens yield between 70MPa and 90MPa. These values are higher compared to quasi-static yield stresses which yield between 55MPa and 68MPa.

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Figure 4.13: Effect of MFI on fracture displacement at impact test for notched specimen.

Figure 4.13 shows the effect of MFI on fracture displacement at impact test. Similarly to quasi-static tests, when specimens have reached plasticity region, the fracture displacement for all specimens do not produce any significant trend.

4.4.5 Summary

The results from both tests on notched specimens do not show any clear pattern of MFI effect on PCABS plastic. The results show all notched specimens failed at higher yield stresses in comparison with specimen without notch. High stress concentration on notch tip contributes to early failure of specimens. In quasi-static test, the results show shorter displacement at fracture with smaller notch diameters. Hence, MFI values did not have significant effect on fracture properties of PCABS but it may have some effect on yield point.

4.5 Strain Rates Effect in Impact Tests.

A series of strain rate graphs for impact tests was compiled and displayed for no-notch and notched specimens. The strain rate for quasi-static tests was constant as mentioned earlier in the chapter, hence no strain rate graphs on quasi-static tests are presented.

A sampling size of 3 specimens for each MFI percentage was plotted. For approximate comparison, an average strain rate for the period was used which would be sufficient for our study. Take note that the strain rate graphs may not accurately reflect the physical strain rates experienced by the specimen. The actual rate would always be much higher at the beginning of impact, and then diminish drastically. The calculation for average strain rate is:

$$\text{Average strain rate} = \frac{(\text{Total amount of elongation}/\text{Original length})}{\text{Total time to fracture}}$$

The total amount of elongation and the total time needed to fracture the specimens are obtained from images taken with high-speed camera.

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Figure 4.14: Effect of MFI values on average strain rate at impact tests.

Figure 4.14 shows the effect of MFI values on average strain rate at impact tests. The results had shown that the strain rate of specimens with no notch averaged at between 95/s and 130/s while those with notches experienced much higher average strain rate. By comparing graph to graph on the value of strain rate, the effect of notch size on strain rate can be established as shown in figure 4.15.

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However, as for effect of MFI, these graphs did not reflect any significant trend. They are rather scattered and inconsistent.

Figure 4.15: Effect of notch sizes on average strain rate at impact tests.

A comparison was made with varying notch diameters. The mean values are used to plot the curves. It was clearly established that smaller notch diameters experience higher strain rate. The shape of the curves for all MFI percentage looked similar and consistent.

4.5.1 Summary

The strain rates measured for specimen with no notch are lower than those with notches. There are no significant trend between MFI and average strain rate. It is noted that specimens with smaller notch diameter will undergo higher strain rate at notch region.

Chapter Five

ESTABLISHING FAILURE CRITERIA BY FINITE ELEMENT ANALYSES

5.1 Establish Failure Criteria

This chapter focused on modeling of test specimen and its loading condition using the finite element method (FEM). Works include determining thresholds that indicate failure mode. Only data for industry accepted MFI 19.54% would be used. The loading condition in the analysis is simulated as close as possible to the actual case to minimize error while maintaining reasonable computational time. Information on stresses and strains at fracture site are extracted and compared. All data generated by FEA in chapter 5 and 6 are true stresses and strains.

5.1.1 Quasi-static Loading

A two dimensional 4-noded linear quadrilateral element was chosen to model a plane stress condition on tensile specimen in ABAQUS software. Material constants such as elastic modulus, Poisson ratio, stress-strain curve were obtained from tensile test experiment and plastic manufacturer GE plastics. (See appendix E for PC/ABS true stress-strain curve and its material data) The boundary condition of the model was introduced at one end of the specimen along the edge with constrains of zero translations and rotations so as to prevent the model from moving as a rigid body. The other end of the specimen was specified with a displacement value obtained from quasi-static test in earlier chapter. For FEM models, a structured meshing method with element aspect ratio below 2.5 is used and convergence tests are performed for both specimens with and without notches. In convergence test, the maximum principal stresses/strains and Von Mises stresses at critical location such as the notch where failure occurs are used. The mesh density is increased by approximately 2 times in subsequent re-meshed to capture the high stress concentration region. The criterion is to ensure that the subsequent stress/strain data fell in the range of $\pm 5\%$ tolerance. See table 5.1.

Crack Prediction of Plastic Housing Subjected to Impact Loading

S/No	Mesh Density at Notch	Max Principal Stress (MPa)	% Tolerance (Absolute)	Von Mises Stress (MPa)	% Tolerance (Absolute)	Max Principal Strain (mm/mm)	% Tolerance (Absolute)
1	2 x 2	102.05	-	109.14	-	0.5763	-
2	4 x 4	110.33	8.1	115.18	5.5	0.6002	6.0
3	6 x 6	123.57	12.0	122.23	6.1	0.6502	8.3
4	8 x 8	125.81	1.8	126.79	3.7	0.6833	5.1
5	10 x 10	126.02	0.17	126.61	0.1	0.6802	0.5

Table 5.1: FEA results for 1.5mm notch specimens at quasi-static loading

From the convergence test table above, the 5th results are used since all the data has satisfied the $\pm 5\%$ tolerance criterion.

The number of elements used to satisfy the convergence tests for each specimen varied with notch sizes and is shown in table 5.2.

Notch Diameter	No-notch	1.5mm	2mm	3mm	4mm	5mm
No. of Elements	840	685	693	756	960	1008

Table 5.2: Number of elements used for each notch size in quasi-static test modeling.

From the results in chapter 4, data on fracture displacement at quasi-static test, served as important inputs in ABAQUS to indicate ultimate failure. Stress and strain data such as maximum principal engineering stress, von mises engineering stress, maximum principal engineering strain, maximum logarithmic strain and equivalent plastic true strain (PEEQ) were recorded for each simulation.

PEEQ is a scalar variable that is used to represent material's plastic strain. If the variable is greater than zero, the material has yielded.

$$\text{Plastic strain, } \epsilon_{\text{Plastic}} = \epsilon_{\text{Total}} - \epsilon_{\text{Elastic}} \tag{5.1}$$

Where ϵ_{Total} and $\epsilon_{\text{Elastic}}$ are total true strain and elastic true strain respectively. This formula is obtained from *Abaqus/ Standard Manual*.

In the modeling, only nodal element with the maximum values at fracture point of the model was tabulated. These values would represent the highest limit or threshold to generate material fracture.

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Figure 5.1: FEM model of specimen (no notch) at quasi-static test.

Figure 5.1 shows the deformed shape of an FE model of specimen without notch when it have undergone quasi-static test. From experiment, the fracture displacement is 16.39mm. With a uniform geometry of the model at the gauge length, it has displayed a uniform stress distribution along the gauge length. Figure 5.2 has indicated that the FEM result correlate acceptably well with the experiment in a load-displacement curve.

Figure 5.2: FEM load-displacement curves for tensile specimen at impact test.

For notch specimens, similar element type and boundary conditions were applied with inputs of displacement obtained from earlier experiments. The FE models for various notch sizes are shown in figure 5.3.

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Figure 5.3: FE models of notched specimens at quasi-static loading.

FE models for notched specimen indicate that high stresses have concentrated on elements near the notch tip. Load-displacement curves for these

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notched specimens are plotted and compared with experimental results in figure 5.4. A typical test data for each notch size is used for comparison. Most of the graphs have shown good correlation between FEM and experimental results. In Table 5.3, stress and strain based thresholds at the critical elements where fracture have occurred are tabulated. A failure criteria table for quasi-static loading is formed.

Figure 5.4: An FEM prediction compared with experimental results of quasi-static tests for notch specimens.

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	Displacement	Max Principal Stress (FEM)	Von Mises Stress (FEM)	Max Principal Strain (FEM)	Equivalent Plastic Strain (FEM)	Max Principal Logarithmic Strain (FEM)
Specimen	At Fracture (mm)	(MPa)	(MPa)	(mm/mm)	(mm/mm)	(mm/mm)
No notch	16.39	129.51	129.55	0.6825	0.6829	0.7472
Notch Diameter						
1.5mm	1.59	126.02	126.61	0.6802	0.6835	0.7419
2mm	1.75	125.63	125.53	0.6738	0.6768	0.7361
3mm	2.12	124.69	124.33	0.6710	0.6725	0.7326
4mm	2.47	121.03	120.81	0.6586	0.6597	0.7183
5mm	3.54	120.65	120.20	0.6571	0.6579	0.7070

Table 5.3: Thresholds obtained from quasi-static FEM simulations at fracture displacement.

For specimen with no notch, it is predicted that potential crack could form when one of these threshold parameters is exceeded. These thresholds would be used to predict potential crack on plastic housing surface underwent uniaxial stress state.

The thresholds for various notch diameters are plotted in figure 5.5. A decreasing trend is spotted. These values are well represented by an equation obtained from power curve fitting in the form of $\sigma = Ad^B$ and $\epsilon = Cd^E$ where σ is the element nodal stress variables, ϵ is the element nodal strain variables, d is the notch diameter variable and A , B , C and E are constants. These failure criteria will be used to predict crack on fillet or rounded features with high stress concentration on plastic housing.

Figure 5.5: Failure criteria for specimens with notch at quasi-static test.

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The equations on the graph will represent stress or strain boundaries where crack occur. The stress based failure criteria show very close relationship with each other likewise for PEEQ and max principal strain criteria. As for logarithmic strain, it predicts crack at relatively much higher strain.

5.1.2 Impact Loading

A two dimensional 4-noded linear quadrilateral element was chosen to model a plane stress condition on tensile specimen in impact test. Material constants such as elastic modulus, Poisson ratio, stress-strain curve were similar to the inputs in quasi-static FEM model. (See appendix E for PC/ABS true stress-strain curve and its material data) The boundary condition of the model was introduced at one end of the specimen along the edge with constrains of zero translations and rotations so as to prevent the model from moving as a rigid body. At the other end of the specimen, a simplified 12.5mm by 10mm rectangular part at thickness 1mm was added to simulate as the drop load in the actual impact test. This imposed mass and test specimen were rigidly joined using “node tying” option in Abaqus CAE. The imposed mass was modeled as steel material with Young’s Modulus of 207 GPa and Poisson ratio of 0.3. Its “equivalent density” was $1.2 \times 10^7 \text{ kg/m}^3$ based on the equivalent mass of the 1.5kg drop load and the volume of the imposed mass. A velocity of 2.8m/s was introduced as boundary condition at the rectangular imposed mass to simulate the impact velocity at actual test. For FEM models, a structured meshing method with element aspect ratio below 2.5 was used and convergence tests were performed for both specimens with and without notches. The number of elements used to satisfy the convergence tests for each specimen varied with notch sizes and is shown in Table 5.4.

Notch Diameter	No-notch	1.5mm	2mm	3mm	4mm	5mm
No. of Elements	1428	1852	1852	1844	3366	3366

Table 5.4: Number of elements used for each notch size in impact test modeling.

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Similar to quasi-static case, the purpose is to obtain failure criteria that will determine potential crack. The simplified FE model is shown in figure 5.6. From earlier experiment, the displacement at fracture was 10.29mm. Therefore, stress and strain based thresholds were obtained from element at the fractured displacement.

Figure 5.6: A simplified FEM model of tensile specimen for impact test.

In figure 5.7, a comparison between experiment and FEM result is carried out. In experiment, it indicates a higher load at yield point due to strain rate effect. In the plastic region, the load begins to decline and then fracture. But FEM predicts a gradual increase in load before fracture. As mentioned earlier in chapter 4, the clamping condition will affect the load cell reading and the reason maybe primarily caused by losses at hinges of the clamps and friction at the grips.

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Figure 5.7: FEM load response curves for specimens at impact test.

For notch specimens, similar element type and boundary conditions were employed. Depending on experimental data from earlier chapter, the stresses and strains thresholds were obtained at different displacement length. In figure 5.8, a comparison of specimens with different notch sizes is presented. All these contour plots have indicated that high stress concentrated on notch tip, similarly to quasi-static case.

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Figure 5.8: FE models of notched specimens at impact loading.

Figure 5.9 compares FEM prediction with experimental results for notched specimens. Most of the graphs have shown that the prediction is relatively acceptable up to a time step of 0.001sec. Most of our specimens in experiments fail within 0.0006sec. It means that data will be used from 0 sec to 0.0006 sec.

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The rest of the oscillatory response after 0.0006sec contributed from system vibration is unwanted.

Figure 5.9: An FEM prediction compared with experimental results of impact tests for notch specimens.

In Table 5.5, threshold parameters are extracted at element nodal point on fracture location. For specimen with no notch, it is predicted that potential crack will form when one of these threshold parameters is exceeded. The thresholds will be used to predict potential crack on plastic housing surfaces.

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	Displacement	Max Principal Stress (FEM)	Von Mises Stress (FEM)	Max Principal Strain (FEM)	Equivalent Plastic Strain (FEM)	Max Principal Logarithmic Strain (FEM)
Specimen	At Fracture (mm)	(MPa)	(MPa)	(mm/mm)	(mm/mm)	(mm/mm)
No notch	10.29	146.28	146.14	0.7791	0.7795	0.8521
Notch Diameter						
1.5mm	0.72	139.15	137.95	0.7617	0.7641	0.8308
2mm	0.77	129.68	129.61	0.6845	0.6863	0.7493
3mm	0.72	112.81	111.22	0.5748	0.5762	0.6306
4mm	0.80	107.36	106.01	0.5446	0.5460	0.5978
5mm	0.81	103.40	102.60	0.5255	0.5262	0.5771

Table 5.5: Thresholds obtained from impact FEM simulations at fracture displacement.

Figure 5.10: Failure criteria for specimens with notch at impact test.

The threshold for various notch diameter are plotted in figure 5.10. A decreasing trend is spotted. Similarly to quasi-static case, these values are well represented by an equation from power curve fitting in the form of $\sigma = Ad^B$ and $\epsilon = Cd^E$ where σ is the element nodal stress variables, ϵ is the element nodal strain variables, d is the notch diameter variable and A , B , C and E are constants. These failure criteria will be used to predict crack on fillets or rounded features with high stress concentration on plastic housing.

Theses failure criteria equations generated will represent stress or strain boundaries where crack begins to initiate. Likewise to quasi-static case, the stress based failure criteria show very close relationship with each other as well as for

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PEEQ and max principal strain criteria. Logarithmic strain will be relatively higher.

5.1.3 Dynatup Drop Dart Test

Dynatup test was used for puncture testing of flat plate specimen. The specimen was securely clamped over a clamping ring and a falling dart was activated by a releasing mechanism to deliver impact load onto specimen at a predetermined height. The main difference was the stress state it had delivered. Specimens in Dynatup had undergone multi-axial stress state while those in the above quasi-static and impact tension tests had undergone uniaxial stress state. Although the test was generally carried out at high rates of loading, the response of the specimen could often be quite similar at much slower rates. This test was extremely nonlinear in nature.

The experiment uses injection-moulded PCABS as specimen. The specimen is a 3mm thickness square (100mm length) which is milled with a $\varnothing 30\text{mm}$ hole at a depth of 1.5mm in the center as shown in figure 5.11. The drop height of the dart is raised incrementally until the drop load is sufficient to puncture the specimen. The drop height which is identified as the critical height for failure, and is used to input into FEM modeling as impact velocity to dictate failure of plastic.

Figure 5.11: Dynatup PC/ABS specimen and puncture specimen.

As a result of biaxial symmetric stress, the failure in a puncture test was expected to occur at the point of maximum theoretical stress that was at the centre of the specimen. A punctured specimen is shown in figure 5.11.

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A two dimensional axis-symmetry 4-noded linear quadrilateral element was chosen to model PC/ABS specimen in Dynatup drop dart test. PC/ABS material constants such as elastic modulus, Poisson ratio, stress-strain curve were similar to the inputs in quasi-static and impact FEM model conducted earlier. (See appendix E for PC/ABS true stress-strain curve and its material data). The boundary condition of the model at the specimen clamp ring was modeled with constrains of zero translations and rotations so as to prevent the model from moving as a rigid body. A simplified Ø12.8mm hemispherical part instance was used to simulate the drop dart used in actual test. A “surface to surface” contact interaction option in Abaqus CAE was specified between the interacting surfaces of the dart and the specimen. The contact relationship was assumed frictionless and has allowed finite sliding between contact surfaces’ nodal points and parts separation after contact. The falling dart was modeled as steel material with Young’s Modulus of 207 GPa and Poisson ratio of 0.3. Its “equivalent density” was $9.872 \times 10^6 \text{ kg/m}^3$ based on the equivalent mass of the 5.42kg drop load and the volume of the hemispherical part instance. Velocity inputs depending on the drop height was introduced as boundary condition at the drop dart to simulate the impact velocity at actual test. Similar element type was chosen. A free meshing method with element aspect ratio below 2 was used on the drop dart and the number of elements was 984. As for PC/ABS specimen, a structured meshing method with element aspect ratio below 2 was used. The total number of elements used, varied with drop height and it was shown in Table 5.6. For FE simulation, convergence test was performed and solution did converge.

Drop Height	0.494m	0.504m	0.857m
No. Of Elements	375	584	584

Table 5.6: Number of elements used for each drop height in Dynatup test modeling.

The 2-D axis-symmetry FE model that is used to carry out the numerical analysis is shown in figure 5.12. As seen in the figure, finite element modeled specimen clamp ring as simplified stationary support. This portion of the model

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will become important as the deflection becomes larger and significant yielding occurs near the supports. But in our case, a Ø30mm hole is milled to half the original thickness of the specimen in the center of the specimen that has greatly reduced the amount of slippage at the clamps and unwanted yielding near the support during loading. It helps to promote a relatively more localized yielding at the center of the specimen. During milling of the hole, inherent defects caused by milling and heat generated by the cutter is carefully kept to the minimum.

Figure 5.12: A 2-D axis-symmetry FEM modeling of specimen at Dynatup test.

A series of drop height is conducted in the experiment in seek of the critical height. FE analyses are performed as shown in figure 5.13.

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Figure 5.13: An 180° rotated view of 2-D FEM models at Dynatup test.

In experiment, specimens began to fail at critical height of 0.504m and onwards. Higher drop height had contributed to shorter duration to reach fracture load.

In figure 5.14, FE models have shown good correlation until 8mm deflection, after that, the agreement between model and experiment begins to disappear. The FE model load-displacement behaviour indicates a distinct maximum in its load-displacement curve in contrast to the experiment, which shows a reduction in the load-displacement slope before it reaches maximum. As it is not possible to capture the failure process during experiment, no observation on the process is conducted. However, the disagreement after 8mm deflection may be caused by two dimensional non-uniform stress state of the specimen during loading mentioned in a text by *G. Trantina* and *R.Nimmer* [6]. Because of the 2D non-uniform stress state, yielding and necking do not take place simultaneously as they do in the simple tensile specimen [6].

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Figure 5.14: Load response curves for specimen at Dynatup experiment and FEM simulation.

Assuming the disagreement is small and frictionless interface between dart and specimen contact, the threshold parameters for 3 different drop heights are obtained as seen in Table 5.7. These thresholds are extracted from the critical element at the center of the specimen. Only the thresholds at the critical height of 0.504m are used as failure criterion for multi-axial loading. It would be used to predict potential crack on plastic housing surface loaded at multiaxial stress state.

	Max Principal Stress	Von Mises Stress	Max Principal Strain	PEEQ, Equivalent Plastic Strain	Max Principal Logarithmic Strain
Drop Height (m)	At Peak (MPa)	(MPa)	(mm/mm)	(mm/mm)	(mm/mm)
0.494**	157.43	146.43	0.7713	1.3963	0.8281
0.504	169.59	146.43	1.2712	2.5508	1.3935
0.857	169.47	146.43	1.3680	2.5020	1.4649

** Specimen did not puncture.

Table 5.7: Thresholds obtained from Dynatup FEM simulation.

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5.1.4 Summary

A failure criteria table for uniaxial quasi-static and uniaxial impact for notch and no notch specimens and the multiaxial impact obtain from earlier finite element analyses are generated in Table 5.8. A verification process is conducted in the next chapter using mobile phone housing as a field of study.

			Failure Criteria Obtained From FEM simulation Of Respective Tests For Prediction Of Housing Fracture				
Types Of Loading	Types Of Test	Test Equipments	Max Principal Stress (MPa)	Von Mises Stress (MPa)	Max Principal Strain (mm/mm)	PEEQ, Equivalent Plastic Strain (mm/mm)	Max Principal Logarithmic Strain (mm/mm)
1) Uniaxial	A) Quasi-static	Instron Universal Machine	> 129.51	> 129.55	> 0.6825	> 0.6829	> 0.7472
	B) Quasi-static (with notch)	Instron Universal Machine	> 128.78d ^{-0.0396}	> 129.44d ^{-0.0464}	> 0.6888d ^{-0.0294}	> 0.6931d ^{-0.0326}	> 0.7563d ^{-0.0379}
	C) Tensile Impact	Impact Test Rig	> 146.28	> 146.14	> 0.7791	> 0.7795	> 0.8521
	D) Tensile Impact (With Notch)	Impact Test Rig	> 153.48d ^{-0.2565}	> 152.79d ^{-0.2598}	> 0.8512d ^{-0.3179}	> 0.8543d ^{-0.319}	> 0.9275d ^{-0.3125}
2) Multiaxial	Impact	Dynatup Drop Dart Tester	> 169.59	> 146.43	> 1.2712	> 2.55081	> 1.39353
Legend: d = Notch/Feature Diameter							

Table 5.8: Failure criteria table for PC/ABS housing crack prediction.

Chapter Six

VERIFICATION STUDIES

6.1 Verify Failure Criteria

The works completed in earlier chapter may have provided us with important failure criteria that can be used to predict potential yielding and failure site in FEM model of phone housing. However, in order to correlate the FEM prediction with experiment, the phone housing has to undergo extreme destructive loading in order to produce crack, and that cannot be achieved by merely dropping it from a height. The housing drop on stationary object is determined by the mass of the housing while the impactor drop on housing is determined by the mass of the impactor. From experiments conducted by Motorola on housing with electronics components, it is not easy to have cracks on housing in one drop attempt as the moulding condition of the housing is optimised by Motorola's engineers. In order to quantify the stress/strains level at failure, it makes more academic sense by increasing the mass of drop impactor as well as the drop height to produce crack for verification study. Hence, a repeatable and more reliable approach is to subject the phone housing to spherical or conical impactor testing. As the research core emphasis is on impact studies, only the verification results for impact loading are conducted.

Figure 6.1: Spherical and conical impactors.

Verification tests are conducted with steel impactors as shown in figure 6.1. Spherical and conical steel impactors are used for drops on housing each weighing 314g and 275g respectively. The impactors are allowed to slide in long

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plastic tubing and strike on the predetermined locations of the housing. The friction in the tube is assumed negligible. Hence, impact velocity is calculated using $\sqrt{2gh}$, where g is the gravitational acceleration of 9.81m/s^2 and h is the drop height.

Figure 6.2: Motorola C350 model phone housing.

Motorola C350 model phone housing without content in figure 6.2 is used in our verification study. The material of the empty phone housing is PC/ABS and the thickness of the housing wall is about 1mm. Motorola Electronics has provided both phone housing and mesh for the testing. Three types of load cases are chosen as follows:

- a) Spherical impactor dropped at height 1.5m on housing,
- b) Conical impactor dropped at height 1.5m on housing,
- c) Conical impactor dropped at height 0.8m on housing.

In each load case, two locations are selected for application of loads and they are chosen at the upper end and the lower end of back housing where fillet or rounded features are located. These regions are known to be crack initiation regions when they are mechanically loaded. Various elements on FE model of back housing are studied and will be mentioned later in the chapter.

A three-dimensional 10 noded tetrahedron quadratic element was chosen to model the phone housing. This type of element is geometrically versatile and is used in many automatic-meshing algorithms. It is very convenient to mesh a complex shape with tetrahedral especially parts with round corners. It is suitable for contact analysis as well. PC/ABS material constants such as elastic modulus,

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Poisson ratio, stress-strain curve were similar to the inputs in earlier FEM modeling. (See appendix E for PC/ABS true stress-strain curve and its material data). The total number of elements used to mesh the entire phone housing is 29760. A free meshing method with element average aspect ratio at 2 was used to mesh this complex housing. The phone housing was positioned face down on a stationary rigid surface. The rigid surface was modeled with constraints of zero translations and rotations so as to prevent it from moving. A “surface to surface” contact interaction option in Abaqus CAE was specified between the interacting surfaces of the phone housing and the rigid surface. The contact relationship was assumed frictionless and has allowed finite sliding between contact surfaces elements and parts separation after contact. Similar contact interactions were also introduced at front and back housing contact and also between impactor and back housing interface where collision initiated. There were two types of impactors used in the simulation. The spherical impactor was modeled as a rigid hemispherical surface and the conical impactor was modeled as a rigid cone surface with point mass of 0.314kg and 0.275kg respectively. The dimension of the impactors was shown in figure 6.1. Velocity inputs depending on the drop height was introduced as boundary condition on the impactors to simulate the impact velocity at actual test.

6.1.1 Load case 1 – Spherical impactor dropped at height 1.5m on housing.

a) *Upper end* of back housing.

Three elements on the upper end were selected. A verification study on two Ø4mm fillets at locations symmetry to each other and a surface near the location of impact was conducted, namely critical element A, A' and B respectively as shown in figure 6.3.

By visually comparing the housing with FEM results, the regions that has undergone highest amount of stress (*contour plot in red*) are displayed with visible cracks and distinct strain markings on the actual housing. It is a good correlation between FEM and experimental results.

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Figure 6.3: A correlation result on upper end of back housing (spherical impactor).

The type of loading at element A and A' is identified as multiaxial stress state impact with notch feature, however this type of criterion has not been established. An alternative method is to use uniaxial impact test with notch feature to predict all multiaxial event with notch feature. From the failure criteria table in previous chapter, this uniaxial impact test with notch feature at element A and A' is a type 1D criterion with notch diameter d at 4mm. The respective stress and strain failure criteria are calculated by the given equations and shown in table 6.1.

Failure Criteria For Crack Prediction Of Ø4mm Fillet On Plastic Housing							
Types Of Loading	Types Of Test	Test Equipments	Max Principal Stress (MPa)	Von Mises Stress (MPa)	Max Principal Strain (mm/mm)	PEEQ, Equivalent Plastic Strain (mm/mm)	Max Principal Logarithmic Strain (mm/mm)
1) Uniaxial	D) Tensile Impact (With Notch)	Impact Test Rig	> 107.36	> 106.01	> 0.5448	> 0.5460	> 0.5978

Table 6.1: Failure criteria for fillet diameter 4mm at impact loading.

In figure 6.4, the stress and strain threshold parameters for critical element A were plotted for 5 milliseconds of the impact event. The duration was sufficient for impactor to travel to 0.027m in depth at an impact velocity of 5.42m/s which had exceeded the 0.017m height of phone housing lying face down on a rigid surface. The type 1D failure criteria were also plotted in the figure.

Crack Prediction of Plastic Housing Subjected to Impact Loading

Figure 6.4: Stress and strain threshold parameters of nodal element A (spherical impactor).

Both the max principal stress and Von Mises stress in element A have satisfied the type 1D criterion ($d = 4\text{mm}$) of the failure criteria table at the time step of 2.7 and 3.8 milliseconds respectively. As for the rest of the strain parameters in element A, they are within acceptable region for *no crack*. The tendency of potential crack formation is high if any of the criteria is satisfied. Evidently, it is verified on the *upper end* of back housing at element A location.

As for critical element A' in figure 6.5, the von mises stress threshold has satisfied the type 1D criterion. However, no crack is noticed at the region near element A'. The reason may be due to inaccuracy in positioning the impactor in FE simulation corresponding with the impactor position in actual experiment. It can be also due to non-uniform geometries or non-symmetrical of the plastic housing during fabrication.

Figure 6.5: Stress and strain threshold parameters of nodal element A' (spherical impactor).

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In critical element B, the type of loading is termed as multi-axial impact loading or type 2 criterion of failure criteria table. It is engaged for crack prediction at impact on general housing surface with multi-axial stress state. The stress state at element B is very similar to that at Dynatup drop dart test. The general surface criteria obtained from Dynatup drop dart test are extracted and shown in table 6.2.

Failure Criteria For Crack Prediction Of General Surfaces On Plastic Housing							
Types Of Loading	Types Of Test	Test Equipments	Max Principal Stress (MPa)	Von Mises Stress (MPa)	Max Principal Strain (mm/mm)	PEEQ, Equivalent Plastic Strain (mm/mm)	Max Principal Logarithmic Strain (mm/mm)
2) Multiaxial	Impact	Dynatup Drop Dart Tester	> 169.59	> 146.43	> 1.2712	> 2.55081	> 1.39353

Table 6.2: Failure criteria for general surface undergo impact loading.

Figure 6.6 has shown that the stress and strain parameters do not satisfy any of the failure criteria, therefore no cracks are observed on the *upper end* of back housing at element B location. The prediction is accurate.

Figure 6.6: Stress and strain threshold parameters of nodal element B (spherical impactor).

b) Lower end of back housing.

A verification study is carried out on a Ø3mm fillet on *lower end* of back housing. Crack is present on the fillet of the housing as shown in figure 6.7. In FE simulation, the regions subjected to highest stress were shown in red plots. By observation, the Ø3mm fillet has produced a fine crack. The general surface does not exhibit any crack.

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Figure 6.7: A correlation result on lower end of back housing (spherical impactor).

This type of loading is considered as multiaxial stress state impact with notch feature. However, as mentioned earlier, this type of criterion has not been established. An alternative method is to use uniaxial impact test with notch feature to predict all multiaxial event with notch feature. From the failure criteria table, this uniaxial impact test with notch feature at element C is a type 1D criterion with 3mm notch diameter. Table 6.3 shows type 1D criterion for Ø3mm fillet. The criteria are plotted in figure 6.8 together with stress and strain threshold parameters of critical element C.

Failure Criteria For Crack Prediction Of Ø3mm Fillet On Plastic Housing							
Types Of Loading	Types Of Test	Test Equipments	Max Principal Stress (MPa)	Von Mises Stress (MPa)	Max Principal Strain (mm/mm)	PEEQ, Equivalent Plastic Strain (mm/mm)	Max Principal Logarithmic Strain (mm/mm)
1) Uniaxial	D) Tensile Impact (With Notch)	Impact Test Rig	> 112.81	> 111.22	> 0.5748	> 0.5762	> 0.6306

Table 6.3: Failure criteria for fillet diameter 3mm at impact loading.

Figure 6.8: Stress and strain threshold parameters of nodal element C at lower end of back housing (spherical impactor).

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The stress threshold parameters have satisfied the failure criteria. Once a failure criterion is satisfied, potential crack may occur. It has been verified in figure 6.7 by visual inspection.

The region at critical element D shows substantially high stress which is plotted in red. This type of loading is termed as multi-axial impact loading or type 2 criterion of failure criteria table. It is engaged for crack prediction at impact on general housing surface with multi-axial stress state.

In the actual housing no cracks or strain marks are noticed, nonetheless failure criteria checks are performed. The general surface criteria are shown in earlier table 6.2.

Figure 6.9 has shown that the stress and strain parameters do not satisfied any of the failure criteria, therefore no cracks are observed on the lower end of back housing at element D location. The prediction is accurate.

Figure 6.9: Stress and strain threshold parameters of nodal element D at lower end of back housing (spherical impactor).

It is appropriate to conduct failure criteria checks for all regions that exhibit high stresses or strains, but it is rather time-consuming. For the following load cases, only critical elements that are deemed high potential crack regions will be presented. These regions are clearly exhibited as visible crack and strain marks on actual housing.

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6.1.2 Load case 2 - Conical impactor dropped at height 1.5m on housing,

a) Upper end of back housing.

A verification study on a Ø4mm fillet and a surface near the location of impact was conducted, namely critical element A and B respectively as shown in figure 6.10. Conical impactor was used to deliver a more localised impact load on the housing. Regions underwent high amount of stress were shown in red in the FEM contour plot.

Figure 6.10: A correlation result on upper end of back housing (conical impactor).

For a type 1D criterion of the failure criteria table with notch diameter d at 4mm, the stress and strain failure criteria are similar to load case 1. And they are plotted together with stress and strain distribution of critical element A as shown in figure 6.11.

Figure 6.11: Stress and strain threshold parameters of nodal element A (conical impactor).

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Both Von Mises stress and PEEQ strain parameters have satisfied the potential crack failure criteria. Crack is verified on the actual housing at the Ø4mm fillet.

In critical element B, the type 2 criterion as shown in earlier table 6.2 is employed for crack prediction at impact on general surfaces. By observation, a conical impactor has shown a larger deformation on housing compared to spherical impactor. The strain distribution in figure 6.12 has indicated a slight increase in values compared to element B at load case 1. However, the stress and strain distribution curves of element B still do not satisfy any of the failure criteria, hence no crack will be predicted. It is verified on the actual housing.

Figure 6.12: Stress and strain threshold parameters of nodal element B (conical impactor).

b) Lower end of back housing.

A verification study is conducted on a Ø3mm fillet impacted with a conical impactor. As seen in figure 6.13, the phone housing produces a larger plastic deflection on the point of impact compared to using spherical impactor. Although more plastic deformation is experienced using the conical impactor, no sign of crack is spotted on the surface. Only the Ø3mm fillet does indicate a small crack. The FE simulation has displayed these regions as high stresses.

Crack Prediction of Plastic Housing Subjected to Impact Loading

Figure 6.13: A correlation result on lower end of back housing (conical impactor).

For a type 1D criterion ($d = \text{Ø}3\text{mm}$), both the stress threshold parameters generated from FEM have satisfied their failure criteria respectively as shown in figure 6.14. The strain threshold parameters remained within *no crack* region. Once a failure criterion was satisfied, potential crack will be predicted. It is verified in the actual housing.

Figure 6.14: Stress and strain threshold parameters of nodal element C at lower end of back housing (conical impactor).

6.1.3 Load case 3 - Conical impactor dropped at height 0.8m on housing

a) Upper end of back housing.

A verification study was conducted with the similar conical impactor, except at a lower height of 0.8m. For 5 milliseconds of the impact event, the duration was sufficient for impactor to travel to 0.020m in depth at an impact

Crack Prediction of Plastic Housing Subjected to Impact Loading

velocity of 3.96m/s which had exceeded the 0.017m height of phone housing lying face down on a rigid surface. No crack was detected on the housing except strain markings as shown in figure 6.15. The stress contour plots show these strain markings area in red. Similarly, critical element A and B were selected for examination.

Figure 6.15: A correlation result on *upper end* of back housing (conical impactor at 0.8m).

A type 1D criterion of the failure criteria table with notch diameter d at 4mm is used for element A, the stress and strain failure criteria are plotted in figure 6.16.

Figure 6.16: Stress and strain threshold parameters of nodal element A (conical impactor at 0.8m).

Crack Prediction of Plastic Housing Subjected to Impact Loading

On the housing, element A location does reveal some strain markings but no crack is observed. It is verified with all the stress and strain threshold parameters remain within acceptable *no crack* region.

A type 2 criterion is used to predict crack on element B. The actual housing has indicated visible strain markings with no crack produce. It is verified on figure 6.17 that none of the stress and strain threshold parameters satisfied the failure criteria.

Figure 6.17: Stress and strain threshold parameters of nodal element B (conical impactor at 0.8m).

b) Lower end of back housing.

A verification study of back housing on a Ø3mm fillet were conducted at a lower drop height of 0.8m. Little plastic deformation and no crack were observed as shown in figure 6.18. Strain markings were spotted on the fillet. The FE simulation had displayed these regions as moderate stress regions in green.

Crack Prediction of Plastic Housing Subjected to Impact Loading

Figure 6.18: A correlation result on *lower end* of back housing (conical impactor at 0.8m).

For a type 1D criterion ($d = \text{Ø}3\text{mm}$), both the stress and strain threshold parameters from FEM results has remained within *no crack* region in figure 6.19. Hence, no crack will be predicted at this load case. It is verified in the actual housing.

Figure 6.19: Stress and strain threshold parameters of nodal element C at lower end of back housing (conical impactor at 0.8m).

Crack Prediction of Plastic Housing Subjected to Impact Loading

6.1.4 Summary

A summarised table in table 6.4 is used to reveal the verification results of the load cases conducted. It has shown a highly accurate correlation between FEM prediction and experimental results for all load cases. The verification study has proven that wherever there are failure criteria being satisfied in an element, most likely crack may form.

Load Case	Location Of Impact	Impactor	Drop Height	Critical Element	No. of Failure Criteria Satisfied (Total 5)	Crack Detected On Actual Housing	Prediction
1a	Upper End	Spherical	1.5m	A	2	Yes	Accurate
	Upper End	Spherical	1.5m	A'	1	No	Inaccurate
	Upper End	Spherical	1.5m	B	0	No	Accurate
1b	Lower End	Spherical	1.5m	C	2	Yes	Accurate
	Lower End	Spherical	1.5m	D	0	No	Accurate
2a	Upper End	Conical	1.5m	A	1	Yes	Accurate
	Upper End	Conical	1.5m	B	0	No	Accurate
2b	Lower End	Conical	1.5m	C	2	Yes	Accurate
3a	Upper End	Conical	0.8m	A	0	No	Accurate
	Upper End	Conical	0.8m	B	0	No	Accurate
3b	Lower End	Conical	0.8m	C	0	No	Accurate

Table 6.4: Summarised results of verification study.

Chapter Seven

CONCLUSION

The impact test rig has successfully generated tensile impact failure consistently onto plastic specimen. During load measurements, the integrated piezoelectric load cell is able to obtain impact load measurements at extremely fast response. The grid method is able to record fracture displacements for material with large plastic deformation as well as at high strain rate.

For specimen with no notch, experiments conducted on PC/ABS plastic materials have generally shown higher yield stress and lower yield strains at impact compared to quasi-static loading. For effect of MFI on yield and fracture behaviours, no observable trend is noticed.

Comparing quasi-static and impact tests, notch specimens at yield do show higher stresses in comparison with specimen without notch. It is noted that strain rate is higher in notch specimens and gets higher when notch diameters become smaller. As for effects of MFI on yield and fracture behaviours, they do not show significant effects on properties of PC/ABS.

An effective methodology is established to predict potential crack on plastic housing under impact loading. The methodology mainly comprises extracting threshold values from FEA results of the specimens to directly function as failure criteria. Both uniaxial and multi-axial failure thresholds are tabulated. The criteria are successfully verified by conducting correlation studies between actual mobile phone housing and FEM models of the housing subjected to drop mass collision. Prediction applied to different load cases and different impact locations such as housing surfaces and fillets, have shown good agreement with failure criteria. The prediction is tested on 1mm thickness plastic housing only.

Chapter Eight

FUTURE WORKS

Future works include:

1. Conduct experiments on different thickness specimens so that failure criteria established can be extended to plastic housing other than 1mm thickness.
2. Apply crack prediction methodology to different materials other than PC/ABS.
3. Expand the application of failure criteria to other loading conditions such as product drop at different orientations.
4. Study the effect of mesh qualities of plastic housing such as mesh density, mesh distortion and element aspect ratio etc. on housing crack prediction.

REFERENCES

- [1] S. Goyal, S. Upasani, D. M. Patel, (1999), "Improving impact tolerance of portable electronic products: case study of cellular phones", *Experimental Mechanics*, vol 39 pp. 43-52.
- [2] Cracknell, P. S., (1993), "Handbook of thermoplastics injection mould design by P.S. Cracknell", London : Blackie Academic & Professional.
- [3] Whelan, A. (Anthony), 1937, "Injection moulding machines", London : Elsevier Applied Science.
- [4] Pye, R. G. W. (Ronald George William), "Injection mould design : a textbook for the novice and a design manual", 4th ed., Harlow : Longman Scientific & Technical in association.
- [5] Günter Mennig, (1998), "Mold-making handbook, 2nd ed., Munich: Hanser Publishers, Cincinnati: Hanser/Gardner Publications.
- [6] G. Trantina, r. Nimmer, (1994), "Structural analysis of thermoplastic components", McGraw-hill, Inc, pp.31-68.
- [7] J.P.F. Inberge, (2001), "Fracture of polycarbonate/ABS blends", Thesis, pp.1-2.
- [8] Egor P. POPOV, (1999), "Engineering mechanics of solids", Prentice Hall International, Inc., pp. 74-75.
- [9] V. Koutsos, (2002) " Introduction to polymer", The University of Edinburgh, Division of Engineering, Materials Science and Engineering, website <http://www.cmse.ed.ac.uk/MSE3/Topics/MSE3-polymers.pdf>
- [10] The Dow Chemical Company, (1995-2003), "Typical characteristics – PP vs ETP" <http://www.dow.com/polyolefins/about/pptechctr/primer/etp.htm>
- [11] Irving H. Shames, Francis A. Cozzarelli, "Elastic and Inelastic stress analysis", (1997), Taylor & Francis, Chap 8, pp. 248-319.
- [12] G. Menges, H. E. Boden, (1986), "Deformation and failure of thermoplastics on impact", *Failure of Plastics*, Hanser Publishers, Chap 9, pp. 169-195.
- [13] General Electric (GE) Company, (1997-2001) "Impact Testing", website <http://www.geplastics.com.hk/hkenglish/devprod/impactt.html>.
- [14] Ward, I. M., (1993), "An Introduction to the Mechanical Properties of Solid Polymers", Wiley.
- [15] GE Plastic, Cyclooy Thermoplastics alloy, product specifications, <http://www.geplastics.com.hk/hkenglish/global/pdf/product/europe/cyloyeng.pdf>

- [16] British Standard, (1999), "Pastics-Verification of pendulum impact-testing-Charpy, Izod and tensile impact-testing", BS ISO 13802:1999, pp.12.
- [17] GE plastics, Lexan (Polycarbonate) resin general purpose grades typical property values, product specifications manual, pp.6
- [18] Qualitest Mechanical Testing Systems, (1999-2002), "Gardner impact tester model IG-1140", website <http://www.qualitest-inc.com/gardner.htm>.
- [19] GE Plastics, Technical Research, design guide, Structural foam design and processing, Mechanical Impact Strength, <http://www.geplastics.com.hk/hkenglish/techsolution/structfoamDesign/properties/>
- [20] University of Illinois at urbana-champaign, college of engineering, http://www.tam.uiuc.edu/courses/TAM224/Lab_manual/09_impact+fracture.pdf
- [21] M. C. Cheres, S. McMichael, (1987), "Instrumented impact test data interpretation", Instrumented impact testing of plastic and composite Material, ASTM STP 936, Philadelphia, pp. 9-23.
- [22] S. N. Kakarala, J. L. Roche, (1987), "Experimental Comparison of several impact test methods", Instrumented impact testing of plastic and composite Material, ASTM STP 936, Philadelphia, pp. 144-162.
- [23] University of Virginia, Dept. of Materials Science and Engineering, "Introduction to Materials Science, Failure", Website <http://www.people.virginia.edu/~lz2n/mse209>.
- [24] The Dow Chemical Company, (1995-2002), "Technical Support-Mechanical Properties", Website <http://www.dow.com/engineeringplastics/tech/guide/display.htm>.
- [25] G. Trantina, r. Nimmer, (1994), "Structural analysis of thermoplastic components", McGraw-hill, Inc, pp.151-236.
- [26] Jonas A. Zukas, et al, "Impact Dynamics", (1982), John Wiley & Sons, Chap 8, pp. 277-328.
- [27] Shiro Matsuoka, "Relaxation Phenomena in polymers", (1992), Hanser Publishers, Chap 3, pp. 80-141.
- [28] R. Rotinat, R. Tie bi, V.Valle, J.-C.Dupre, (2001), "Three optical procedures for local large-strain measurement, Journal of Strain, vol 37, pp.89-98.
- [29] National Instruments, (2002), "Strain Gauges", Website <http://zone.ni.com/devzone/conceptd.nsf>.

- [30] Andreas ETTEMEYER, (1997), "Literature on speckle-interferometry", Dr. Ettemeyer Gmbh & Co., pp. 161-162.
- [31] B. Han, D. Post, P. Ifju, (2001), "Moiré interferometry for engineering mechanics: current practices and future developments", Journal of strain analysis, vol 36, pp. 101-117.
- [32] Dr. Salih Gungor, (2001), "Moiré interferometry for stress analysis", Department of Engineering Science, University of Oxford, website <http://www.eng.ox.ac.uk/~ftgwww/SGresearch.html>.
- [33] S. barone, M. Berghini, L Bertini, (2001), "Grid pattern for in-plane strain measurements by dgital image processing", Journal of strain analysis, vol 36, pp.51-59.
- [34] RDP Electronics Ltd, "Strain gauge load cells", Website <http://www.rdpe.com/load/31.htm>
- [35] Kistler, " Products-force sensor", http://www.kistler.com/web/kistler_portal.nsf.
- [36] Christien-Albrechts-University of Kiel, Faculty of Engineering, "Test Conditions For Extrusion Plastometer", Website <http://www.tf.uni-kiel.de/matwis/matv>
- [37] Plastics Technology Laboratories, Inc., "Melt flow index", Website <http://www.ptli.com/testlopedia/tests/mfi-D1238melt.asp>
- [38] General Electric Company, (1997-2002), "Physical testing- Melt Mass-Flow Rate/Melt Volume-Flow Rate ASTM D 1238 (ISO 1133)", GE Plastics, Website <http://www.geplastics.com.hk/hkenglish/devprod/physicalt.html>
- [39] Jack A. Collins, "Failure of materials in Mechanical design", (1993), John Wiley & Sons, Chap 15, pp.526-582.
- [40] Annual book of ASTM Standard, "Standard test method for tensile properties of rigid plastics", (1996), D638, Vol. 08.01.
- [41] Jack A. COLLINS, (1993), "Failure of materials in mechanical design", John Wiley & Sons, Chap 5, pp. 112-139.
- [42] The Dow Chemical Company, (1995-2002), "Technical support-designing with thermoplastic-mechanical properties", Website <http://www.dow.com/engineeringplastics/>

Appendix A

(Parts and Assembly Drawings For Impact Test Rig)

ITEM	DRAWING NO	DESCRIPTIONS	MATERIALS	QUANTITY
01	02-DROPTTEST-01	SLIDING SHAFT	STAINLESS STEEL	01
02	02-DROPTTEST-02	FIXED CLAMP JAW	STAINLESS STEEL	01
03	02-DROPTTEST-03	MOVEABLE CLAMP JAW	STAINLESS STEEL	02
04	02-DROPTTEST-04	GUIDING ROD	STAINLESS STEEL	03
05	02-DROPTTEST-05	BASE CLAMP	STAINLESS STEEL	01
06	02-DROPTTEST-06	LOAD CELL MOUNTING	STAINLESS STEEL	01
07	02-DROPTTEST-07	CIRCULAR BRACKET	STAINLESS STEEL	01
08	02-DROPTTEST-08	FRAME	STAINLESS STEEL	01
09	02-DROPTTEST-09	LOAD CELL	STAINLESS STEEL	01
10	02-DROPTTEST-10	ROD INSERT	STAINLESS STEEL	01

MANYANG TECHNOLOGICAL UNIVERSITY

TITLE: DROP TEST ASSEMBLY	DRAWN: FREDDY TEO
GEN TOLERANCE +/- 0.1	DATE: 04/02/02
ANG TOLERANCE +/- 0.5DEG	SCALE:
	PROJ: THIRD ANGLE
	MATL: STAINLESS STEEL
	ALL DIMENSIONS IN MM

NOTE: Part 01 And Part 07 Are To Be Welded Together.

NANYANG TECHNOLOGICAL UNIVERSITY			
TITLE: DROPTTEST - XSECTION		DRAWN: FREDDY TEO	
DRW NO: 02-DROPTTEST-00		DATE: 04/02/02	
MATL: STAINLESS STEEL		PROJ: THIRD ANGLE	ALL DIMENSIONS IN MM

SCALE 0.150

NANYANG TECHNOLOGICAL UNIVERSITY			
TITLE: DROPTTEST ASSEMBLY		DRAWN: FREDDY TEO	
DRW NO: 02-DROPTTEST-00		DATE: 04/02/02	
MAYL: STAINLESS STEEL		PROJ: THIRD ANGLE	
GEN TOLERANCE +/- 0.1		SCALE:	
ANG TOLERANCE +/- 0.5DEG		ALL DIMENSIONS IN MM

SCALE 0.800

NOTE: Part 01 And Part 07 Are To Be Welded Together

NANYANG TECHNOLOGICAL UNIVERSITY			
TITLE: SLIDING SHAFT		DRAWN: FREDDY TEO	
GEN TOLERANCE ± 0.1	DRW NO: 02-DROPTTEST-01	SCALE:	DATE: 04/02/02
ANG TOLERANCE $\pm 0.5\text{DEG}$	MATL: STAINLESS STEEL	PROJ: THIRD ANGLE	ALL DIMENSIONS IN MM

SCALE 1.000

SCALE 2.000

MANYANG TECHNOLOGICAL UNIVERSITY			
TITLE: FIXED CLAMPED JAW	DRAWN: FREDDY TEO		
DRW NO: 02-DROPTTEST-02	SCALE: DATE: 04/02/02		
MATL: STAINLESS STEEL	PROJ: THIRD ANGLE	ALL DIMENSIONS IN MM	

M6 THREADED HOLE THRU

KNURLING AREA 15 X 13 MM

R7.500

SCALE 3.000

SCALE 2.000

NANYANG TECHNOLOGICAL UNIVERSITY			
TITLE:	MOVEABLE CLAMP JAW	DRAWN:	FREDDY TEO
GEN TOLERANCE	+/- 0.1	DRW NO:	02-DROPTST-03
ANG TOLERANCE	+/- 0.5DEG	MATL:	STAINLESS STEEL
		PROJ:	THIRD ANGLE
			ALL DIMENSIONS IN MM

SCALE 1.000

SCALE 4.000

M3 EXT THREAD X DEPTH 5 MM

MANYANG TECHNOLOGICAL UNIVERSITY			
TITLE: GUIDING ROD		DRAWN: FREDDY TEO	
GEN TOLERANCE +/- 0.1	DRW NO: 02-DROPTST-04	SCALE:	DATE: 04/02/02
ANG TOLERANCE +/- 0.5DEG	MATL: STAINLESS STEEL	PROJ: THIRD ANGLE	ALL DIMENSIONS IN MM

KNURLING AREA 15 X 15 MM

SCALE 0.500

NANYANG TECHNOLOGICAL UNIVERSITY			
TITLE: BASE CLAMP	DRAWN: FREDDY TEO	DATE: 04/02/02	ALL DIMENSIONS IN MM
GEN TOLERANCE +/- 0.1	DRW NO: 02-DROPTST-05	SCALE:	PROJ: THIRD ANGLE
ANG TOLERANCE +/- 0.5DEG	MATL: STAINLESS STEEL		

SCALE 0.800

NANYANG TECHNOLOGICAL UNIVERSITY			
TITLE: LOAD CELL MOUNTING		DRAWN: FREDDY TEO	
GEN TOLERANCE +/- 0.1		DATE: 04/02/02	
ANG TOLERANCE +/- 0.5DEG		SCALE:	
		PROJ: THIRD ANGLE	
		MATL: STAINLESS STEEL	
		ALL DIMENSIONS IN MM

SCALE 0.800

Note: Part 01 And Part 07 Are
To Be Welded Together

NANYANG TECHNOLOGICAL UNIVERSITY			
TITLE: CIRCULAR BRACKET		DRAWN: FREDDY TEO	
GEN TOLERANCE +/- 0.1		DATE: 04/02/02	
ANG TOLERANCE +/- 0.5DEG		PROJ: THIRD ANGLE	
		MATL: STAINLESS STEEL	
		ALL DIMENSIONS IN MM

Note: All Joints Are To Be Arc-Welded.

NANYANG TECHNOLOGICAL UNIVERSITY			
TITLE: FRAME		DRAWN: FREDDY TEO	
GEN TOLERANCE +/- 0.1		SCALE: DATE: 04/02/02	
ANG TOLERANCE +/- 0.5DEG		PROJ: THIRD ANGLE ALL DIMENSIONS IN MM

$\varnothing 11.000$

2 X M5 Threaded Holes X Depth 15 MM

SCALE 4.000

SCALE 4.000

NANYANG TECHNOLOGICAL UNIVERSITY			
TITLE:	LOAD CELL	DRAWN:	FREDDY TEO
GEN TOLERANCE	± 0.1	DRW NO:	02-DROTEST-09
ANG TOLERANCE	$\pm 0.5\text{DEG}$	MATL:	STAINLESS STEEL
		SCALE:	DATE: 04/02/02
		PROJ:	THIRD ANGLE
			ALL DIMENSIONS IN MM

SCALE 2.000

SCALE 3.000

NANYANG TECHNOLOGICAL UNIVERSITY			
TITLE: ROD INSERT	DRAWN: FREDDY TEO		
GEN TOLERANCE +/- 0.1	DRW NO: 02-DROPTST-10	SCALE:	DATE: 04/02/02
ANG TOLERANCE +/- 0.50DEG	MATL: STAINLESS STEEL	PROJ: THIRD ANGLE	ALL DIMENSIONS IN MM

Appendix B

(Impact Force Calculations)

Plastic Housing Crack Prediction - Appendix B

Impact Force Calculations

Estimation of impact load requires for impact test rig.

Assumptions:

- 1) Materials behave elastically, and no dissipation of energy takes place at the point of impact or at the supports due to local inelastic deformation of materials.
- 2) The inertia of a system resisting an impact may be neglected.
- 3) The deflection of a system is directly proportional to the magnitude of the applied force whether a force is dynamically or statically applied.
- 4) Using principle of conservation of energy, at the instant a moving load is stopped, its kinetic energy is completely transformed into the internal strain energy of the resisting system.

Drawings not to scale.

Figure A1: Schematic Diagram of Impact Test Rig

Criterion:

-To deliver an impact load that will exceed fracture stress of plastic at static load.

To estimate the dynamic load that is adequate to fracture plastic specimen, a drop load of 1.5 kg is used. Material properties manual from General Electric (GE) Plastic, using polycarbonate, tensile yield stress is, $\sigma_{\text{yield}} = 60\text{Mpa}$, specimen length is, $L = 35\text{mm}$ and elastic modulus is, $E_{\text{specimen}} = 2.1\text{GPa}$. Steel cylinder with elastic modulus, $E_{\text{cylinder}} = 200\text{GPa}$, is used.

(Formulas taken from Egor P. POPOV, "Engineering Mechanics of Solids", pp.116-119)

Appendix C

(PC/ABS Moulding And MFI Test Report)

Temp	
A: 270	MFI must pass
B: 295	
C: 305	
D: 315	
E: 325	
F: 335	

Using Cicoloy C1200MO-GY4496
Fully opened runner for all the above temperatures.
Use whole sample (long & short test bar) for MFI
All using same molding parameter(P1 please record)
Cycle time 40sec.
submit 200 shots to Motorola, 50 shots to do MFI

A

BANSHING INDUSTRIAL CO., PTE LTD

Specimen A

MOULD TESTING REPORT

JOB NO

CUSTOMER :	MOTOROLA - S	PART DESCRIPTION :	TEST BAR
PROGRAM :	-	MATERIALS :	PC+ABS CYCLODY
PART NO. :	N/A	LOT NO. :	
TOOLING NO. :	2781	MFI REPORT :	% TEST :
MACHINE TONNAGE :	40	MACHINE NO. :	41
TOOLING TEST :	T1/T2/T3/T4/T5	CAVITY NO. :	
DATE :	27/12/02		1+1

PROBLEM ENCOUNTER

- 1) TOOLING INSERT PROBLEM
- 2) POOR POLISH [CAV . CORE]
- 3) POOR FINISH / TEXTURE
- 4) PART STUCK / DRAG [CAV . CORE]
- 5) RUNNER STUCK [CAV . CORE]
- 6) DRAG MARK [CAV . CORE]
- 7) GATING HIGH / POOR GATING
- 8) WARPAGE
- 9) SHORT MOULDING
- 10) AIR TRAP [CAV . CORE]
- 11) BURN MARK
- 12) FLASHES / BURRS
- 13) EJECTION STRESS MARK
- 14) COOLING LEAKAGE [CAV . CORE]
- 15) SINK MARK
- 16) SILVER STREAK
- 17) FLOW MARK / LINE
- 18) BUBBLE
- 19) WELD LINE / PARTING LINE
- 20) EJECTOR MARK / BROKEN PIN
- 21) OTHERS

PART WEIGHT / PC [gm]	short 0.65	long 0.70
RUNNER WEIGHT [gm]	2.27	
TOTAL WEIGHT [gm]	3.62	

TOOLING TEST REQUIRED ☐ OK ☐ MOD ☐ REPAIR

REMARKS :

WATER CHANNEL

CORE SIDE

CAVITY SIDE

TEMPERATURE	°C	MOLD HEATER [1][2][3][4]							
		NOZZLE				270			
		HEATER 1				270			
		HEATER 2				270			
		HEATER 3				240			
		HEATER 4				-			
		HOPPER / DEHUMIDIFIER				104			
		MOULD CAVITY [HOT]				No COOLING			
PRESSURE	KG/CM	MOULD CORE [HOT]				WATER			
		1ST INJECTION	P1			68	% / bar		
		2ND INJECTION	P2			40	%		
		3RD INJECTION				-	%		
		4TH INJECTION (HOLDING)	P3			30	%		
		5TH INJECTION (HOLDING)				-	%		
		PACK [M/C : 24 / 25 / 26 / 15]				-	sec	-	
		HOLDING [M/C : 24 / 25 / 26 / 15]				-	sec	-	
TIMER	SEC	SCREW BACK	ON	OFF		10	kmf / cm2		
		INJECTION TIME				3			
		FULL TIME				1.17 - 1.21			
		HOLDING	TP 2			0.8			
		CURING				31			
		INTERVAL / AIR BLOW	ON	OFF	(2)	-	(3)	-	
		EJECTOR COUNT				1			
		EJECTOR HOLD			(4)	0.5	(8)	1	
VELOCITY & STROKE	POSITION	TOTAL CYCLE				40			
		1ST INJECTION	V-1 / S-1		V%	10	S (mm)		
		2ND INJECTION	V-2 / S-2			6	20		
		3RD INJECTION	V-3 / S-3			22	12		
		4TH INJECTION	V-4 / S-4			30	10		
		5TH INJECTION	V-5 / S-5			50	9		
		MOULD OPENING				8	20%	35%	
		MOULD OPENING	M/C : 24 / 25 / 26 / 15		mm		mm	mm	
VELOCITY & STROKE	SPEED	MOULD CLOSING				45	45%		
		MOULD CLOSING	M/C : 24 / 25 / 26 / 15		mm		mm	mm	
		EJECTOR ADVANCE / RETRACT				12%	60%	4mm	
		MOULD CLAMPING (MAX)				99	%		
		XFER [M/C : 24 / 25 / 26 / 15] mm				-			
		SCREW REVOLUTION	RPM			35	%		
		MATERIAL FEEDING	SM			25	mm		
		SCREW DECOMPRESS	SD			2	mm		
VELOCITY & STROKE	SPEED	CUSHION				4.54 - 6.02	mm		

NO OF MOLD PLATE : ☒ 2 ☐ 3 ☐ 4 M/C OPEN SI ☐ mmTOOLING SIZE [mm] : L W H

TEST BY :		TIME	10 gm
PREPARED BY :	Ken	DATE	27/12

NOTE : KINDLY ADHERE TO ABOVE PARAMETER SETTINGS

A) 1 MP a = 10 . 2 kgf / cm2

B) 1 kN = 0. 102 tonf = 102 . 0 kgf

LETLET 9/2002

Specimen B

BANSHING INDUSTRIAL CO., PTE LTD

MOULD TESTING REPORT

JOB NO

CUSTOMER :	MOTOROLA - S	PART DESCRIPTION :	TEST BAR
PROGRAM :	-	MATERIALS :	PC+ABS CYCLOLOY
PART NO. :	N/A	LOT NO. :	
TOOLING NO. :	2781	MFI REPORT :	% TEST :
MACHINE TONNAGE :	40	MACHINE NO. :	41
TOOLING TEST :	T1/T2/T3/T4/T5	CAVITY NO. :	
DATE :	30/12/02		1+1

PROBLEM ENCOUNTER

- 1) TOOLING INSERT PROBLEM
- 2) POOR POLISH [CAV. CORE]
- 3) POOR FINISH / TEXTURE
- 4) PART STUCK / DRAG [CAV. CORE]
- 5) RUNNER STUCK [CAV. CORE]
- 6) DRAG MARK [CAV. CORE]
- 7) GATING HIGH / POOR GATING
- 8) WARPAGE
- 9) SHORT MOULDING
- 10) AIR TRAP [CAV. CORE]
- 11) BURN MARK
- 12) FLASHES / BURRS
- 13) EJECTION STRESS MARK
- 14) COOLING LEAKAGE [CAV. CORE]
- 15) SINK MARK
- 16) SILVER STREAK
- 17) FLOW MARK / LINE
- 18) BUBBLE
- 19) WELD LINE / PARTING LINE
- 20) EJECTOR MARK / BROKEN PIN
- 21) OTHERS

PART WEIGHT / PC [gm]	0.65	0.70
RUNNER WEIGHT [gm]	2.27	
TOTAL WEIGHT [gm]	3.62	

TOOLING TEST REQUIRED ☐ OK ☐ MOD ☐ REPAIR

REMARKS :

WATER CHANNEL

CORE SIDE

CAVITY SIDE

A) 1 MPa = 10.2 kgf / cm²

LET1ET 8/2002

B) 1 kN = 0.102 tonf = 102.0 kgf

NOTE : KINDLY ADHERE TO ABOVE PARAMETER SETTINGS

TEMPERATURE °C	MOLD HEATER [1][2][3][4]	-	-	-	-
	NOZZLE	295			
	HEATER 1	295			
	HEATER 2	295			
	HEATER 3	240			
	HEATER 4	-			
	HOPPER / DEHUMIDIFIER	104			
	MOULD CAVITY [HOT]	No COOLING			
MOULD CORE [HOT]	WATER				
PRESSURE KG/CM	1ST INJECTION P1	68	% / bar		
	2ND INJECTION P2	40	%		
	3RD INJECTION	-	%		
	4TH INJECTION (HOLDING) P3	30	%		
	5TH INJECTION (HOLDING)	-	%		
	PACK [M/C : 24 / 25 / 26 / 15]	-	sec	-	
HOLDING [M/C : 24 / 25 / 26 / 15]	-	sec	-		
SCREW BACK	ON	OFF	10	kmf / cm ²	
TIMER SEC	INJECTION TIME	3			
	FULL TIME	1.17 - 1.21			
	HOLDING TP 2	0.8			
	CURING	31			
	INTERVAL / AIR BLOW	ON	OFF	(2) -	(3) -
	EJECTOR COUNT	1			
	EJECTOR HOLD	(4) 0.5	(8) 1		
	TOTAL CYCLE	40			
VELOCITY & STROKE POSITION		V%	S (mm)		
	1ST INJECTION V-1 / S-1	10	24.5		
	2ND INJECTION V-2 / S-2	6	20		
	3RD INJECTION V-3 / S-3	22	12		
	4TH INJECTION V-4 / S-4	30	10		
	5TH INJECTION V-5 / S-5	50	9		
	MOULD OPENING	8	20 %	35 %	
	MOULD OPENING M/C : 24 / 25 / 26 / 15	mm	mm	mm	
	MOULD CLOSING	45 %	45 %		
	MOULD CLOSING M/C : 24 / 25 / 26 / 15	mm	mm	mm	
	EJECTOR ADVANCE / RETRACT	12 %	60 %	41 mm	
	MOULD CLAMPING (MAX)	99	%		
	XFER [M/C : 24 / 25 / 26 / 15] mm	-			
	SCREW REVOLUTION RPM	35	%		
MATERIAL FEEDING SM	25	mm			
SCREW DECOMPRESS SD	2	mm			
CUSHION	4.54 - 6.02			mm	
NO OF MOLD PLATE :	2	3	4	M / C OPEN SI	mm
TOOLING SIZE [mm] :	L	W	H		
TEST BY :		TIME	10 am		
PREPARED BY :	Ken	DATE	30/12/02		

Specimen C

BANSHING INDUSTRIAL CO., PTE LTD

MOULD TESTING REPORT

JOB NO

CUSTOMER: Motorola-S PART DESCRIPTION: TEST BAR
 PROGRAM: - MATERIALS: PC+ABS CYCLOLOY COLOUR: GY4496
 PART NO.: N/A LOT NO.: - GRADE: C120070
 TOOLING NO.: 2781 MFI REPORT: - % TEST: -

MACHINE TONNAGE: 40 MACHINE NO.: 41
 TOOLING TEST: T1/T2/T3/T4/T5 CAVITY NO.: -
 DATE: 2/1/03 1+1

PROBLEM ENCOUNTER

- 1) TOOLING INSERT PROBLEM
- 2) POOR POLISH [CAV. CORE]
- 3) POOR FINISH / TEXTURE
- 4) PART STUCK / DRAG [CAV. CORE]
- 5) RUNNER STUCK [CAV. CORE]
- 6) DRAG MARK [CAV. CORE]
- 7) GATING HIGH / POOR GATING
- 8) WARPAGE
- 9) SHORT MOULDING
- 10) AIR TRAP [CAV. CORE]
- 11) BURN MARK
- 12) FLASHES / BURRS
- 13) EJECTION STRESS MARK
- 14) COOLING LEAKAGE [CAV. CORE]
- 15) SINK MARK
- 16) SILVER STREAK
- 17) FLOW MARK / LINE
- 18) BUBBLE
- 19) WELD LINE / PARTING LINE
- 20) EJECTOR MARK / BROKEN PIN
- 21) OTHERS

PART WEIGHT / PC [gm] 0.65 0.70
 RUNNER WEIGHT [gm] 2.27
 TOTAL WEIGHT [gm] 3.62

TOOLING TEST REQUIRED ☒ OK ☐ MOD ☐ REPAIR

REMARKS :

A) 1 MPa = 10.2 kgf / cm²

LETJET 8/2002

B) 1 kN = 0.102 tonf = 102.0 kgf

NOTE: KINDLY ADHERE TO ABOVE PARAMETER SETTINGS

TEMPERATURE	°C	MOLD HEATER [1][2][3][4]					
		- - - -					
		NOZZLE				305	
		HEATER 1				305	
		HEATER 2				305	
		HEATER 3				240	
		HEATER 4				-	
		HOPPER / DEHUMIDIFIER				104	
PRESSURE	KG / CM	MOULD CAVITY [HOT]				No COOLING	
		MOULD CORE [HOT]				WATER	
		1ST INJECTION P1				68	% / bar
		2ND INJECTION P2				40	%
		3RD INJECTION				-	%
		4TH INJECTION (HOLDING) P3				30	%
		5TH INJECTION (HOLDING)				-	%
		PACK [M/C : 24 / 25 / 26 / 15]				-	sec
TIMER	SEC	HOLDING [M/C : 24 / 25 / 26 / 15]				-	sec
		SCREW BACK				10	kmf / cm ²
		INJECTION TIME				3	
		FULL TIME				1.17 - 1.21	
		HOLDING TP 2				0.8	
		CURING				31	
		INTERVAL / AIR BLOW				(2) - (3) -	
		EJECTOR COUNT				1	
VELOCITY & STROKE	POSITION	EJECTOR HOLD				(4) 0.5 (8) 1	
		TOTAL CYCLE				40	
						V %	S (mm)
		1ST INJECTION V-1 / S-1				10	24.5
		2ND INJECTION V-2 / S-2				6	20
		3RD INJECTION V-3 / S-3				22	12
		4TH INJECTION V-4 / S-4				30	10
		5TH INJECTION V-5 / S-5				50	9
VELOCITY & STROKE	SPEED	MOULD OPENING				8	20 % 35 %
		MOULD OPENING M/C : 24 / 25 / 26 / 15				mm	mm mm
		MOULD CLOSING				45 %	45 %
		MOULD CLOSING M/C : 24 / 25 / 26 / 15				mm	mm mm
		EJECTOR ADVANCE / RETRACT				12 %	60 % 41mm
		MOULD CLAMPING (MAX)				99	%
		XFER [M/C : 24 / 25 / 26 / 15] mm				-	
		SCREW REVOLUTION RPM				35	%
VELOCITY & STROKE	SPEED	MATERIAL FEEDING SM				25	mm
		SCREW DECOMPRESS SD				2	mm
		CUSHION				4.54 - 6.02	mm

NO OF MOLD PLATE: 2 3 4 M/C OPEN SI mmTOOLING SIZE [mm]: L W H

TEST BY: - TIME: 10am
 PREPARED BY: Ken DATE: 2/1/03

BANSHING INDUSTRIAL CO., PTE LTD

Specimen D

MOULD TESTING REPORT

JOB NO

CUSTOMER :	MOTOROLA-S	PART DESCRIPTION:	TEST BAR
PROGRAM :	-	MATERIALS	PC+ABS CYCLODY
PART NO. :	N/A	LOT NO.	
TOOLING NO. :	2781	MFI REPORT :	%
MACHINE TONNAGE :	40	MACHINE NO. :	41
TOOLING TEST :	T1/T2/T3/T4/T5	CAVITY NO.	
DATE :	3/1/03		1+1

PROBLEM ENCOUNTER

- 1) TOOLING INSERT PROBLEM
- 2) POOR POLISH [CAV. CORE]
- 3) POOR FINISH / TEXTURE
- 4) PART STUCK / DRAG [CAV. CORE]
- 5) RUNNER STUCK [CAV. CORE]
- 6) DRAG MARK [CAV. CORE]
- 7) GATING HIGH / POOR GATING
- 8) WARPAGE
- 9) SHORT MOULDING
- 10) AIR TRAP [CAV. CORE]
- 11) BURN MARK
- 12) FLASHES / BURRS
- 13) EJECTION STRESS MARK
- 14) COOLING LEAKAGE [CAV. CORE]
- 15) SINK MARK
- 16) SILVER STREAK
- 17) FLOW MARK / LINE
- 18) BUBBLE
- 19) WELD LINE / PARTING LINE
- 20) EJECTOR MARK / BROKEN PIN
- 21) OTHERS

	short	Long
PART WEIGHT / PC [gm]	0.65	0.70
RUNNER WEIGHT [gm]	2.27	
TOTAL WEIGHT [gm]	3.62	

TOOLING TEST REQUIRED ☐ OK ☐ MOD ☐ REPAIR

REMARKS :

A) 1 MPa = 10.2 kgf / cm²

LET111 9/2002

B) 1 kN = 0.102 tonf = 102.0 kgf

NOTE : KINDLY ADHERE TO ABOVE PARAMETER SETTINGS

TEMPERATURE	°C	MOLD HEATER [1][2][3][4]	-	-	-	-
		NOZZLE	315			
		HEATER 1	315			
		HEATER 2	315			
		HEATER 3	240			
		HEATER 4	-			
		HOPPER / DEHUMIDIFIER	104			
		MOULD CAVITY [HOT]	NO COOLING			
PRESSURE	KG/CM	MOULD CORE [HOT]	WATER			
		1ST INJECTION P1	68	% / bar		
		2ND INJECTION P2	40	%		
		3RD INJECTION	-	%		
		4TH INJECTION (HOLDING) P3	30	%		
		5TH INJECTION (HOLDING)	-	%		
		PACK [M/C : 24 / 25 / 26 / 15]	-	sec	-	
		HOLDING [M/C : 24 / 25 / 26 / 15]	-	sec	-	
TIMER	SEC	SCREW BACK	ON	OFF	10	kmf / cm ²
		INJECTION TIME	3			
		FULL TIME	1.17 - 1.21			
		HOLDING TP 2	0.8			
		CURING	31			
		INTERVAL / AIR BLOW	ON	OFF	(2) - (3) -	
		EJECTOR COUNT	1			
		EJECTOR HOLD	(4) 0.5	(8) 1		
VELOCITY & STROKE	POSITION	TOTAL CYCLE	40			
		1ST INJECTION V-1 / S-1	V%	S (mm)		
		2ND INJECTION V-2 / S-2	10	24.5		
		3RD INJECTION V-3 / S-3	6	20		
		4TH INJECTION V-4 / S-4	22	12		
		5TH INJECTION V-5 / S-5	30	10		
		MOULD OPENING	8	20 %	35 %	
		MOULD OPENING M/C : 24 / 25 / 26 / 15	mm	mm	mm	
VELOCITY & STROKE	SPEED	MOULD CLOSING	45	%	45 %	
		MOULD CLOSING M/C : 24 / 25 / 26 / 15	mm	mm	mm	
		EJECTOR ADVANCE / RETRACT	12 %	60 %	4mm	
		MOULD CLAMPING (MAX)	99	%		
		XFER [M/C : 24 / 25 / 26 / 15] mm	-			
		SCREW REVOLUTION RPM	35	%		
		MATERIAL FEEDING SM	25	mm		
		SCREW DECOMPRESS SD	2	mm		
VELOCITY & STROKE	SPEED	CUSHION	4.54 - 6.02	mm		
		NO OF MOLD PLATE :	(2) 3 4	M/C OPEN SI	mm	
		TOOLING SIZE [mm] :	L	W	H	
		TEST BY :		TIME	3/1/03	
		PREPARED BY :	Ken	DATE	3/1/03

BANSHING INDUSTRIAL CO., PTE LTD

Specimen F

MOULD TESTING REPORT

JOB NO

CUSTOMER: **MOTOROLA-S** PART DESCRIPTION: **TEST BAR**
 PROGRAM: **-** MATERIALS: **PC+ABS CYCLOLOY** COLOUR: **GY4496**
 PART NO.: **N/A** LOT NO.: **-** GRADE: **C120amd**
 TOOLING NO.: **2781** MFI REPORT: **-** % TEST: **-**

MACHINE TONNAGE: **40** MACHINE NO: **41**
 TOOLING TEST: **T1/T2/T3/T4/T5** CAVITY NO.: **-**
 DATE: **8/1/03** **41**

PROBLEM ENCOUNTER

- 1) TOOLING INSERT PROBLEM
- 2) POOR POLISH [CAV. CORE]
- 3) POOR FINISH / TEXTURE
- 4) PART STUCK / DRAG [CAV. CORE]
- 5) RUNNER STUCK [CAV. CORE]
- 6) DRAG MARK [CAV. CORE]
- 7) GATING HIGH / POOR GATING
- 8) WARPAGE
- 9) SHORT MOULDING
- 10) AIR TRAP [CAV. CORE]
- 11) BURN MARK
- 12) FLASHES / BURRS
- 13) EJECTION STRESS MARK
- 14) COOLING LEAKAGE [CAV. CORE]
- 15) SINK MARK
- 16) SILVER STREAK
- 17) FLOW MARK / LINE
- 18) BUBBLE
- 19) WELD LINE / PARTING LINE
- 20) EJECTOR MARK / BROKEN PIN
- 21) OTHERS

PART WEIGHT / PC [gm] **0.65** **0.70**
 RUNNER WEIGHT [gm] **2.27**
 TOTAL WEIGHT [gm] **3.62**

TOOLING TEST REQUIRED ☒ OK ☐ MOD ☐ REPAIR

REMARKS :

WATER CHANNEL

CORE SIDE

CAVITY SIDE

A) 1 MPa = 10.2 kgf / cm²

LETLEY 8/2002

B) 1 kN = 0.102 tonf = 102.0 kgf

NOTE : KINDLY ADHERE TO ABOVE PARAMETER SETTINGS

TEMPERATURE	°C	MOLD HEATER [1][2][3][4]	-	-	-	-
		NOZZLE	335			
		HEATER 1	335			
		HEATER 2	335			
		HEATER 3	240			
		HEATER 4	-			
		HOPPER / DEHUMIDIFIER	104			
		MOULD CAVITY [HOT]	NO COOLING			
		MOULD CORE [HOT]	WATER			
PRESSURE	KG/CM	1ST INJECTION P1	69	% / bar		
		2ND INJECTION P2	40	%		
		3RD INJECTION	-	%		
		4TH INJECTION (HOLDING) P3	30	%		
		5TH INJECTION (HOLDING)	-	%		
		PACK [M/C : 24 / 25 / 26 / 15]	-	sec	-	
		HOLDING [M/C : 24 / 25 / 26 / 15]	-	sec	-	
TIMER	SEC	SCREW BACK	ON	OFF	10	kmf / cm2
		INJECTION TIME	3			
		FULL TIME	1.17 - 1.21			
		HOLDING TP 2	0.8			
		CURING	31			
		INTERVAL / AIR BLOW	ON	OFF	(2) - (3) -	
		EJECTOR COUNT	1			
VELOCITY & STROKE	POSITION	EJECTOR HOLD	(4) 0.5	(8) 1		
		TOTAL CYCLE	40			

VELOCITY & STROKE	SPEED	POSITION	V%		S (mm)	
			1ST INJECTION	V-1 / S-1	10	24.5
			2ND INJECTION	V-2 / S-2	6	20
			3RD INJECTION	V-3 / S-3	22	12
			4TH INJECTION	V-4 / S-4	30	10
			5TH INJECTION	V-5 / S-5	50	9
			MOULD OPENING		8	20 % 35 %
			MOULD OPENING M/C : 24 / 25 / 26 / 15		8 mm	mm mm
			MOULD CLOSING		45 % 45 %	
			MOULD CLOSING M/C : 24 / 25 / 26 / 15		mm	mm mm
			EJECTOR ADVANCE / RETRACT		12 % 60 %	41 mm
			MOULD CLAMPING (MAX)		99	%
			XFER [M/C : 24 / 25 / 26 / 15] mm		-	
			SCREW REVOLUTION RPM		35	%
			MATERIAL FEEDING SM		25	mm
			SCREW DECOMPRESS SD		2	mm
			CUSHION		4.54 - 6.02	mm

NO OF MOLD PLATE: **2** **3** **4** M/C OPEN SI **mm**TOOLING SIZE [mm]: L **-** W **-** H **-**

TEST BY: **-** TIME: **10am**
 PREPARED BY: **Ken** DATE: **8/1/03**

Raw Resin

BANSHING INDUSTRIAL CO., PTE LTD
13 SERANGOON NORTH AVE 5
SINGAPORE 554787

ASTM D. 1238 Procedure A

CUSTOMER	MOTOROLA
PART NUMBER	
LOT NUMBER	700272
GRADE	C1200MO-G

RUN NO.	TEST PAR.	LOAD KG	TIME SEC.	TEMP DEG C	CUTOFF G	F. RATE G/10	DATE	OPER.
1	CYCOLOY	5.0	30	260	0.56	11.2		YING
2	CYCOLOY	5.0	30	260	0.58	11.6		YING
3	CYCOLOY	5.0	30	260	0.60	12		YING
AVER.						11.6		
S.D.						.4		

A

Specimen A

BANSHING INDUSTRIAL CO., PTE LTD
13 SERANGOON NORTH AVE 5
SINGAPORE 554787

ASTM D. 1238 Procedure A

CUSTOMER	MOTOROLA
PART NUMBER	
LOT NUMBER	700272
GRADE	C1200MO-G

RUN NO.	TEST PAR.	LOAD KG	TIME SEC.	TEMP DEG C	CUTOFF G	F. RATE G/10	DATE	OPER.
1	CYCOLOY	5.0	30	260	0.69	13.8		YING
2	CYCOLOY	5.0	30	260	0.69	13.8		YING
3	CYCOLOY	5.0	30	260	0.70	14		YING
AVER.						13.867		
S.D.						.11563		

☒ ACCEPT	☐ REJECT
Rate Material: 11.6g/10min	Date Tested 27-12-02
End Part 13 867g/10min	27-12-02
19.54 %	

Specimen B

B

BANSHING INDUSTRIAL CO., PTE LTD
13 SERANGOON NORTH AVE 5
SINGAPORE 554787

ASTM D. 1238 Procedure A

CUSTOMER	MOTOROLA
PART NUMBER	
LOT NUMBER	700272
GRADE	C1200MO-G

RUN NO.	TEST PAR.	LOAD KG	TIME SEC.	TEMP DEG C	CUTOFF G	F. RATE G/10	DATE	OPER.
1	CYCOLOY	5.0	30	260	1.02	20.4		YING
2	CYCOLOY	5.0	30	260	1.09	21.8		YING
3	CYCOLOY	5.0	30	260	1.08	21.6		YING
AVER.						21.27		
S.D.						.7571		

TEST		☒ REJECT
Raw Material: 11.6 g/10min	Date Tested 30-12-02	
End Part: 21.27 g/10min	30-12-02	
End Part must not exceed 20% of Raw Material Result: 83.36 %		

Specimen C

BANSHING INDUSTRIAL CO., PTE LTD
13 SERANGOON NORTH AVE 5
SINGAPORE 554787

ASTM D. 1238 Procedure A

CUSTOMER	MOTOROLA
PART NUMBER	
LOT NUMBER	700272
GRADE	C1200MO-G

RUN NO.	TEST PAR.	LOAD KG	TIME SEC.	TEMP DEG C	CUTOFF G	F. RATE G/10	DATE	OPER.
1	CYCOLOY	5.0	30	260	1.30	26		YING
2	CYCOLOY	5.0	30	260	1.33	26.6		YING
3	CYCOLOY	5.0	30	260	0.92	18.4		YING
AVER.						23.67		
S.D.						4.571		

☐ ACCEPT	☒ REJECT
Raw Material: 11.6 g/10min	Date Tested: 2-01-03
End Part: 23.67 g/10min	2-01-03
End Part must not exceed 20% of Raw Material Result: 104.05%	

Specimen D

BANSHING INDUSTRIAL CO., PTE LTD
13 SERANGOON NORTH AVE 5
SINGAPORE 554787

ASTM D. 1238 Procedure A

CUSTOMER	MOTOROLA
PART NUMBER	
LOT NUMBER	700272
GRADE	C1200MO-G

RUN NO.	TEST PAR.	LOAD KG	TIME SEC.	TEMP DEG C	CUTOFF G	F. RATE G/10	DATE	OPER.
1	CYCOLOY	5.0	30	260	1.71	34.2		YING
2	CYCOLOY	5.0	30	260	1.80	36		YING
3	CYCOLOY	5.0	30	260	1.80	36		YING
AVER.						35.4		
S.D.						1.0394		

☐ ACCEPT	☒ REJECT
Raw Material: 11.6 g/10min	Date Tested: 3-01-03
End Part: 35.4 g/10min	3-01-03
End Part must not exceed 20% of Raw Material	
Result: 203.17%	

Specimen F

BANSHING INDUSTRIAL CO., PTE LTD
13 SERANGOON NORTH AVE 5
SINGAPORE 554787

ASTM D. 1238 Procedure A

CUSTOMER
 PART NUMBER
 LOT NUMBER
 GRADE

MOTOROLA
 700272
 C1200MO-GY

RUN NO.	TEST PAR.	LOAD KG	TIME SEC.	TEMP DEG C	CUTOFF G	F. RATE G/10	DATE	OPER.
1	CYCOLOY	5.0	30	260	2.12	42.4		YING
2	CYCOLOY	5.0	30	260	1.42	28.4		YING
3	CYCOLOY	5.0	30	260	1.42	28.4		YING
AVER.						33.07		
S.D.						8.083		

☐ ACCEPT	☒ REJECT
Raw Material: 11.6 g/10min	Date Tested: 8-01-03
End Part: 33.07 g/10min	8-01-03
End Part must not exceed 20% of Raw Material Result: 185.08%	

Appendix D

(Quasi-static and Impact Tests Experimental Data For
PC/ABS Specimens)

**Quasi-Static Tests Results For No Notch And Notch Specimens
(Notch Ø: 1.5mm, 2mm, 3mm, 4mm, 5mm)**

JsampleA Chart 2

PC/ABS Jsample A MFI 19.54%

NsampleA15 Chart 1

Quasi-Static Test Notch 1.5mm Specimen A MFI 19.54%

Quasi-Static Test Notch 1.5mm Specimen B MFI 83.36%

Quasi-Static Test Notch 1.5mm Specimen C MFI 104.05%

Quasi-Static Test Notch 1.5mm Specimen D MFI 205.17%

Quasi-Static Test Notch 1.5mm Specimen F MFI 185.08%

Quasi-Static Test Notch 2mm Specimen A MFI 19.54%

Quasi-Static Test Notch 2mm Specimen B MFI 83.36%

Quasi-Static Test Notch 2mm Specimen C MFI 104.05%

Quasi-Static Test Notch 2mm Specimen D MFI 205.17%

Quasi-Static Test Notch 2mm Specimen F MFI 185.08%

NsampleA3 Chart 1

Quasi-Static Test Notch 3mm Specimen A MFI 19.54%

Quasi-Static Test Notch 3mm Specimen B MFI 83.36%

Quasi-Static Test Notch 3mm Specimen C MFI 104.05%

Quasi-Static Test Notch 3mm Specimen D MFI 205.17%

Quasi-Static Test Notch 3mm Specimen F MFI 185.08%

Quasi-Static Test Notch 4mm Specimen A MFI 19.54%

Quasi-Static Test Notch 4mm Specimen B MFI 83.36%

Quasi-Static Test Notch 4mm Specimen C MFI 104.05%

Quasi-Static Test Notch 4mm Specimen D MFI 205.17%

Quasi-Static Test Notch 4mm Specimen F MFI 185.08%

NsampleA5 Chart 1

Page 1

Quasi-Static Test Notch 5mm Specimen A MFI 19.54%

Quasi-Static Test Notch 5mm Specimen B MFI 83.36%

Quasi-Static Test Notch 5mm Specimen C MFI 104.05%

Quasi-Static Test Notch 5mm Specimen D MFI 205.17%

Quasi-Static Test Notch 5mm Specimen F MFI 185.08%

**Impact Tests Results For No Notch And Notch Specimens
(Notch Ø: 1.5mm, 2mm, 3mm, 4mm, 5mm)**

PCABS: Effect of MFI at Impact Test

PCABS: Impact test for MFI 19.54%

PCABS: Impact test for MFI 83.36%

PCABS: Impact test for MFI 104.05%

A2 Chart 1

Appendix E

(True Stress-Strain Curve And Material Data For PC/ABS)

Appendix E

True stress-strain curve data for material model inputs in FEM analysis.

Figure D1: True stress-strain curve obtained from tensile test.

Material model inputs in ABAQUS.

(Stress, strain and density units are in KPa, mm/mm and Kg/mm³ respectively)

```
** MATERIALS
**
*Material, name=MYPCABS
*Density
1.2e-06,
*Elastic
2e+06, 0.375
*Plastic
50421.7, 0.0
62899.4, 0.040805
58481.3, 0.102282
58256.9, 0.129678
79239.3, 0.389964
146428., 0.781161

*Material, name=PORON-C (lens adhesive)
*Density
4.8e-07,
*Hyperfoam, n=2, moduli=INSTANTANEOUS
5596.5, 2.4614, 0.00012854, -14.045, 0.2, 0.2
*Viscoelastic, time=PRONY
0.9427, 0.9427, 6.81e-05
**
```