# DESIGN AND FABRICATION OF CHEVRON-NOTCH PLAIN-STRAIN FRACTURE TOUGHNESS TESTING SYSTEM FOR METALLIC MATERIALS


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## DECLARATION

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## Statement 1

This thesis is the result of my own investigation, except where otherwise stated. Other sources are acknowledged by giving explicit references. Bibliography/references are appended.

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Title of thesis: **Design and Fabrication of Chevron Notch Plain- Strain Fracture Toughness Testing System for Metallic Materials**

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## NOMENCLATURE & ACRONYMS

In this section the nomenclature and acronyms used in the report are listed with the correspondent International System (IS) units.

### Nomenclature

| | |
|---|---|
| $K_{QvM}$ | Plain-Strain fracture toughness |
| $K_{IvM}$ | Plane-Strain Chevron-Notch fracture toughness |
| B | Thickness (mm) |
| W | Length (mm) |
| PM | Maximum load (N) |
| $\sigma_{YS}$ | Yield strength (MPa) |
| $Y^{*}{}_{m}$ | Minimum Stress intensity factor |

### Acronyms

| | |
|---|---|
| ASTM | American Society for Testing and Materials |
| DIC | Digital Image correlation |
| Al | Aluminium 5052 |
| EDM | Electrical Discharge Machining |
| CAD | Computer-aided Design |

# ABSTRAK

## REKABENTUK DAN FABRIKASI ‘CHEVRON-NOTCH’ BIASA-TERIKAN PATAH UNTUK MENGUJI  BAHAN-BAHAN LOGAM

Keliatan patah adalah sebuah kuantitatif bahan. Keliatan patah adalah langkah-langkah keupayaan bahan yang mengandungi kecacatan untuk menahan beban yang dikenakan dan digunakan untuk mengukur kekuatan ketegangan patah untuk bahan-bahan logam dipiawaikan dalam ASTM E399. Walau bagaimanapun, ianya pengetahuan yang luas bahawa kaedah ini agak membosankan. ASTM E1304 menawarkan beberapa kelebihan berbanding kaedah piawai ASTM E399. Oleh itu, kajian ini adalah untuk membangunkan dan reka terikan patah sistem ujian keliatan plain Chevron-Notch untuk bahan matellic mengikut ASTM E1304.

Chevron-Notch ketegangan biasa adalah sistem ujian keliatan patah telah disahkan dengan menentukan chevron-notch keliatan-terikan patah keliatan $K_{IvM}$ daripada aloi aluminium 5052 menggunakan “Ultimate Testing Machine Instron 3367”. Dengan menggunakan ujian ini, dataran-terikan keliatan patah $K_{QvM}$ aluminium 5052 telah ditakrifkan. Sebelum menjalankan ujian keliatan patah, satu ujian tegangan telah dijalankan, dan kekuatan alah bahan telah dikira. Dalam percubaan ini, korelasi imej digital, DIC digunakan untuk mengukur anjakan anjakan mulut retak membuka, CMOD. Dari bidang anjakan DIC, nilai CMOD sebagai fungsi beban telah berjaya ditentukan. Nilai kenaikan CMOD apabila kenaikan beban digunakan.

Walau bagaimanapun, pesawat-terikan patah chevron-notch keliatan, $K_{IvM}$ Al 5052 yang diperolehi dalam kajian ini dianggap tidak sah kerana nilai lebar, Bcalculate adalah lebih tinggi daripada lebar sebenar, nilai B. Keliatan patah spesimen itu $K_{QvM}$ yang kita dikira adalah lebih tinggi daripada keliatan patah yang sebenar.

# ABSTRACT

## DESIGN AND FABRICATION OF CHEVRON-NOTCH PLAIN-STRAIN FRACTURE TOUGHNESS TESTING SYSTEM FOR METALLIC MATERIALS

Fracture toughness is a quantitative property of the material. Fracture toughness measures the ability of a material containing a flaw to withstand an applied load. The most common method of measuring plain strain fracture toughness for metallic materials is standardized in the ASTM E399. However, it is widely acknowledged that the method is quite tedious. ASTM E1304 offers several advantages over the standard method of the ASTM E399. This research is, therefore, to develop and fabricate the Chevron-Notch plain strain fracture toughness testing system for metallic material according to ASTM E1304.

The Chevron-Notch plain strain fracture toughness testing system was validated by determining the chevron-notch plane-strain fracture toughness of $K_{IvM}$ of aluminium alloy 5052 using Ultimate Testing Machine Instron 3367. By using this test, the plain-strain fracture toughness $K_{QvM}$ of the aluminium 5052 was defined. Before conducting the fracture toughness test, a tensile test was conducted, and the yield strength of the material was calculated. In this experiment, the digital image correlation, DIC was used to measure the displacement of the crack mouth opening displacement, CMOD. From the DIC displacement fields, the CMOD value as a function of load was successfully determined. The CMOD value increases when the applied load increases.

However, the plane-strain chevron-notch fracture toughness, $K_{IvM}$ of Al 5052 obtained in this study is considered invalid as the value of the width, $B_{calculate}$ is higher than the actual width, B value. The fracture toughness of the specimen is $K_{QvM}$ that we

calculated is higher than the real fracture toughness. These finding results illustrate the chevron-notch test need to improve by more strategical dimensions to design the specimen and jig and create the methodological framework to develop a complex specimen.

# CHAPTER 1

# INTRODUCTION

## 1.1 Overview of The Project

Fracture toughness is an important material property that corresponds to the critical state of the stress intensity factor, K required for crack initiation and the subsequent propagation [1]. The stress intensity factor defines the amplitude of the crack-tip singularity and stresses near the crack tip [2]. The fracture toughness, $K_c$ of the specimens varies if its thickness is below one-inch thickness. The fracture toughness for a specimen with one-inch thickness is called plane-strain fracture toughness, $K_{Ic}$ as shown in Figure 1.1.

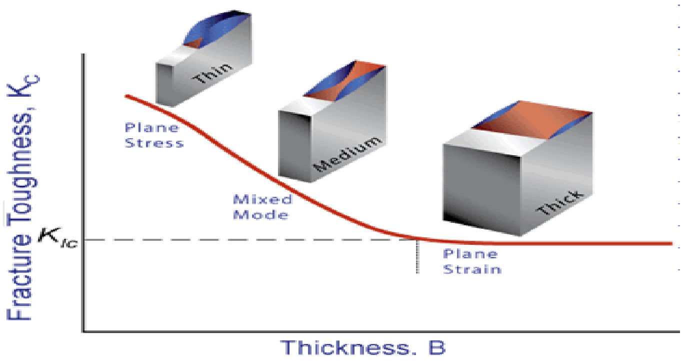



Figure 1.1: Fracture toughness curve

Referring to Figure 1.1, the fracture toughness value which is higher than the plane-strain fracture toughness, $K_{Ic}$ is the upper bound fracture toughness whereas the plane-strain fracture toughness is considered as the lower bound fracture toughness. The relationship between stress intensity, $K_I$, and fracture toughness, $K_{Ic}$, is like the relationship between stress and tensile stress. The stress intensity, $K_I$, represents the level of stress at the tip of the crack and the fracture toughness, $K_{Ic}$, is the highest value of stress intensity that a material under very specific conditions that material can withstand without fracture [3].

The $K_{Ic}$ testing is the test used to determine the fracture toughness of metallic materials. Then, crack tip opening displacement is a test to measure the physical opening of the fatigue crack tip at the point of failure.

The standard test procedures like ASTM E-399, ASTM B-645, ASTM E-1820 and BS 5762, etc are well established to determine the fracture toughness of metallic materials. The standard fracture toughness test procedures use standard specimen like, SENB specimens and arc-shaped or disc-shaped compact specimen, etc which are complex in nature.

## 1.2 Problem Statement

ASTM E399 standard is the most common standard method and argued to be one of the most accurate ways of measuring $K_{IC}$ of low ductility high strength alloys. This method however difficult and exhausting to perform and specimen preparation procedure is tedious [4]. Furthermore, the plain-strain fracture toughness, $K_{Ic}$, ASTM E399 standard has many procedures before the fracture toughness test.

Chevron-Notch ASTM E1304 offers several advantages over the standard method of ASTM E399 such that it can reduce the cost when the test is using a smaller specimens. The fracture toughness value can be obtained at very specific locations in a structure. Besides, the fracture toughness ASTM E1304 used the smaller specimen geometry than that prescribed by ASTM E399. E1304 standard is not required the fatigue pre-cracking before the test. In preparing the sample, E1304 standards are used less machining than E399 standards [5, 6]. For these reasons, chevron-notched samples have been often preferable to measure the fracture toughness of a variety of materials [5, 7].

## 1.3 Objectives

As the ASTM E1304 offers flexibility in determining the fracture toughness of metallic material, and some tedious procedures in E399 can be skipped. Therefore, the objective of this project is:

i. To design the Chevron-Notch plain strain fracture toughness testing system for metallic materials following ASTM E1304.
ii. To fabricate the Chevron-Notch plain strain fracture toughness testing system for metallic materials following ASTM E1304.
iii. To validate the system by determining the Chevron-Notch plane strain fracture toughness, $K_{IvM}$, of aluminium 5052.

## 1.4 Scope of Work

The work scope of this project involves studying and learning about the fundamental knowledge of fracture toughness testing between the ASTM E399 and ASTM E1304. Solidworks will be the main tool to be used in designing the jig and the specimen for this experiment. After designing, the specimen and the jig will be fabricated using the EDM wire cut and lathe machine. The aluminium alloy 5052, Al 5052 is the main material used in this project. The material used for the jig is 304 stainless steel. Digital image correlation (DIC) will be used to measure the crack mouth opening displacement, CMOD value. The fracture toughness testing will be conducted using the Instron 3367 ultimate tensile machine. The flow of the work scope as shown in Figure 1.2.

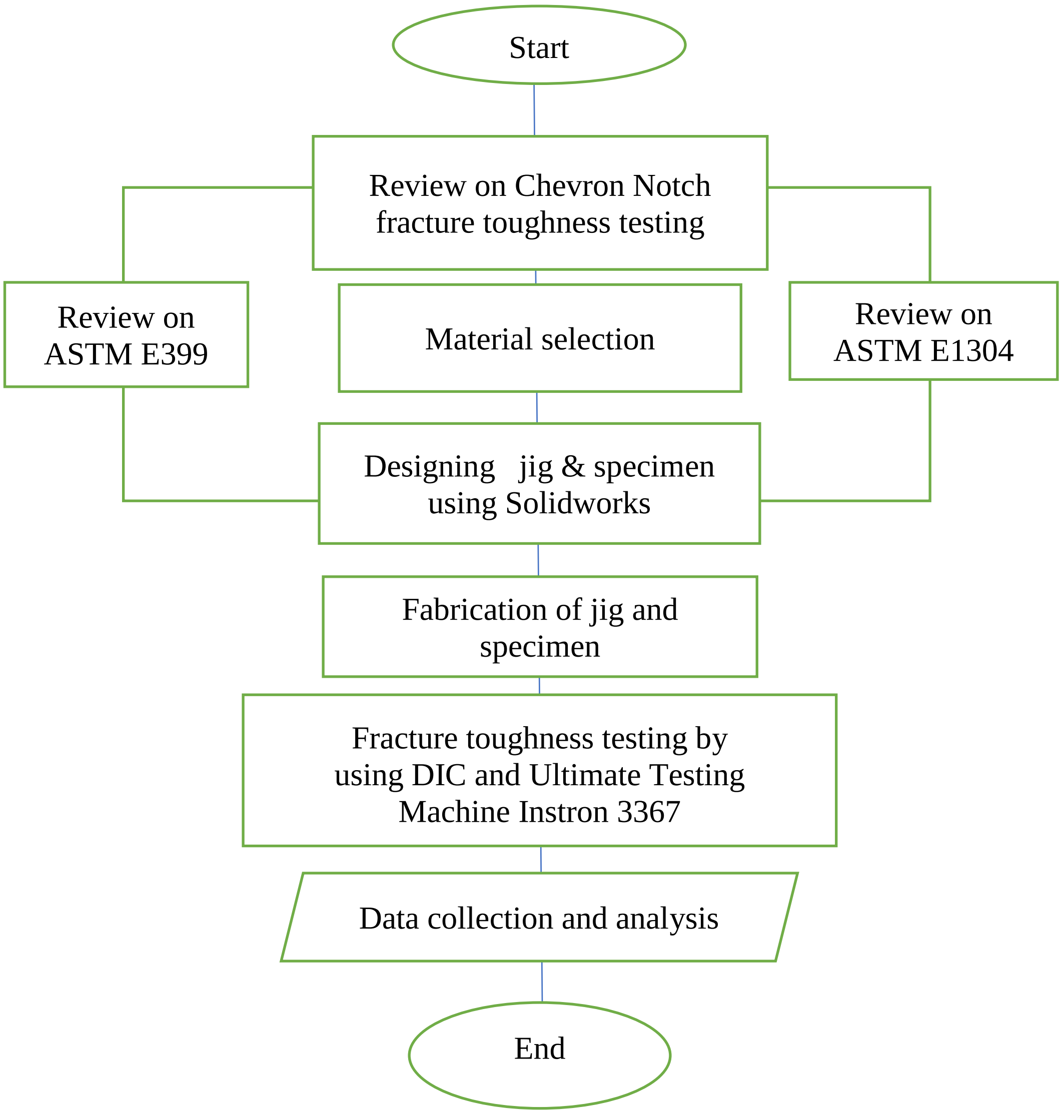



Figure 1.2: Flow chart scope of work

## 1.5 Thesis Structure

The thesis is divided into 5 chapters, that includes this chapter. In chapter 2, journals, articles and research works that related to the topic are presented. The literature reviews include the fundamental knowledge of fracture toughness, an overview of the ASTM E399 standard and ASTM E1304 standards, including the specimen dimension, and the experiment procedures.

Chapter 3 presents the methodology of the project. In this chapter, the fabrication steps, experimental setups and measurement techniques of fracture toughness are discussed. The results of the research are discussed in chapter 4, where the experiment data and the analysis of the data are presented.

Lastly, chapter 5 concludes this research in which the achievement of the research objectives is discussed. Some future works and improvement are suggested.

# CHAPTER 2

# LITERATURE REVIEW

## 2.1 Fracture Mechanics

Fracture mechanics is used to determining the effect of crack-like defects will have on the structural stability of any structure [5]. The goal of fracture mechanics analysis is to find the exact amount of stress apart will withstand before the defects grow to failure. This amount of stress was used to determine the minimum load or critical defect size that will cause the analyzed part to fail [7].

In general, there are three crack separation modes as shown in Figure 2.1 [8]. Mode I is the opening mode with the applied to be in the normal direction of the crack plane. A critical value of Mode I stress intensity factor $K_{Ic}$ is an appropriate fracture parameter when a material behaves in a linear elastic manner prior to failure [8]. Mode II is the sliding mode where shear stress is acting parallel to the plane of the crack and perpendicular to the crack front. Mode III corresponds to the tearing mode where shear stress is acting parallel to both the plane of crack and the crack front.

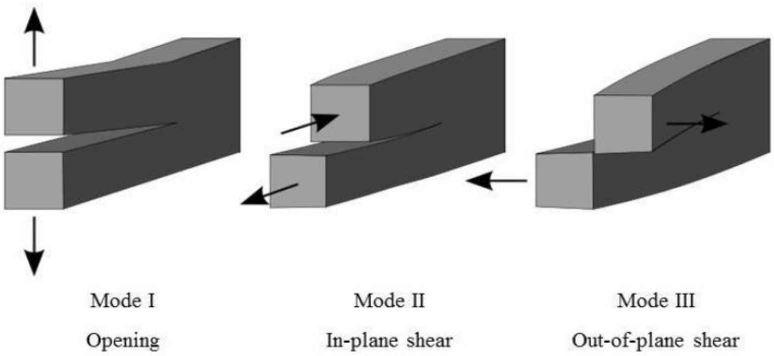



Figure 2.1: Three mode of crack surface. (a) Mode1- opening; (b) mode II- Sliding mode; (c)- Mode III- Tearing mode [8]

## 2.2 Plain Strain Fracture Toughness Testing ASTM E399

The ASTM E399 standard is basically used linear elastic fracture mechanics as its basis for calculating fracture toughness. For this reason, specimen sizing requirements are predicated on maintaining a crack tip plastic zone size that is a small fraction of the planar dimensions of the specimen. Basically, the specimens are sized so that the dimensions of crack size, a thickness, B and remaining ligament size (W-a) are greater than the ratio of 2.5 $(K_{Ic}/\sigma_{ys})^2$, i.e., so that

$$a, B, (W - a > \left(\frac{K_{Ic}}{\sigma_{ys}}\right)^2 \text{ ... ... ... ... ... Equation 2.1}$$

where $\sigma_{ys}$ is the 0.2% offset yield strength and the $K_{ic}$value meets all the test criteria [3].

The plane-strain fracture toughness, $K_{Ic}$ defined by ASTM E 399 standard is assumed to represent a size insensitive lower bound value. The specimen needs the fatigue pre-cracking before the test and the thickness of the specimen was assumed to be the limiting dimension and use the large size specimen to identify the fracture toughness. The test method is also specific about ensuring that the thickness of a $K_{Ic}$ specimen is substantially larger than the crack tip plastic zone size [5, 8].

There are five types of specimens that are permitted in ASTM standards that characterize fracture initiation and crack growth, although no single standard allows all five configurations, and the design of a specimen type may vary between standards. The configurations that are currently standardized include the compact specimen, the single-edge-notch bend, SEB geometry, the arc-shaped specimen, the disk specimen, and the middle tension (MT) panel. Figure 2.2 shows a drawing of each specimen type [5].

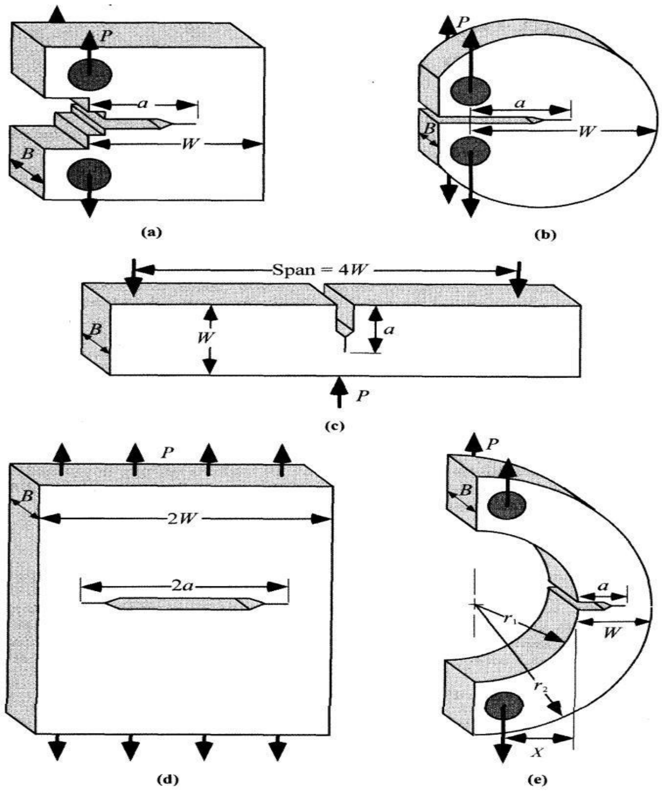



Figure 2.2: Standardized ASTM E399 fracture mechanics test specimens [9]

## 2.3 Plain Strain Fracture Toughness Testing ASTM E1304

In 1977 L.M. Barker proposed an alternative method for measuring plane-strain fracture toughness [7, 8]. This method was designed to simplify plane-strain fracture toughness procedures and to allow a broader range of materials to be tested successfully [10]. The method has been standardized with ASTM E1304 that employs the Chevron-Notch specimen. The standard offers several advantages over the standard method of ASTM E399. For instance, the ASTM E1304 uses the minimum and smaller specimen geometry [11]. In preparing the chevron-notch specimens, the ASTM El304 standards use less machining than ASTM E399 standards (4, 8).

The chevron-notched specimens are often preferable to measure the fracture toughness since the fracture toughness value can be obtained at very specific locations in a structure [5, 7]. ASTM E1304 standard does not require the fatigue pre-cracking before the fracture toughness test. Hence, the lack of a need for fatigue pre-cracking allows for simpler testing procedures [7].

Since this E399 method use of a steady state slowly moving crack as opposed to the start of crack extension from a fatigue pre-crack, $K_{Ic}$ cannot be used. $K_{Iv}$ is used to denote the plane strain chevron-notch fracture toughness. Following the ASTM E 1304-89, a peak load test is used to estimate fracture toughness [10]. Then, load-displacement curves will be obtained independent of the displacement rates within the recommended peak load time range.

At a crack length known as the critical crack length. the crack becomes unstable when it requires lower rather than higher loads to advance the crack. Therefore, to evaluate fracture toughness, the load to advance a crack of a specific length must be known. This may be at the geometry-dependent on the critical crack length and the point at which the load is a maximum. The crack length at any point during the test may be determined using a compliance technique.

From the works of Yevgeny Deryugin, the specimen VT6 Alloy and 12GBA tube steel 21 mm ×10 mm×6 mm in size were cut from the workpiece by electroerosion method. Then, a notch 0.3mm thick was made with a chevron angle 60°. The crack length at the pre-fracture stage was determined by the specimen image. Thus, the loading of the was performed by the intrusion of a narrow wedge into a notch at motion 5μm/s. The constant motion rate of the wedge provides for stable crack propagation initiation at chevron. All calculation parameters were determined by experimental data [7]. This method allows the fracture toughness of the material to be clarified without the amount of plasticity deformation and in front of the crack [11].

Figure 2.3 schematically compares the stress-intensity factor against the crack length for chevron and straight notch configurations. When the crack length is equally to $a_o$, the stress-intensity factor in the chevron-notched specimen is very high, because a finite load is applied over a very small net thickness. When a is smaller than $a_1$, then, $K_I$ the values for the two notch configurations are identical, since the chevron notch no longer has an effect. The $K_I$ for the chevron-notched specimen is a minimum at a crack length, which is between $a_o$ and $a_1$ [12].

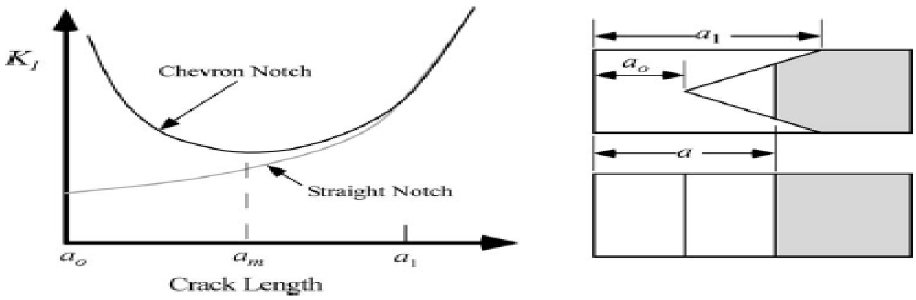



Figure 2.3: Comparison of stress-intensity factors in specimens with chevron and straight notches [7]

### 2.3.1 Specimen size

Chevron Notch has a V-shaped ligament, such that the notch depth varies through the thickness, with the minimum notch depth at the center. It is required that the specimen's lateral dimension, B, equal or exceed $1.25(K_{Iv}/\sigma_{YS})^2$ or $1.25(K_{IvM}/\sigma_{YS})^2$, where $\sigma_{YS}$ is 0.2% offset yield strength of the material in direction of loading in the test [2]. The general shape of the Chevron-notch specimen is illustrated in Figure 2.4. Two narrow slits are cut in the sides of this test specimen such that the two specimen halves are joined by a triangular ligament of material. Each specimen configuration has three important characteristic dimensions, which are the crack length, a, the thickness, B, and the width, W.

The rod and bar dimensions for specific compliance calibration are provided in Figure 2.4. Then, the dimensional tolerances and surface finishes shall be followed in specimen preparation. The surface of the chevron-notch specimen has to be 64-μin to make the specimen qualified for fracture toughness test. Then, the side grooves may be made with a plunge cut with a circular blade. In this case, β is the angle between the chords spanning the plunge cut arcs, and it is necessary to use different values of β and distance to chevron tip, $a_0$, to ensure the front crack has the same width (3).

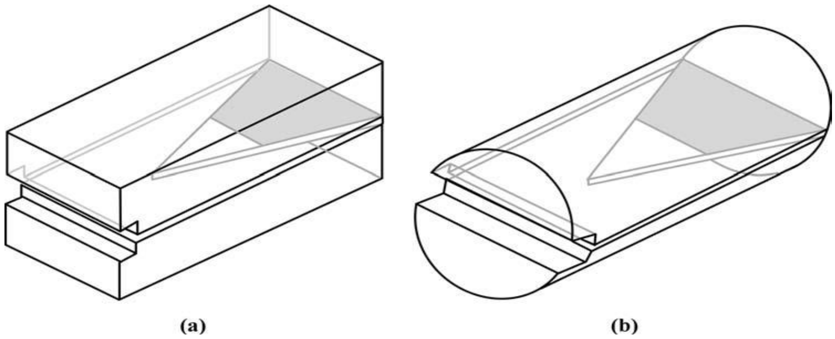



Figure 2.4 : Two common designs of chevron-notched specimens: (a) short bar and (b) short rod [2].

The dimension of $a_0$ must be achieved when forming the side grooves. The grip groove surfaces have to be flat and parallel to the chevron-notch within ±2°. Therefore, the notch on centreline within ±0.005B and perpendicular or parallel to the surfaces. The imaginary line must be perpendicular (± 2°) to the plane of the specimen slot [2, 13]. The design of the specimen is in accordance to the ASTM1304 Standard as shown in Figure 2.5. The standard dimension for the chevron-notch specimen is according to Table 2.1 [2].

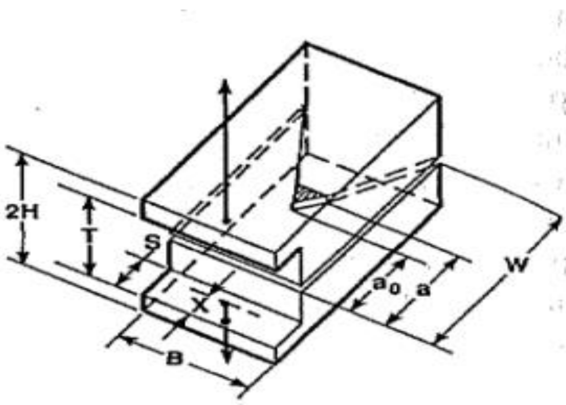



Figure 2.5: Definite dimensions of a chevron-notched bar specimen [14]

Table 2.1 : Standard dimension for bar specimen [2]

| Symbol | Name | Value: W/B = 1.45 | Value: W/B = 2.0 | Tolerance |
|---|---|---|---|---|
| $B$ | Thickness | $B$ | $B$ | ... |
| $W$ | Length | $1.450B$ | $2.000B$ | $\pm 0.010B$ |
| $a_o$ | Distance to chevron tip | $0.481B$ | $0.400B$ | $\pm 0.005B$ |
| $S$ | Grip groove depth | $0.150B$ | $0.150B$ | $\pm 0.010B$ |
| | alternate groove | $0.130B$ | $0.130B$ | $\pm 0.010B$ |
| $X$ | Distance to load line | $0.100B$ | $0.100B$ | $\pm 0.003B$ |
| | alternate groove | $0.050B$ | $0.050B$ | $\pm 0.003B$ |
| $T$ | Grip groove width | $0.350B$ | $0.350B$ | $\pm 0.005B$ |
| | alternate groove | $0.313B$ | $0.313B$ | $\pm 0.005B$ |
| $t$ | Slot thickness | $\leq 0.030B^A$ | $\leq 0.030B^A$ | ... |
| $\phi$ | Slot angle | 54.6° | 34.7° | ±0.5° |
| $H$ | Half-height | | | |
| | (square specimen) | $0.500B$ | $0.500B$ | $\pm 0.005B$ |
| | (rectangular specimen) | $0.435B$ | $B$ | $\pm 0.005B$ |

### 2.3.2 Experimental method

This test is occurs when the load is applying to the mouth of a chevron notched specimen to induce an opening displacement of the specimen mouth. The autographic is recorded by load versus mouth opening displacement and the slope of periodic unloading -reloading cycles that are used to calculate the length of the crack based on compliance technique. The crack length is determining indirectly as a slope ratio. The geometry, plasticity, residual stresses and crack growth characteristics of the specimen are dependent on the characteristic force versus mouth opening displacement trace.

The test procedures are very similar to those for a compact tension test, except that no fatigue pre-crack is required. In this case, a tensile load is applied to force the two specimen halves apart (Mode 1 loading). When this mouth opening load reaches an adequate level, a natural crack is initiated at the tip of the chevron.

There is two types of force that recognized by used displacement trace such as smooth behaviour and crack jump behaviour. For the metal that exhibits smooth crack behaviour, the crack initiates at a low force at the tip of the sufficiently sharp chevron. If the loading system is sufficiently stiff, the crack can be made to continue its smooth crack under the decreasing force. Then, to determine the location of the crack, the two unloading reloading cycle is performed, and the force used to determine $K_{Iv}$.

There is an alternative procedure that omits the unloading cycle and uses the maximum test force to calculate a plane strain fracture toughness $K_{IVM}$ where M represents maximum force. Figure 2.6 is the side and plan view of the chevron-notch specimen. The load cause cracks to initiate at the point of chevron and to advance downward through the shaded area and thus splitting the specimen in two. The toughness is measured when the crack front spans about one-third of the specimen's B dimension[15].

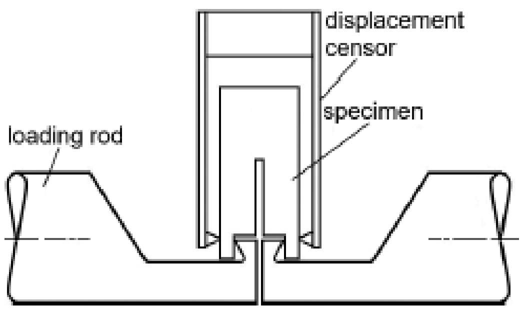



Figure 2.6: Loading configuration of the chevron-notched specimen [7]

### 2.3.3 Calculation

Condition value $K_{QvM}$ of plain strain

$$K_{QvM} = Pc\, Y_m^* * (B\sqrt{W}) \quad \text{Equation 2.2}$$

Where B = specimen width , if $B \geq 1.25(K_{QvM}/\sigma_{YS})^2$

$P_m$ = maximum load,

W = specimen length to load line,

$Y^*_m$= minimum stress intensity factor coefficient,

In some specimen sizes, geometry and material combination, the maximum force can occur during the initiation of the crack at the tip of the chevron-notch shaped ligament. Such forces must not be used in the $K_{IvM}$ calculation since they are not related to plane-strain toughness. In these cases, force $P_m$ used to determine $K_{IvM}$ is not a maximum force in the test but the maximum load in a specific region of the tests as follows.

The $K_{QvM}$ for the specimen is taken as the average of several value. If $B \geq 1.25 (K_{QvM}/\sigma_{YS})^2$, and if all other validity criteria are satisfied, the test is valid if the $K_{QvM}$ value equal to $K_{IvM}$ value. The value from both tests are not interchangeable and $K_{Iv}$ value normally higher than $K_{Ic}$ in some materials. Therefore, toughness values determined by this test method cannot be used interchangeably with $K_{Ic}$.

# CHAPTER 3

# METHODOLOGY

## 3.1 Material Properties of Specimen

Aluminium alloy 5052 contains nominally 2.5% magnesium and 0.25% chromium as shown in Table 3.1. It has good workability, medium static strength, high fatigue strength, good weldability, and very good corrosion resistance, especially in marine atmospheres. It also has a low density and excellent thermal conductivity common to all aluminium alloy [16].

Table 3.1: Aluminium Alloy 5052(18).

| Chemical Element | % Present | Chemical Element | % Present |
|---|---|---|---|
| Manganese (Mn) | 0.0 - 0.10 | Zinc (Zn) | 0.0 - 0.10 |
| Iron (Fe) | 0.0 - 0.40 | Chromium (Cr) | 0.15 - 0.35 |
| Copper (Cu) | 0.0 - 0.10 | Others | 0-0.15 |
| Magnesium (Mg) | 2.20 - 2.80 | Aluminium (Al) | Balance |
| Silicon (Si) | 0.0 - 0.25 | | |

The aluminium 5052 is suitable for many ranges of applications such as treadplate, boiler making, rivets, containers and road signs. It is commonly used in sheet, plate and tube form.

## 3.2 Mechanical properties

The mechanical properties of the specimens were determined through a tensile test conducted in accordance to the ASTM E8/E8M standard.

### 3.2.1 Preparation tensile test and Fabrication procedure.

The dimensions of the dog bone specimen were determined from the ASTM E8/E8M. The drawing of the dog bone is shown in Figure 3.1 that includes the front, right and top views, and Figure 3.2 is the three -dimensional dog bone specimen.

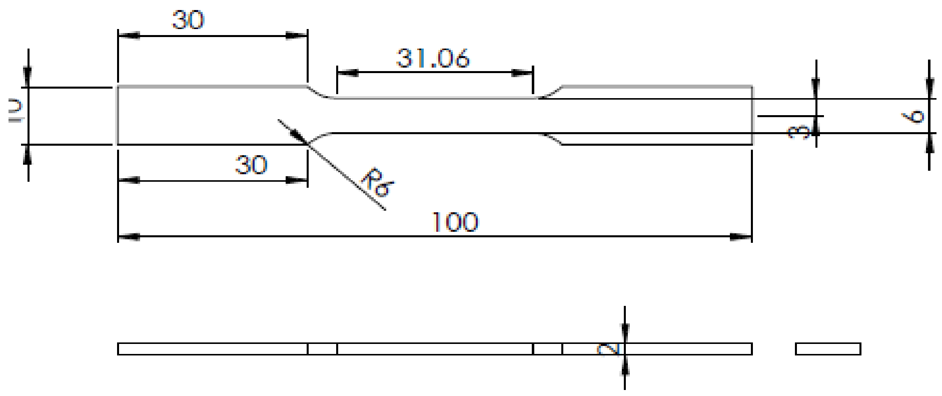



Figure 3.1: Front View and Top View of a dog bone for tensile test

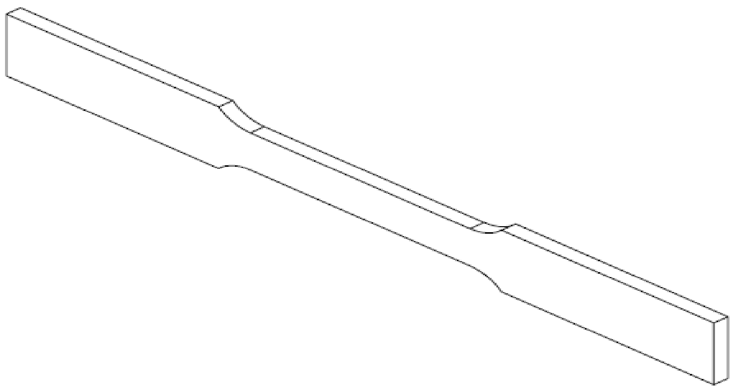


Figure 3.2: Dog bone specimen for tensile test

Figure 3.3 shows the standard size and shape of a flat tensile specimen that fabricates accordance to E8 standard.

The tensile testing was conducted using an Instron load frame and the BlueHill data acquisition software. Three samples of each material were tested in the Instron load frame, and the data was gathered into an Excel spreadsheet. The data was used to calculate various mechanical properties of Al 5052 alloy, including the elastic modulus, yield strength, and ultimate tensile strength.

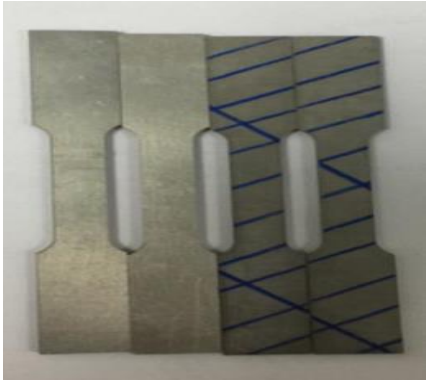


Figure 3.3: Dog bone specimen for tensile test

### 3.2.2 Test Procedures

In general, a tensile test requires a specimen to be gripped at both ends by an apparatus, which slowly pulls lengthwise on the piece until it fractures [17]. The pulling force is called a load, which is plotted against the material length change, or displacement. The load is converted to stress value and the displacement is converted to a strain value and the test is measure and records the specimen dimensions necessary to determine the cross-sectional area at its smallest point. The distance between the gage marks after the specimen is broken is used to determine the percent elongation at break [18]. The load cell was zeroed to ensure that the software only measured the tensile load applied to the specimen.

BlueHill data acquisition software was started. Then, the specimen was loaded into the jaws of the Instron load frame thus that it was equally spaced between the two clamps as shown in Figure 3.4. The extensometers were attached to the reduced gage section of the specimen and were set correctly when attaching it to the gage.

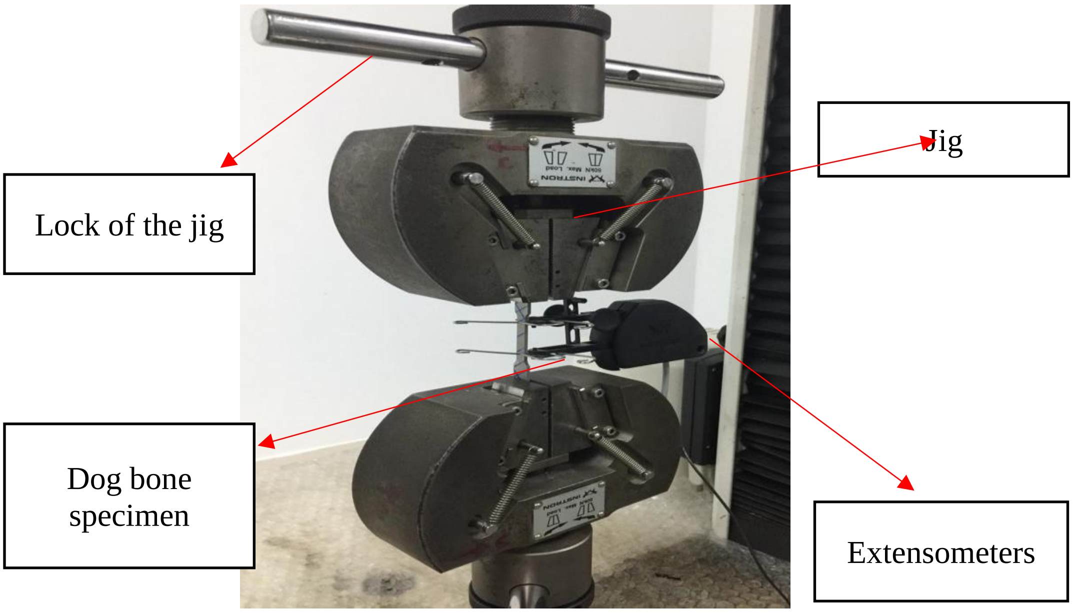



Figure 3.4 : Material is grip at the Instron 3367

The specimen was loaded by moving the crosshead upward at 0.5 mm/min. The software stopped using data from the extensometers and started gathering the strain information using the position of the moving crosshead. A warning message came up on the computer screen, instructing the operator to remove the extensometers to prevent damage. The test continued until fracture as shown in Figure 3.5. The specimen was removed, and the crosshead was reset to the initial position to start another tensile test. The testing procedure was repeated for the rest of the specimens with and without using extensometers.

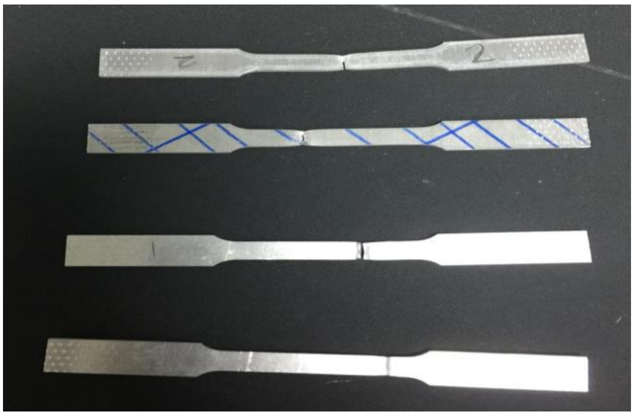


Figure 3.5: The specimen after the fracture test

### 3.2.3 Stress-strain curve of Aluminum 5052

After finished the experiment, a complete profile of the tensile properties of Al 5052 was obtained. When plotted on a graph, this data results in a stress-strain curve which shows how the material reacted to the forces being applied. The data of the tensile test can be referred in Appendice 6.

#### 3.2.3(a) The stress-strain curve without using extensometers

The average value of the experiment result is shown in Table 3.2. Then, a stress-strain curve was plotted by using the raw data as in Figure 3.6.

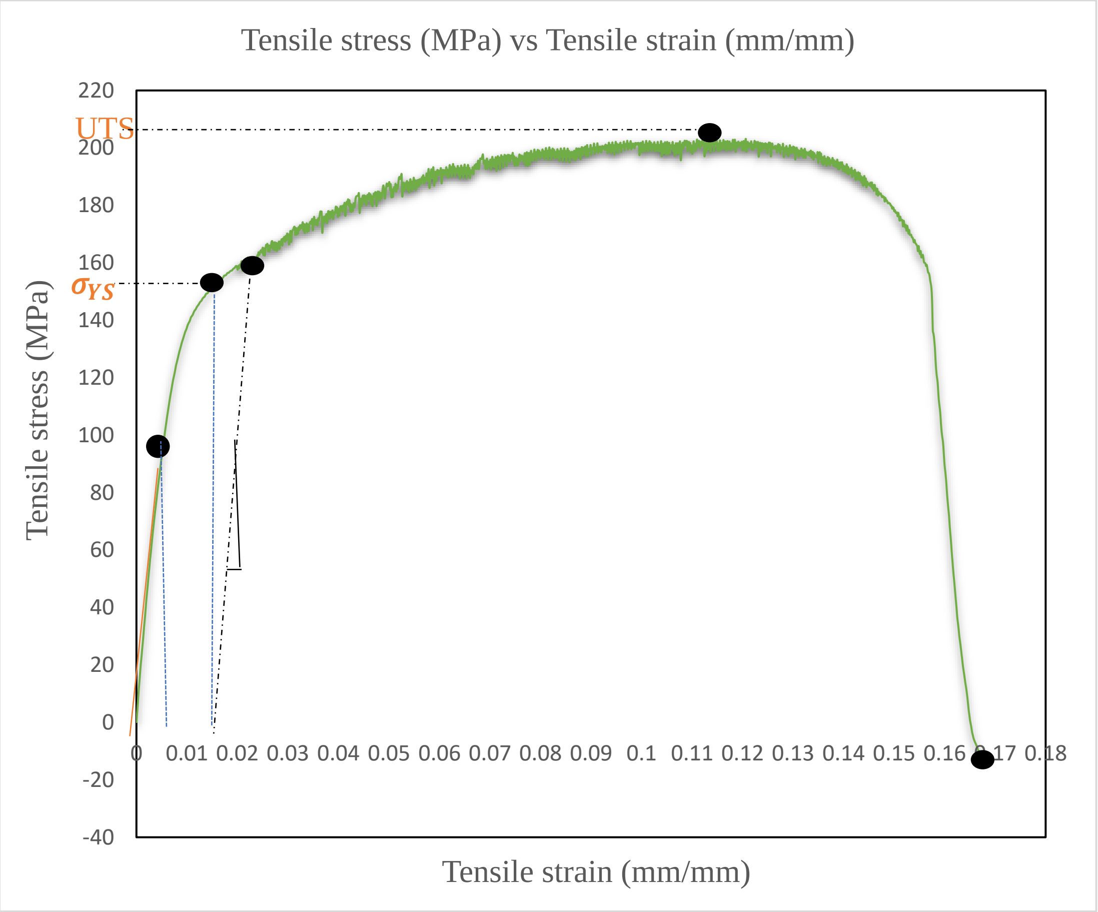



Figure 3.6: Stress-Strain Curve

Table 3.2: Mechanical properties of Aluminum 5052 without using extensometers

| **Mechanical properties** | **Experimental value** |
|---|---|
| Maximum load (N) | 2439.96821 |
| Strain at Maximum load (%) | 11.461 |
| Stress at maximum load (MPa) | 203.331 |
| Young Modulus ( MPa) | 21181.794 |
| Tensile extension at Maximum Tensile stress (mm) | 3.55982 |
| Extension at Maximum Tensile strain (mm) | 1.63484 |
| Maximum tensile stress (MPa) | 203.33069 |
| Tensile strain at maximum load (mm/mm) | 0.05263 |
| Tensile stress at Maximum Strain ((MPa)) | 183.19316 |
| Yield strength (MPa) | 123 |

### 3.2.3(b) The stress- strain curve by using extensometers

The average value of the experiment result is shown in Table 3.3. Then, the stress-strain curve was plotted by using the raw data as in Figure 3.7.

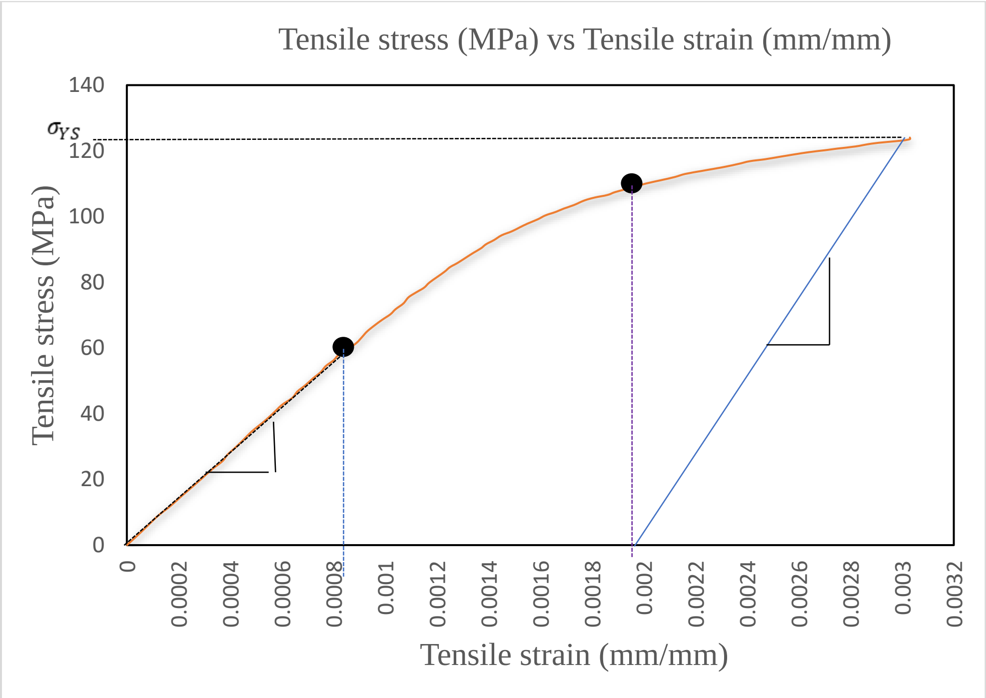



Figure 3.7: 2% Yield stress-strain curve

Table 3.3: Mechanical properties Aluminium 5052 by using extensometers

| Mechanical properties | Experimental value |
|---|---|
| Maximum load (N) | 2289.85928 |
| Strain at maximum (%) | 0.303 |
| Stress at maximum (MPa) | 190.822 |
| Young Modulus ( MPa) | 70368.915 |
| Extension at maximum load (mm) | 3.36037 |
| Maximum tensile stress (MPa) | 190.82161 |
| Tensile strain at maximum tensile (mm/mm) | 0.07574 |
| Extension at maximum tensile strain (mm) | 0.07574 |
| Load at maximum strain (N) | 1619.92762 |
| Tensile strain at maximum (mm/mm) | 0.00303 |
| Yield strength (MPa) | 123 |

## 3.3 Stress Analysis of the Testing System

A stress analysis was performed to assess the capability of the system to run the fracture toughness testing, specifically for Al5052, without undergoing deformation. The boundary conditions were applied after mesh and material properties of jig and specimen were created and assigned according to the properties as given in Table 3.4 and Table 3.1. Two boundary conditions; fixed support and distributed force, were applied. Both boundary conditions were applied based on the conditions during the chevron-notch test. The fixed support was applied to the lower jig and distributed force was applied on the upper jig in Y-axis direction at 10 kN as shown in Figure 3.8.

Figure 3.9 shows the testing system under 10 kN load, where the deformation field appears to be in between 3.315 kPa to 5.40 GPa. The maximum stress of 5.40 GPa develops at the mouth opening and crack-tip of the chevron-notch specimen as illustrated in Figure 3.10. This would initiate a small surface crack that eventually propagates through the component to complete failure.

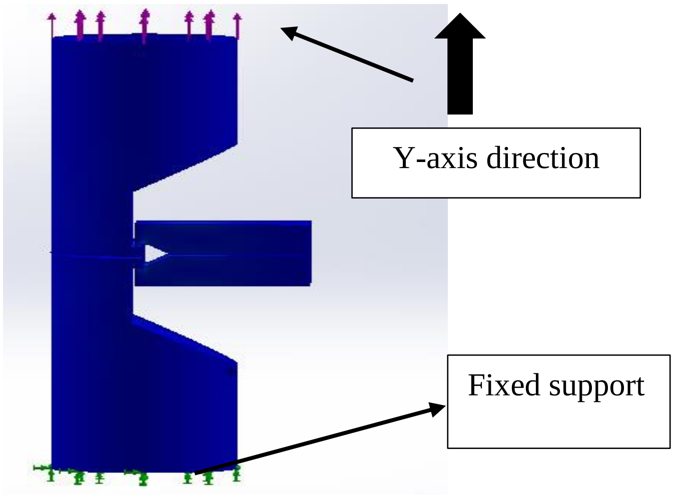



Figure 3.8: Set the fixed support and apply load on the assemble part

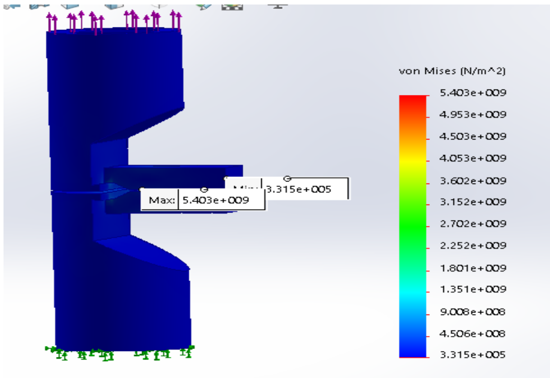



Figure 3.9: Stress analysis for assemble part after applied load 10kN

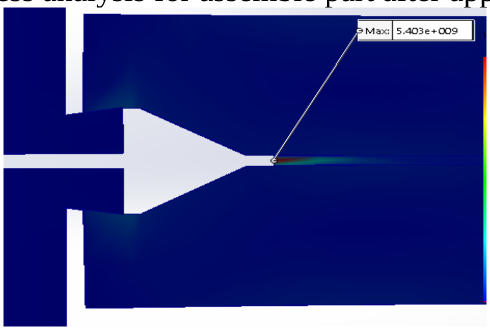



Figure 3.10: Maximum stresses at the Al 5052 specimen after applying 10 kN load

This demonstrates the reliability of the system as it is capable of running the fracture toughness testing, especially on Al 5052 chevron-notch specimen without undergoing deformation.

### 3.4 Material Properties of Jig

AISI 304 steel is used as the material for the jigs suggested in the ASTM 1304 standards. 304-grade stainless steel is comprised of no more than 0.8% carbon and at least 50% iron as shown in Table 3.4 The chromium contents protect the iron from oxidation (rust), meanwhile, Nickel also enhances the corrosion resistance of stainless steel.

Alloy 304 exhibits excellent corrosion, oxidation, and durability. Although 304 can be used in most industrial applications, most commonly it can be found present in kitchen equipment, architectural paneling, threaded fasteners, springs, and marine. The mechanical properties of the specimen were determined according with the datasheet stainless steel 304 as in Table 3.5.

Table 3.4: 304 Stainless steel [19]

| **Chemical Element** | **% Present** | **Chemical Element** | **% Present** |
|---|---|---|---|
| Manganese (Mn) | Max 2 | Sulphur (S) | Max 0.03 |
| Iron (Fe) | 66.345-74.00 | Chromium (Cr) | 18-20 |
| Carbon, (C) | Max 0.08 | Silicon (Si) | Max 1 |
| Nickel (Ni) | 8 - 10.5 | Plumbum (P) | Max 0.045 |

Table 3.5: Mechanical properties of 304 Stainless steel [20]

| Mechanical properties | Experimental value |
|---|---|
| Tensile Strength, MPa | 600 |
| Proof Strength, (Offset 0.2%), MPa | 310 |
| Elongation (% in 50mm) | 60 |
| Hardness( Brinell) | 170 |
| Endurance (fatigue) (MPa) | 240 |
| Tensile Strength, MPa | 600 |
| Proof Strength, (Offset 0.2%), MPa | 310 |

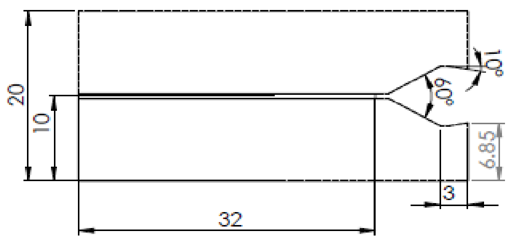
## 3.5 Material Properties of Chevron-Notch Specimen

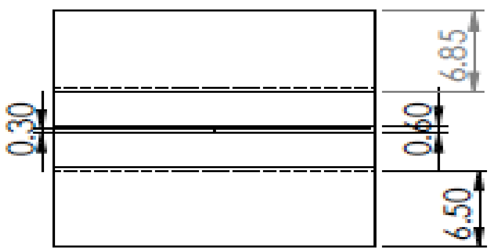
The material used for the chevron notch specimens is aluminium 5052. Aluminium 5052 is most commonly alloyed with copper, zinc, magnesium, silicon, manganese, and lithium. Aluminium is a lightweight material with a very good strength to weight ratio with very high corrosion resistance.

## 3.6 Preparation for Experiment

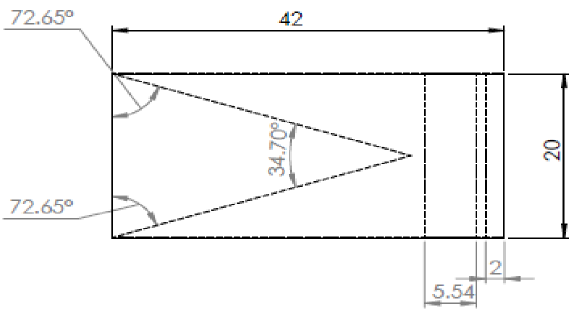
### 3.6.1 Standard Chevron-Notch Specimen

The dimensions of the chevron notched specimen were determined from the ASTM E1304. The drawing of the specimen is shown in Figure 3.11 below that includes the front, right and top views, and Figure 3.11 (iv) is the three -dimensional design of the chevron-notch specimen.




(i) Front view (ii) Right view




(iii)Top view