MINIATURE SPECIMEN FRACTURE TOUGHNESS TESTING: A CONCISE REVIEW

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MINIATURE SPECIMEN FRACTURE TOUGHNESS TESTING: A CONCISE REVIEW

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DECLARATION

This work has not previously been accepted in substance for any degree and is not being concurrently submitted in candidate for any degree.

Signed ……………………………… (Muhammad Asyraf bin Azhar)

Date: 24th July 2022

STATEMENT 1

This thesis is the result of my own investigation, excepts where otherwise stated.

Other sources are acknowledged by giving explicit references.

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NOMENCLATURE

a	Crack length
a_o	Original crack length
A_{pl}	The area under a load-plastic displacement curve
A_{tot}	The total area under a load-displacement curve
A(T)	Arc-shaped tension specimen
b	Crack remaining ligament
b_o	Original crack ligament
B	Specimen thickness
B_e	Effective specimen thickness
B_N	Specimen net-section thickness
C	Specimen load-line compliance
C(T)	Compact tension specimen
CMOD	Crack mouth opening displacement
CTOA	Crack tip opening angle
CTOD	Crack tip opening displacement
DC(T)	Disk-shaped compact tension specimen
E	Young’s modulus
J	*J*-integral
J_c	Critical *J*-integral at fracture instability
J_{Ic}	Plane strain fracture toughness characterized by *J*-integral
J_Q	Provisional J_{Ic} fracture toughness
J_{el}	Elastic component of *J*-integral
J_{pl}	Plastic component of *J*-integral
J_{max}	Maximum *J*-integral allowable in a valid *J*-*R* curve test
J_R	*J*-based crack extension resistance
K	Stress intensity factor
K_I	Stress intensity factor for model-I crack
K_{Ic}	Plane strain fracture toughness characterized by *K*-factor
K_{max}	The maximum stress intensity factor
K_{Jc}	Critical *K* value converted from J_c or J_{Ic}
LLD	Load-line displacement
M(T)	Middle-cracked tension panel specimen
N	Total number of fracture tests
P	Applied load
P_{max}	Maximum applied load or force
R-curve	The crack extension resistance curve
SE(B)	Single-edge notched specimen
V	Total crack-mouth opening displacement (CMOD)
V_{el}	Elastic component of CMOD
V_{pl}	Plastic component of CMOD
W	Specimen width
δ	Crack-tip opening displacement (CTOD)
Δ	Total load-line displacement (LLD)
Δ_{el}	Elastic component of LLD
Δ_{pl}	Plastic component of LLD
Δa	Crack extension, = $a - a_o$

Δa_{max}	Maximum crack extension allowable in a valid *J-R* curve test
Δa_p	Measured effective crack extension
η, γ	LLD-based geometric factors
η_{el}	Elastic η-factor
η_{pl}	Plastic η-factor
$\eta_{CMOD}, \gamma_{CMOD}$	CMOD-based geometric factors
v	Poisson's ratio
σ_{TS}	Tensile strength of a material
σ_{YS}	Yield strength of a material
σ_Y	Effective yield stress equal to an average of yield stress and tensile stress

ABSTRAK

Keliatan patah kecil telah dilakukan kerana banyak isu dibawa keluar, dan satu faktor utama adalah bahan yang tersedia terhad. Keliatan patah kecil boleh memberikan maklumat berguna yang berkaitan dengan sifat bahan dengan hanya menggunakan sebahagian kecil bahan. Tesis ini menyediakan ulasan teknikal ujian keliatan patah kecil, penyeragaman, dan penilaian untuk bahan logam. Kajian semula membincangkan parameter mekanik patah utama untuk spesimen kecil, J-integral, bermula dengan asasnya, dan takrifannya dan berkembang melalui anggaran percubaan, prosedur ujian dan prosedur standardisasi ASTM. Garis panduan untuk memilih parameter patah yang sesuai untuk menerangkan keliatan patah bahan dibincangkan, serta arahan untuk mengukur nilai keliatan patah yang ditakrifkan dalam format lengkung rintangan menggunakan spesimen tegangan padat makmal. Piawaian ujian biasa gabungan E1820 untuk menentukan parameter J ialah piawaian ujian keliatan patah ASTM yang berkenaan yang diambil kira dalam kerja ini. Kaedah dan teknik juga dibincangkan dalam kertas ini, termasuk kaedah pematuhan pemunggahan elastik dan penilaian dan pengurangan data dalam menentukan keluk J – R dan anggaran JQ. Semakan itu juga termasuk kajian awal dan kemajuan terkini dalam teknik dan prosedur ujian keliatan patah yang dicipta oleh Persatuan Pengujian dan Bahan Amerika (ASTM). Ujian keliatan patah kecil disemak dalam tesis ini dengan mengikut piawaian ASTM E1820 dan memberikan keputusan yang memuaskan tanpa menggunakan spesimen panel yang besar.

ABSTRACT

The miniature fracture toughness was done as many issues are brought out, and one main factor of those is limited available material. The miniature fracture toughness could provide useful information related to the properties of the material with only use small part of the material. The thesis provides a technical review of miniature fracture toughness testing, standardization, and evaluation for metallic materials. The review discusses the key fracture mechanics parameters for miniature specimen, *J*-integral, starting with their fundamentals, and definitions and progressing through the experimental estimation, test procedures, and ASTM standardization procedures. Guidelines for selecting a suitable fracture parameter to describe the material's fracture toughness are discussed, as well as instructions for measuring the value of fracture toughness defined in a format of resistance curve using laboratory compact tension specimens. A combined common test standard E1820 for determining *J* parameters is the applicable ASTM fracture toughness test standard taken into account in this work. The method and technique are also discussed in this paper, including the elastic unloading compliance method and data evaluation and reduction in determining the $J - R$ curve and estimation of J_Q. The review also includes the early studies and most recent advancements in fracture toughness test techniques and procedures created by the American Society for Testing and Materials (ASTM). The miniature fracture toughness testing is reviewed in this thesis with following ASTM E1820 standard and gave satisfactory results without utilize large panel specimen.

CHAPTER 1: INTRODUCTION

1.1 Overview of the Project

Fracture toughness is the ability of the material under the influence of defect to take the load before failing and its parameters provide crucial information about the material's behavior in the presence of a sharp crack. Irwin's pioneering work, which highlighted the critical significance role that the energy release rate plays in determining the structural integrity of brittle materials, gave rise to the concept of toughness [1]. In fracture mechanics, if the stress intensity factor in the crack tip equals the material's fracture toughness, the crack will begin to propagate [2]. Usually, the result of fracture toughness is represented in terms of toughness parameter such as *K*-factor (K_{IC}) or critical *J*-Integral (J_{IC}) [3]. In many circumstances, this information is essential for design or decision-making regarding the component's continued use or removal from service. Anywhere a material is used, there is a presence of a defect or a flaw that is not completely avoidable and gives a chance of failure by fracture.

For decades, fracture mechanics has been utilized, and procedures for standard-sized specimens have been well established in the community. Standardized specimens are considered large because they were primarily created for large structural assessments against brittle failure [4]. Sometimes, there may not always be enough experimental material to use for these standard specimens [5]. Hence, establishment of a new technique for using a smaller specimens must be developed, and methods using smaller-sized specimens must be offered, together with their validity limits and relationships to standard obtained results, to provide a solution for a wide range of applications.

Over the years, fracture toughness for miniature specimen has evolved but not mature yet, which can be applied to assess the applicable mechanical properties of aged structures and components without causing them to fail [6]. A lot of researchers and experts show interest in testing fracture toughness with small size specimens. Now, the issue of the mechanical test of the small specimen is certainly popular whether it can give best valid result as the standard one, quite similar, or not.

1.2 Objectives

1. To review of fracture toughness testing on the miniature compact tension specimen.
2. To review the fracture toughness parameter using *J*-integral method for miniature testing.

1.3 Problem Statement

Fracture in structures is a big issue that engineer's society encounter, and testing is done as a precaution step to avoid structural failure. However, in many of these critical circumstances, there is a limited of experimental material, therefore evaluation should be based on miniature specimen testing. The using of the standard size specimen will also cause in the material waste and use advanced large machine as to provide more load for the test, sometimes the equipment availability also one of the issues. The fracture toughness testing of the miniature specimen is still under development. Plus, there are very limited literature focusing on the fracture toughness of miniature specimen.

1.4 Scope of the Project

The purpose of this project is to review and how to develop and conduct fracture toughness testing of the miniature compact tension specimen. Starting from the preparation of the specimen, including their geometry, size and dimension, polishing, pre-cracking, side grooving until the real test of the fracture toughness. The elastic unloading compliance technique is reviewed in this project to determine the ductile fracture mechanics. Furthermore, the review is conducted as to evaluate the fracture toughness parameter using *J*-integral method and study further about $J – R$ curve. By using the elastic unloading compliance method, the data of load versus load-line displacement are converted into J and crack growth values to construct the $J – R$ curve. From the $J – R$ curve, following the data reduction and evaluation method that are explained in Section 3.3, the parameter fracture toughness of *J*-integral could be obtained.

CHAPTER 2: LITERATURE REVIEW

2.1 Fracture Mechanics

The study of fracture mechanics focuses on how cracks spread across materials. It is a very effective method for predicting and identifying structural failure. Griffith (1920) believe the material has crack-like defects, and that work must be done on it to provide the energy required to propagate the crack by forming two new crack surfaces [7]. Griffith (1920) also introduced Griffith's equation defined the fracture stress, σ_F, of a sharp elliptical crack of length $2a$ in an elastic material as:

$$\sigma_F = \sqrt{\frac{2ET}{\pi a}} \tag{1}$$

where E is the material modulus of elasticity and T is the surface energy defined as the work done in splitting the atomic bonds to produce two new crack surfaces [7]. From Alan (2013) however, the Griffith's equation is limited to a brittle material, where no plastic deformation occurs prior to fracture [8]. From Roylance (2001) when the material is more ductile, using only the surface energy as a factor to predict fracture is insufficient [9]. G. R. Irwin put his effort and work introducing the concept of the toughness, the critical significance of the energy release rate. Irwin (1948) proposed changing the surface energy from Griffith criterion to plastic work G developed a tip or crack [1]. Yarema (1995) stated a fundamentally new variation of the Griffith theory was established by G. R. Irwin, greatly extending its theoretical basis and fostering its widespread adoption in engineering practice [10].

2.2 Linear Elastic Fracture Mechanic (LEFM)

LEFM is an approach of crack analysis based on linear elastic theory, where it is only valid with relationship between load and crack-opening is linearly. From Hutchinson (1983) solutions from linear elasticity can be utilized to evaluate, or more specifically, correlate to the test specimen data when the zone of inelasticity is small enough [11]. The elastic force within the material is causing for the stress state at the crack tip when the plastic zone at the crack tip is small compared to the crack length. This was supported by Jois and Höwer (2021), while employing the LEFM to structural components, engineers must consider that when evaluating residual strength capability or stable crack growth under cyclic loading, the plastic deformation in the material must be restricted to a small region at the crack tip [12]. It can be said that LEFM theory only applicable to the brittle material.

It is necessary to take into account the energy used for plastic deformation at the crack tip in order to ensure the LEFM results are correlated with test data. Irwin (1958) and Dugdale (1960) separately calculated the size of the plastic zone created at the crack tip by considering that local crack tip stresses are equivalent to the material's yield stress [13], [14]. Irwin (1958) created a model where the plastic zone that created at the crack tip was presumed to be shaped like a circle [13]. Dugdale (1960) assumed that the plastic zone ahead of the crack tip is in the form of a strip [14]. In both of the models, the effective crack length was utilized as to determine the stress intensity factor instead of physical crack length.

In determining the fracture toughness parameter, LEFM use critical fracture value, K_{IC}, act as an indicator to indicate the amount of the stress can be applied to cause cracking. This was supported by Irwin (1957), the *K* factor was proposed as this is a evaluate of the elastic crack-tip field intensity and represents the LEFM [15].

2.3 Elastic Plastic Fracture Mechanics

EPFM is an approach of cracks analysis based on nonlinearity, which means, the cracks developed when the large region of the material are subject to plastic deformation at crack tip. When LEFM cannot be applied anymore in the fracture toughness, the EPFM theory will be able to apply. Anderson (1984) stated that LEFM theory is unsuitable for predicting the fracture strength of ductile material due to tough metals undergo significant plastic deformations in the vicinity of the crack tip before completely failure [16]. This was supported by Irwin (1948) and Orowan (1949) stated that when ductile material fractures, the stored strain energy is consumed for both of the development of two new cracked surfaces, as well as the work done in plastic deformation near the crack tip [1], [17]. According to Orowan (1949), the energy needed for plastic deformation at the crack tip in tough metals is substantially greater than the surface energy [17]. Irwin (1948) explained for the ductile material, the energy that needed to separate crack surfaces is insignificant in contrast to the work done in plastic deformation at the crack tip and can be neglect [1].

For EPFM, from Rice (1968), the *J*-Integral was suggested to elaborate the intensity of elastic-plastic crack-tip fields and represents the elastic-plastic fracture mechanics [18]. Rice (1968) also demonstrated the existence of an integral under such an elastic (linear or nonlinear) deformation of a component with a crack, known as *J*-integral, which is path independent when calculated by linking any two points on the opposite crack flank [18].

2.4 Specimen's Geometries

Based on the American Society for Testing and Material (ASTM) (2011), several specimens are allowed for fracture toughness testing that is expected to give the best valid result. The specimen could come with (a) Compact Tension (CT) specimen, (b) Disk-Shaped Compact specimen, (c) Arc-Shaped specimen, (d) Middle Tension (MT) specimen, and (e) Single-Edge-Notched Bend (SE(B)) specimen [19]. This was shown by Zhu and Joyce (2012), ASTM fracture test standards allow for six different types of conventional fracture test specimens, however, no single standard allows for all six configurations [3]. All the specimens have the same characteristics and dimensions in terms of labeled width (W), total thickness (B), and crack length (a), following the standard of ASTM.

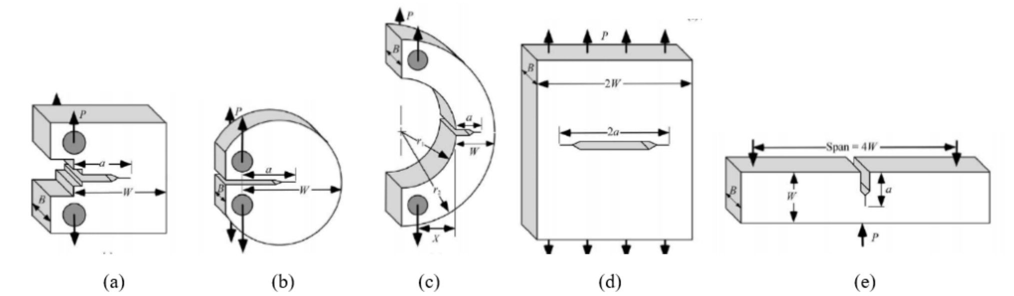

Figure 1: Type of Geometries Suggested by ASTM E1820 [19]

However, the most popular geometries used for the fracture toughness testing are CT specimens and SENB specimens. According to Medeiros and Dias (2013), for conventional fracture toughness tests, typically the measurement of fracture toughness was taken by using specimens with deep cracks, such as SENB and CT specimens [20]. This statement was also supported by Zhu (2015), among the fracture toughness geometries, the CT and SENB specimen are the two most commonly used in the test [21].

2.5 Size of Specimen Constraint Effect

The constraint effect is the name given to the influenced parameters that effecting the measurement of fracture toughness when plasticity dominates crack propagation. Based on Zhu and Joyce (2012), experiments have demonstrated that the fracture toughness parameters (K, G, J and δ) in EPFM theory are strongly influenced by the section thickness of specimen, size criteria, crack shape, crack depth, and loading configuration [3]. As a means of achieving estimation of fracture toughness properties, ASTM standards purposely select the specimen's designs that maximize the crack-tip constraint, such as deep cracked, relatively thick or side-grooved, and mostly bend loaded specimens.

For miniature specimen, it is obviously the constraint effect on fracture toughness in the category of the width and thickness of the specimen. The fracture toughness testing is usually conducted with a specimen that is big enough, fulfilling the size requirements according to the ASTM E399 standard. Weygand and Aktaa (2009) stated that geometrical size effect plays crucial part in the determination of the fracture toughness [22]. Based on Figure 2, the size or the thickness of the specimen dependence is associated with the transition from plane stress to plane strain. For the thickness dependent, the fracture toughness, K_C is called as the apparent fracture toughness, while K_{IC} is called as plane strain fracture toughness when it becomes an intrinsic material property and thickness independent. As the thickness of the specimen rises, it moves from plane stress to plane strain. Milne, Ritchie and Karihaloo (2003) stated that, in plane strain, the specimen will have a flat fracture surface, while in plane stress, the specimen will have shear lips fracture surface [23]. Besides, in the transitional condition, it can have a combination of flat and shear lip.

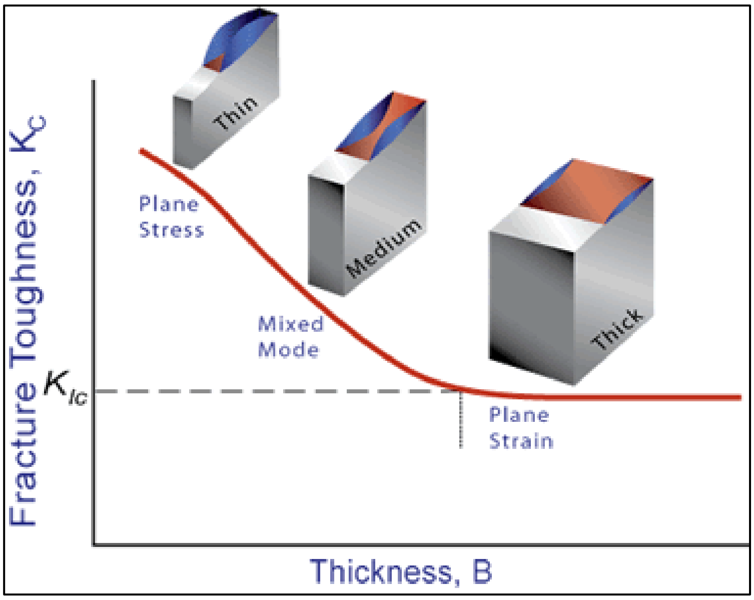

Figure 2: Variation of fracture Toughness due to Thickness [24]

Fracture toughness specimens having standard proportions, and fracture resistance (K_I) values differ amongst specimens with variable absolute sizes. According to NDT Resource Center (2013) the difference occurs because the stress states adjacent to the flaw vary with the specimen's thickness (B) until it reaches a critical dimension [25].

The value of K_I becomes generally constant once the thickness of the specimen surpasses the critical size, and this value, K_{Ic}, is a genuinely material property known as plane-strain fracture toughness. Based on Farag (2013) it can be said that stress intensity, K_I, and fracture toughness, K_{Ic}, have a common relationship as stress and tensile stress relation. The stress intensity, K_I, symbolizes 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 can withstand until it fails under very specific (plane-strain) conditions [26]. Zhu and Joyce (2012) stated that as the stress intensity factor hits the K_{Ic} values, unstable fracture takes place [3].

2.6 Elastic Unloading Compliance Method

Since the $J - R$ curve's introduction, great effort has been made to establish simple and accurate ways to assess the fracture toughness of various materials. Zhu and Joyce (2012) stated that one of the most often used methods to construct a $J - R$ curve with only one single specimen is the elastic unloading compliance method [3].

This was supported by Gao (2020), the elastic unloading compliance method is one of the most widely used approaches to estimate the crack lengths and has been used a lot by researchers [27].

Hutchinson and Paris (1979) demonstrated the *J*-integral has been shown to be useful in describing the crack propagation process if the applied deformation is small enough and the remaining ligament is large enough to allow a region of proportional strain field to easily encompass the local crack-tip non-proportional strain field [28]. Clarke et al. (1976) suggested by only conducting one single specimen test and use the elastic unloading compliance technique to obtain the *J* resistance curve by measuring the crack extension at a particular position on an experimental load versus load-line displacement data [29]. Throughout the experimental test technique, small elastic unloading was periodically applied, and the change in compliance with this unloading was used to determine the crack extension.

Joyce and Gudas (1979) improve the elastic unloading compliance method with designed an interactive computer-enhanced system for the control and collecting of digital data during a laboratory fracture mechanics test [30]. To Kuhn et al. (2000) it is not possible to utilize the elastic unloading compliance method for the materials without linear elastic loading characteristics or under rapid loading situations [31].

With the elastic unloading compliance method used, a load against the CMOD graph is obtained. The common trend and shape of the graph with the elastic unloading compliance method is as shown in Figure 3. Based on Xiang et al. (2014) an unloading-reloading sequence is represented by each short straight line and the remaining portion of the curve is similar to the load-displacement curve in a tensile test, with early elastic deformation followed by plastic deformation and a load drop after crossing the maximum load level [32].

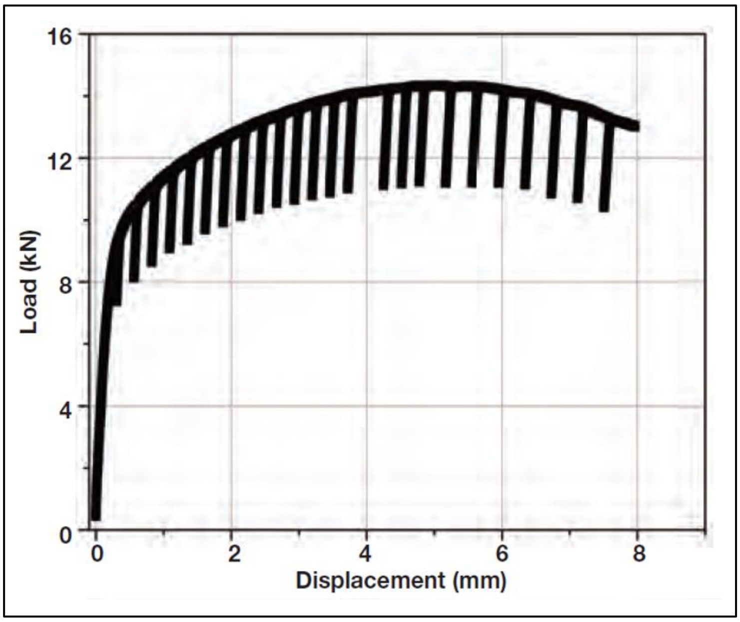

Figure 3: Typical Load versus Displacement Graph for Elastic Unloading Compliance Method [32]

2.7 *J – R* Curve

The LEFM or the *K*-factor theory are no longer relevant for cracks that are primarily caused by plastic deformation. Consequently, to characterize the materials' fracture resistance, the elastic-plastic fracture or the *J*-integral theories are applied by calculating and determining the J_C, J_{Ic}, or $J – R$ curves. From Mehta (2016) a $J – R$ curve is a graph of the resistance of steady crack expansion considered based on *J* plotted against ductile crack propagation, typically taken as Δa_p, the observed physical crack extension [33]. Zhu and Joyce (2012) said that to develop efficient test procedures and test methodologies for determining the critical values of the toughness parameters *G*, *K*, *J*, CTOA, and δ and ascertaining the relevant crack growth resistance curves such as $K – R$ curve, $J – R$ curve and $\delta – R$ curve, extensive analytical, computational, and experimental investigations have been carried out globally since the 1950s [3]. Figure 4 shows the common trend and shape of the $J – R$ curve graph. This pattern is supported by Joyce and Gudas (1979) conducted the unloading compliance method of a single specimen test and obtained detailed computerized compliance data the $J – R$ curve constructed is curve shape rather than a straight line [30]. This statement has also been supported by Hiser et al. (1984) and Jablonski (1985) based on their experimental observation [34], [35].

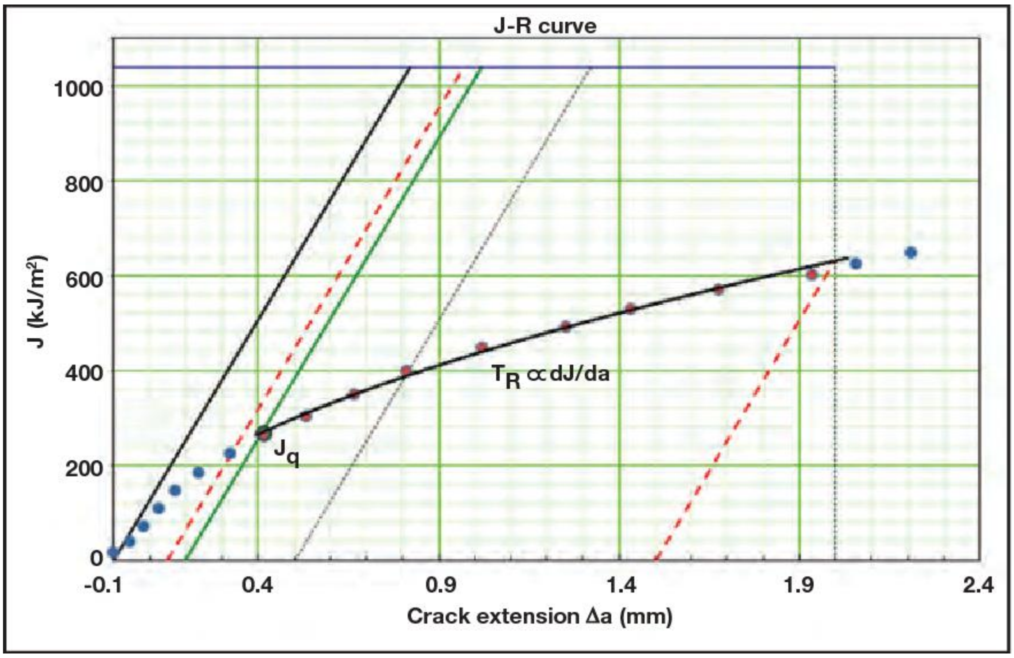

Figure 4: Typical $J - R$ curve [32]

The J-integral is computed from the total J estimate by utilizing the formulas provided in the ASTM E1820 standard based on the initial crack size and disregarding crack growth correction (refer Section 3.3 for the methodologies and formulas in converting load plotted against load-line displacement graph to J plotted against ductile crack propagation graph). The approach was only applicable for minor quantities of crack extension. From Zhu and Joyce (2012) a partial $J - R$ curve can be formed using the data points collected from the multiple specimen method, or another one utilizing four crack length measurements within the specified range when conducting a single specimen test with using the elastic compliance method [3]. As all necessary test requirements were satisfied, the J_q value was determined by the intersection of a linear fit to the (J, Δa) pairs in an inclusion zone between crack extension limitations and a blunting line.

Based on Zhu and Leis (2009) a size-independent $J - R$ curve that is equivalent to the corresponding $K - R$ curve can be produced for specimens with plane stress or thin sections for the material of aluminum alloys [36]. This is also supported by Haynes and Gangloff (1997), who these investigators developed a crack growth resistance curve for different materials using compact tension specimens with regard to K and J parameters and ascertained that the $J - R$ curve shows quite alike to the K

– *R* curve for high strength aluminum alloys, and *J* – *R* curve could be generated for different metals [37].

A single specimen test can yield an accurate *J* – *R* curve by using CMOD data. The crack propagation, however, involves numerous analysis steps and is indirect and challenging. Zhu et al. (2008) discovered a functional relation between LLD and CMOD and proposed a long-overdue CMOD approach to directly assess crack growth corrected *J* – *R* curves [38]. Zhu et al. (2008) created a CMOD-based incremental *J*-integral equation based on the deformation theory of plasticity and Ernst et al. [39]'s theories as follows [38]:

$$J_{pl(i)} = \left[J_{pl(i-1)} + \left(\frac{\eta_{pl(i-1)}}{b_{(i-1)}} \right) \frac{A_{pl(i)} - A_{pl(i-1)}}{B_N} \right] \left[1 - \gamma_{(i-1)} \left(\frac{a_{(i)} - a_{(i-1)}}{b_{(i-1)}} \right) \right] \tag{2}$$

where all the information in the Equation (2) is elaborated in details in the Section 3.3

The CMOD direct approach and the incremental equation of *J* plastic calculation for a *J* – *R* curve evaluation were officially adopted by ASTM E1820 in 2009. In the elastic unloading compliance method, only *P*-LLD data are needed to be recorded in the fracture toughness testing, reducing the complexity of the standard test procedures in E1820. To Zhu (2009), as a result of adopting CMOD-based incremental *J*-integral equations, the *J* – *R* curve testing is made easier and more affordable, and the outcomes are more accurate [40].

CHAPTER 3: METHODOLOGY

In this chapter, the step by step of the miniature fracture toughness test are elaborated with following the ASTM E1820 standard, and also by referring to the other experts and researcher done for their case. In short, the specimen preparation including the specimen's geometry, polishing specimen, fatigue pre-cracking and side grooving are explained. For conducting the miniature fracture toughness test, the elastic unloading compliance method is used and applied. Based on load against crack growth plot, $J - R$ curve is constructed. Data calculation and evaluation are done based on the ASTM standard.

For fracture toughness testing, the specimen is needed to be prepared first before the real test is run. The specimen needed to be fabricated as required, following the geometry in the fracture toughness testing standard to gain a valid result. In addition to that, the specimen also needs to be polished and pre-cracked. Once the preparation is completed, fracture testing can begin.

3.1.1 Specimen's Geometry

According to the ASTM E1820, there are some of the standard shape and geometry of the specimens, which are single-edge-notched bend SENB specimen, CT specimen, (DCT) specimen, arc-shaped specimen and MT specimen [19]. All these shapes of the specimen are expected to give the best valid result for the fracture toughness testing. In the fracture toughness testing, typically used specimen are SEND and CT specimens.

This thesis will focus on the compact tension specimen with miniature size containing a through-thickness tensile crack mode I crack as in Figure 5. The figure shows the specimen width, W (the point of the center hole to the end of the specimen), specimen thickness, B, a is the crack length of the specimen and P is a load applied for the testing. In most cases, W is often equivalent to $2B$, and a/W is 0.5. However, to achieve valid fracture toughness result and to mitigate the impact of the crack-tip constraint on that fracture toughness parameter, different specimen size criteria are specified in various fracture test standards as long as the qualification requirements are met.

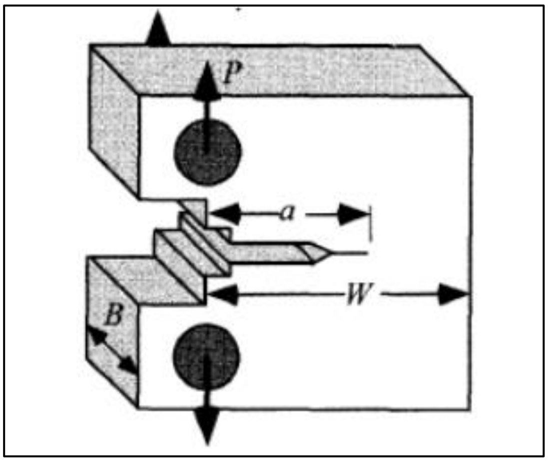

Figure 5: Standardized Fracture Mechanics Test Specimen of Compact Specimen [41]

The geometry of the test specimen come in miniature size with lower thickness and width. Some of them can be fabricated from the broken failure specimen or directly from the raw material. From Sokolov (2016) the miniature CT specimens with dimension of 10 x 10 x 4 mm^3, 10 mm in length, 10 mm in height, and 4 mm in thickness were machined from one broken half of the pre-crack Charpy V notch specimens with a material of HSST Plate 13B [42]. One broken half of the PCVN specimen is enough to machine 4 miniature CT specimen. Also, from Sokolov (2017), two miniature CT specimens with dimension of 10 x 10 x 4 mm^3, 10 mm in length, 10 mm in height, and 4 mm in thickness were machined from a broken half Charpy impact test specimen with material of un-irradiated Linde 80 WF-70 weld [43]. Figure 6 and Figure 7 show the layout of miniature CT specimens within broken Charpy half specimen from Sokolov's investigation in 2016 and 2017 respectively.

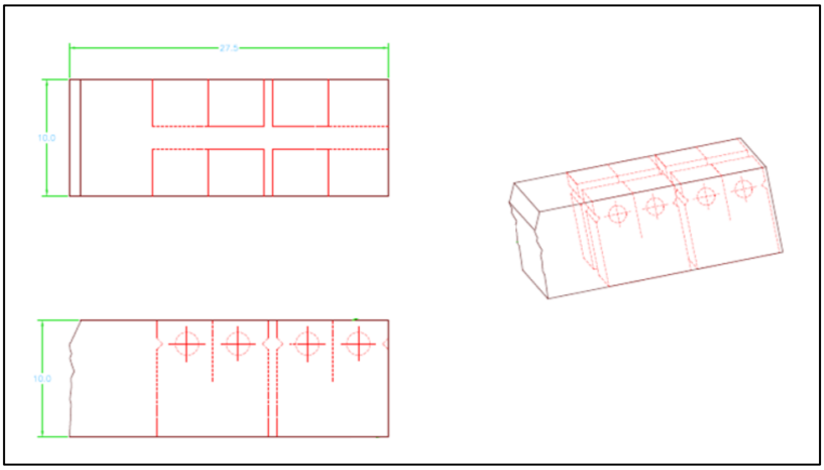

Figure 6: Layout of 4 Miniature CT Specimens within Broken Charpy Half Specimen [42]

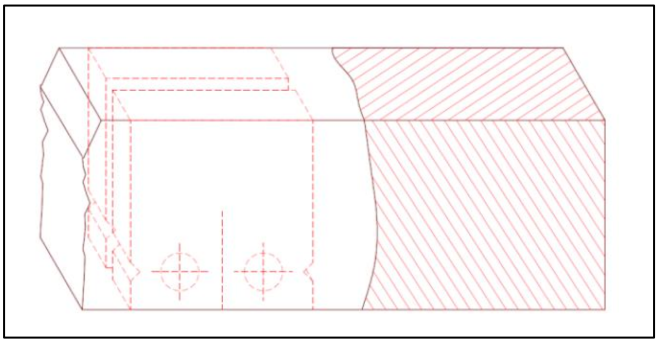

Figure 7: Layout of 2 Miniature CT Specimens within Broken Charpy Half Specimen [43]

Else, from Camila et al. (2013) the material of GLARE 3 5/4 0.3 is used. Five 0.3 mm sheets of 2024-T3 alloy with size of 0.3 mm thickness are bonded together by four layers of bidirectional equally distributed S-glass fibers and then, these fiber-metal laminates were cut and made into compact tension specimens [44]. From Prakash (2004) an Al-Cu alloy 2014-T6511 is cut and made into the shape of a compact specimen [45]. Based on Shinko and Yamamoto (2022), as the miniature compact tension specimen is small, it can be machined from a broken Charpy specimen [46].

Compact tension specimen is a single edge-notched and fatigue-cracked plate loaded in tension and serves as the industry standard compact specimen. Figure 8 displays two specimen geometries with different knife edge that have been successfully employed for *J* testing. The specimen could come with different width and thickness as long as it meets requirement in the ASTM E1820 standard ($2 \leq W/B \leq 4$). However, many researchers conducted miniature fracture testing for compact tension specimens with different geometry of the knife edge, but still the main idea of the geometry is still there.

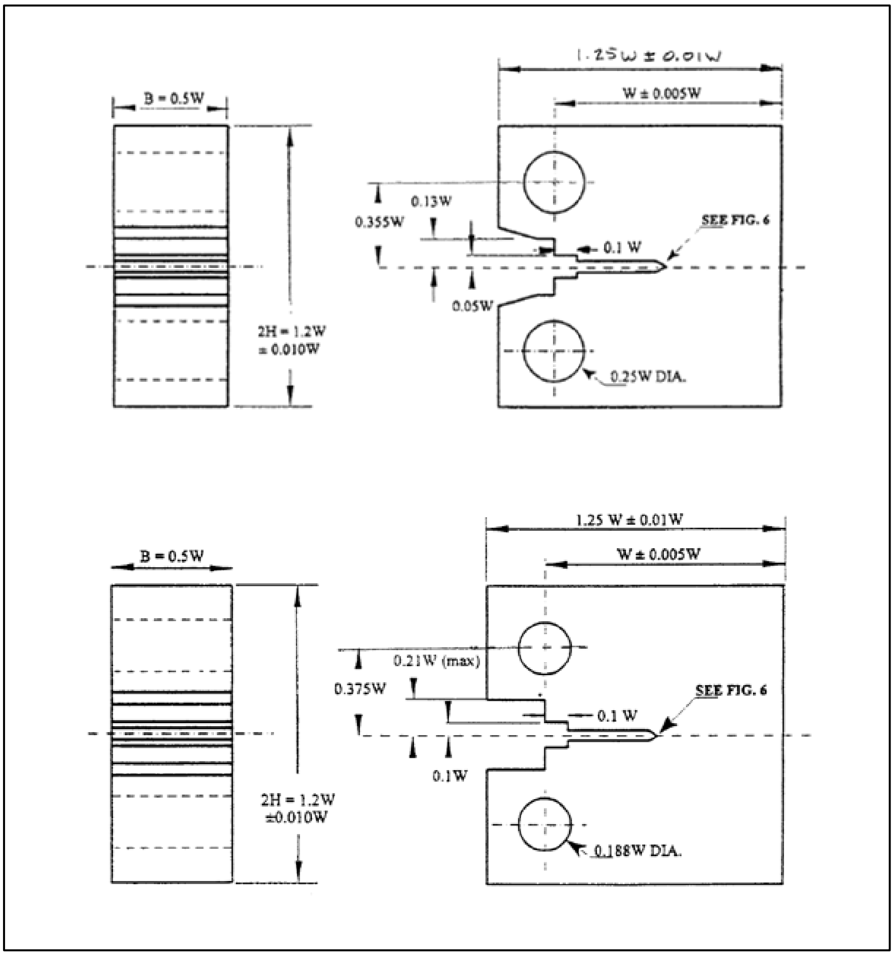

Figure 8: Two Common Designs of Compact Tension Specimen for Fracture Toughness Testing [19]

3.1.2 Polishing Specimen

For this method, the specimen needs to be polished from low grit to higher grit to gain a smooth surface finish. Suggested to start with a range of 40 to 8000 grit, but still, the range of the grit is depending on the material of the specimen itself. To gain the mirror surface finish, it is advised to use the rotary grinder or the grinder with alumina powder or diamond paste with a lower grain size. Triwatana et al. (2013) polished their specimen with diamond paste having a grain size of 3 to 5 μm [47].

The purpose of the mirror surface finish is to make it easier to observe the crack propagation for the pre-cracking process. Rust and corrosion surfaces will give difficulty for cracking observation and prevent a clear view of the crack propagation.

3.1.3 Fatigue Pre-Cracking

For the fracture toughness test, the pre-cracking process is a must process needed before the test is conducted to achieve a sharp crack on the specimen. All the specimens require to be pre-cracked in fatigue according to the ASTM E1820 standard. Experienced experts have demonstrated that it is hard and unfeasible to attain a reproducibly sharp, narrow machined notch that will simulate a natural crack adequately sufficient to offer a reliable and acceptable fracture toughness test result, that is why fatigue pre-cracked is needed.

This is also supported by ASTM 339 (2009) that in the fracture toughness test, the specimens require a sharp pre-crack [48]. Kumar et al. (2021) the pre-cracking of the specimens is essential to study the fracture mechanics of various materials [49]. The pre-cracking specimen is a sample that is utilized to precisely determine the cracking's distribution and is a preferred technique for discovering the distribution of cracks.

The pre-crack on the specimen is produced by cyclically loading the notched of the specimen usually could take up from 10^4 cycles to 10^6 cycles, depending on the size of specimen, notch set up, and stress intensity level. Suresh (1991) said cyclic loading on notched specimens allows mode I pre-crack brittle and semi-brittle materials with stable crack growth [50]. For J and δ determination, the crack size, combined average length of the fatigue crack and crack starting configuration is restricted to fall between 0.45 and 0.70 W. For miniature specimen, most of the researchers took the *a/W* to be 0.5. Camila et al. (2016) did the pre-cracking process of the specimen according to the ASTM E1820 standard with *a/W* of CT specimen 0.5 [44]. Prakash (2004) also took the *a/W* of CT specimen 0.5 with a pre-crack method by K-decreasing technique under constant load cycling [45]. Shinko and Yamamoto (2022) took the *a/W* of all their specimens to be approximately 0.5 [46].

The maximum force shall be less than P_m, for the CT specimen, the equation is given as:

$$P_m = \frac{0.4 B {b_o}^2 \sigma_Y}{2W + a_o} \tag{3}$$

where, $B =$ Thickness, $W =$ Width, $b_o =$ Uncracked Ligament $= W - a$

$$\sigma_Y = \frac{\sigma_{TS} + \sigma_{YS}}{2} \tag{4}$$

where, σ_{TS} = Tensile Strength and σ_{YS} = Yield Strength

It has been advised that the maximum force for the fatigue pre-cracking is about 50% of the P_m so that the crack propagation could be controlled. For $R = P_{MIN}/P_{MAX} = 0.1$, this value is generally most effective to be used. From Philips (1996) it is necessary to do the fatigue pre-cracking at a low enough stress intensity to reduce the plastic zone before the fracture [51]. Kumar (2021), sometimes, it is difficult to create a fatigue crack in certain materials as they create an unstable crack propagation and lead to a fracture before achieving a sufficiently long enough fatigue pre-crack [49]. Pre-cracking must be carried out in a minimum of two steps.

It is advised that the user begins with the loading of roughly 0.7 K_{IC}, and then gradually raise the load if the pre-crack does not grow after 10^5 cycles to make the crack starts to extend. For the second pre-cracking phase, which shall include at least the last 50% of the fatigue pre-crack, the specimen must be subjected to the maximum stress intensity factor specified by:

$$K_{2max} = 0.6\left(\frac{\sigma_{YS}^{f}}{\sigma_{YS}^{T}}\right)K_F \tag{5}$$

where $K_F = K_Q$, K_{JQ}, K_{JQc} or K_{JQu} depending on the result of the test and K_F is determined from the corresponding J_F with relationship given as:

$$K_F = \sqrt{\frac{EJ_F}{(1-v^2)}} \tag{6}$$

where E is material Young's modulus and v is the Poisson ratio.

3.1.4 Side-Grooving

According to the ASTM E1820 standards, it is necessitating the use of specimens with bending dominance and a fixed range of crack depth to width ratios, placing restrictions on the remaining ligament to thickness ratios, demand a minimum size, and frequently in most case need side grooves along the crack ligament [19]. A side groove is a type of groove that is made as a deep line cut on the surface of the specimen. The purpose is to guide and ensure the crack produced is straight as desired. From Chen et al. (2013) one goal of employing side grooved specimen is to establish a straight crack front and to limit the number of tests that are invalidated by curved crack fronts [52]. Based on Zhu and Joyce (2012) if the specimen has side grooves and complies with all other ASTM standards, the specimen can primarily be subjected to plane strain conditions, allowing for the measurement of plane strain fracture toughness [3]. Figure 9 shows the common look of the CT specimen after side grooved. The B the specimen's thickness and B_N is specimen net-section thickness.

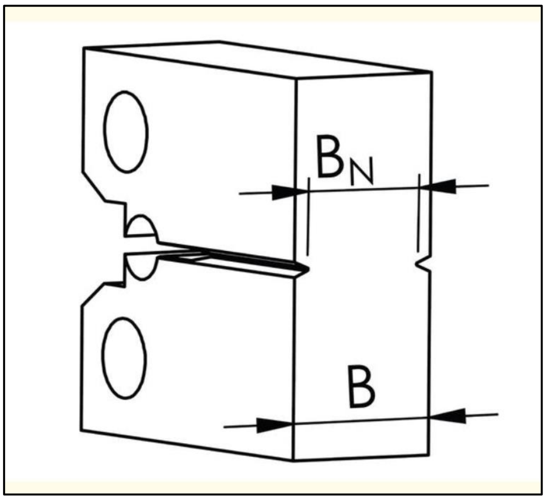

Figure 9: Compact Tension Test Specimen with Side Groove [5]

It has been said that the side groove is one of the factors that contribute to conservative results. To Chen et al. (2013) it is advised to use side grooved specimens when utilizing the compliance method of crack size estimation [52]. This is compatible with the ASTM E1820 standard for using the specimens with side grooves when the compliance technique of crack prediction is utilized. Since the fracture toughness testing for miniature specimen utilize elastic unloading method, side grooving is really recommended on the specimen.

The dimensions and size of the side groove should be followed as stated in ASTM standards to ensure valid results are obtained. Based on the ASTM E1820 standard, the overall thickness reduction cannot be greater than 0.25B with included angle of side groove not more than 90^{o}. The root of the side groove must be positioned along the specimen's centreline as in Figure 9. For many materials, it has been observed that a total reduction of 0.20B is effective. Chen et al. (2013) conducted a fracture toughness test with a 20% of thickness reduction side groove and give a valid test result with a straight crack extension front [52]. From Shinko and Yamamoto (2022), the miniature CT specimen with thickness of 4 mm is side grooving with a reduction of 20% of the thickness, give the B_N equal to 3.2 [46].

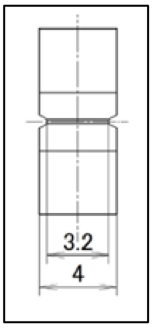

Figure 10: Side Groove Geometry of Miniature CT Specimen by Shinko and Yamamoto [46]

3.2 Elastic Unloading Compliance Method

The elastic unloading compliance method is one of the evaluations for fracture toughness resistance data based upon single specimen testing according to ASTM E1820. The procedure is fundamentally implemented by calculating the instantaneous value of the specimen compliance at unloading/reload sequences during the measurement of the P against the LLD plot. The specimen response is defined in terms of the P-LLD. This method allows for the precise J and Δa estimations at various data points, enabling the $J - R$ curve to be created.

The specimen is placed under the displacement gauge, machine crosshead, or actuator displacement. The specimen is loaded so that it takes between 0.3 and 3.0 minutes to reach the force P_m, as specified in Equation (3). The time for the unloading/reload procedure should be performed as it is required to accurately estimate the crack size but should only take up to 10 minutes maximum. It should be noted that before the specimen reaches its maximum force, at least 8 data points are expected. Before taking compliance measurements, load relaxation may take place for many materials, leading to a time-dependent nonlinearity in the unloading slope. Holding the specimen for a while until the force stabilizes at a constant displacement before starting the unloading is one way to counteract this impact. Return the force to zero without causing the crosshead to move farther than the currently allowed maximum displacement after completing the last unloading cycle.

Based on ASTM E1820, during the testing, the maximum suggested range for each sequence of unloading/reloading should not be greater than 50% of the maximum pre-cracking load, P_m, or the current load, whichever is smaller. Prakash (2004) conducted the test with increment of COD for about 0.05 mm after each peak load with using a loading rate of 0.5 mm/min and unloading to 50% of peak load over 15 seconds under the load control [45].

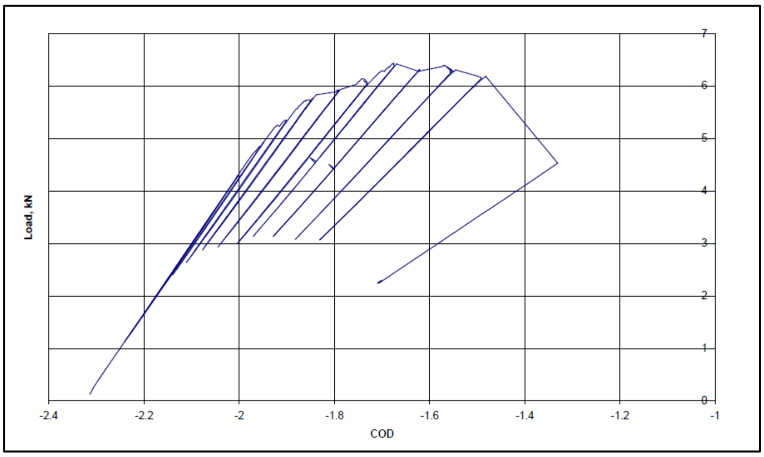

Figure 11: Load-CMOD Graph Obtained for Single *J* Integral Test on Al-Cu Alloy CT Specimens [45]

From Camila et al. (2016), they used a digital camera to evaluate optical crack growth and install it on a Zeiss Stemi Sv6 stereo-microscope. The monotonic loading during the test was conducted under displacement control with a constant 0.5 mm/min displacement rate. The unloading/reloading sequence was conducted under load control at 1.5 kN/min loading rate for elastic compliance evaluation [44]. From Prakash (2004) the fracture toughness test was performed in stroke control with load-line displacement (LLD) increment as the feedback for the test control. With the help of the MTL-Windows 6 software's super-average mode of data collecting, load and crack opening displacement data were continually logged [45].

The displacement interval between the unload/reload phases should not be more than $0.01b_o$, with the average being around $0.005b_o$. Using bigger increments between unloading will result in less accurate $J-R$ curves although the outcome result will be conservative. It may be essential to do additional unload/reload sequences in the early region of the *J* – *R* curve if a toughness initiation value is being considered.

3.3 *J* – *R* Curve Evaluation

This procedure outlines a single-specimen approach in calculating the *J* – *R* curve of metallic materials. The plot data of *P* against LLD that gained from elastic unloading compliance method are used for the *J* – *R* curve construction. According to Xiang et al. (2014), *J* – *R* curve, the *J*-integral versus crack growth resistance is a helpful tool for assessing a material's structural integrity when there are already flaws present [32]. Referring to *J* – *R* curve graph, the work or energy per unit of fracture surface area required to cause crack growth can be calculated. *J* – *R* curve can be used to evaluate the material's fracture toughness near to the start of steady crack propagation (J_Q).

J–*R* curve is made up of two parts, *J*-Integral and cracks growth. Using the recommended equations in this calculation section (for the compact tension specimen), *J* can be determined at any point on the *P* versus LLD record. The curve produced involves a calculation of these two aspects. *J*-Integral can be calculated as follows:

$$J_i = J_{el(i)} + J_{pl(i)} \tag{7}$$

where $J_{el(i)}$ is an elastic component of *J*-Integral while $J_{pl(i)}$ is a plastic component of the *J*-Integral and *(i)* indicate the iteration of the data. Regarding the compact tension specimen, any position data that matching $a_{(i)}$, $v_{(i)}$, and $P_{(i)}$ on the specimen *P* against the LLD record calculate as follows:

$$J_{el(i)} = \frac{(K_{(i)})^2(1-v^2)}{E} \tag{8}$$

where v is Poisson's ratio, *E* is Young's modulus, and $K_{(i)}$ is stress intensity factor and depending on the specimen configuration, crack size, load level, and others factors.

$$K_{(i)} = \frac{P_{(i)}}{(BB_N W)^{\frac{1}{2}}} f\left(\frac{a_i}{W}\right) \tag{9}$$

where

$$f\left(\frac{a_i}{W}\right) = \frac{\left\{\left(2+\frac{a_i}{W}\right)\left[0.886+4.64\left(\frac{a_i}{W}\right)-13.32\left(\frac{a_i}{W}\right)^2+14.72\left(\frac{a_i}{W}\right)^3-5.6\left(\frac{a_i}{W}\right)^4\right]\right\}}{\left(1-\frac{a_i}{W}\right)^{3/2}} \quad (10)$$

For *J*-Integral of the plastic deformation, $J_{pl(i)}$ is calculated as follows:

$$J_{pl(i)} = \left[J_{pl(i-1)} + \left(\frac{\eta_{pl(i-1)}}{b_{(i-1)}}\right)\frac{A_{pl(i)} - A_{pl(i-1)}}{B_N}\right]\left[1 - y_{(i-1)}\left(\frac{a_{(i)} - a_{(i-1)}}{b_{(i-1)}}\right)\right] \quad (11)$$

where

$$\eta_{pl(i-1)} = 2.0 + 0.522\ b_{(i-1)}/\mathrm{W} \quad (12)$$

$$y_{(i-1)} = 1.0 + 0.76\ b_{(i-1)}\mathrm{W} \quad (13)$$

b is crack remaining ligament and a is crack length

The quantity $A_{pl(i)} - A_{pl(i-1)}$ in Equation (14) represents the increase in plastic area under the *P* versus plastic LLD record between lines of constant displacement at the positions or points $i-1$ and i as shown in Figure 12. The amount $J_{pl(i)}$ is constructed in two processes by first increasing the current $J_{pl(i-1)}$ and then by altering the total amount accumulated result to take into account for the crack growth increment. The quantity $J_{pl(i)}$ indicates the total crack growth corrected plastic *J* at point i. According to recommended elastic compliance spacing, small and uniform crack growth increments are necessary for an accurate evaluation of $J_{pl(i)}$ from the above relationship. The following equation can be used to determine the quantity $A_{pl(i)}$:

$$A_{pl(i)} = A_{pl(i-1)} + \frac{\left[P_{(i)} + P_{(i-1)}\right]\left[\mathrm{v}_{pl(i)} - \mathrm{v}_{pl(i-1)}\right]}{2} \quad (14)$$

where

$v_{pl(i)}$ = plastic part of the load-line displacement, $v_{pl(i)} = v_i - P_{(i)} C_{LL(i)}$

$C_{LL(i)}$ = experimental compliance, $(\Delta v / \Delta P)_i$, corresponding to the current crack size, a_i

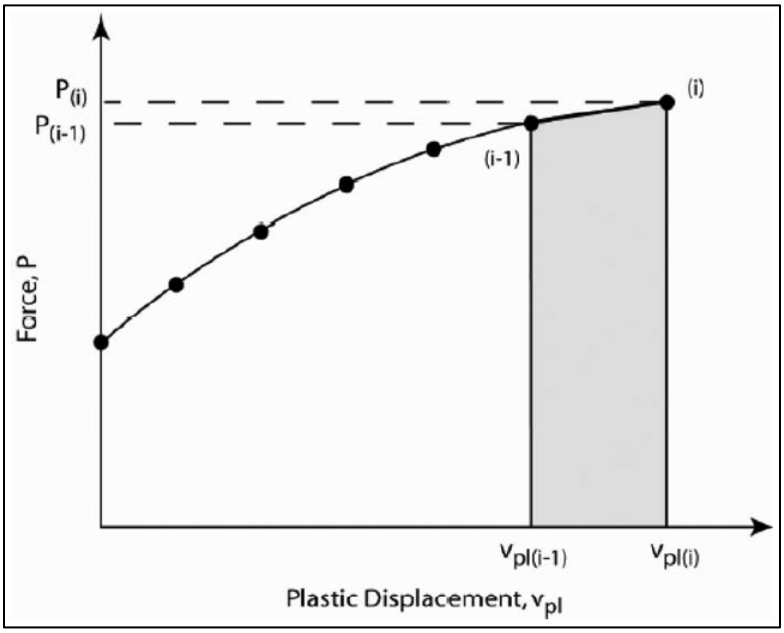

Figure 12: Definition of Plastic Area for Resistance Curve *J* Calculation [19]

The calculation of the crack size is provided below if employing an elastic compliance approach on a single compact specimen.

$$\frac{a_i}{W} = 1.000196 - 4.06319u + 11.242u^2 - 106.043u^3 + 464.335u^4 - 650.677u^5 \tag{15}$$

where

$$u = \frac{1}{\left[B_e E C_{c(i)}\right]^{1/2} + 1} \tag{16}$$

where

$C_{c(i)}$ = specimen load-line crack opening elastic compliance $(\Delta v / \Delta P)$ on an unloading/reloading sequence corrected for rotation,

$$B_e = B - (B - B_N)^2 / B \tag{17}$$

As the J and Δa data are obtained, the $J - R$ curve then can be constructed. With some steps and techniques, applying the data reduction method, the $J - R$ curve can be analyzed, and based on the plot graph, the value of J_Q could be obtained. An exclusion line parallel to the construction line that intersects the abscissa at 0.15 mm (0.006 inches) is drawn after plotting the construction line. When the construction line intersects the abscissa at 1.5 mm (0.006 inches), a second exclusion line parallel to it is drawn. All J and Δa data points that fall within the region bounded by these two parallel lines are plotted and capped by J_{limit}. Then, a parallel line at a 0.2 mm (0.008 inches) offset value from the construction and exclusion lines is plotted. Between the 0.15 mm (0.006 inches) exclusion line and a parallel line offset by 0.5 mm (0.02 inch) from the construction line, at least one $J - \Delta a$ point must be present. The same goes for the between 0.5 mm (0.02 inch) offset line and 1.5 mm (0.06 inch) exclusion line, at least one $J - \Delta a$ data point shall be present. Anywhere inside the exclusion zone is where the other $J - \Delta a$ pairings could be. Figure 13 shows the construction lines for data qualification, while Figure 14 shows the region for data qualification.

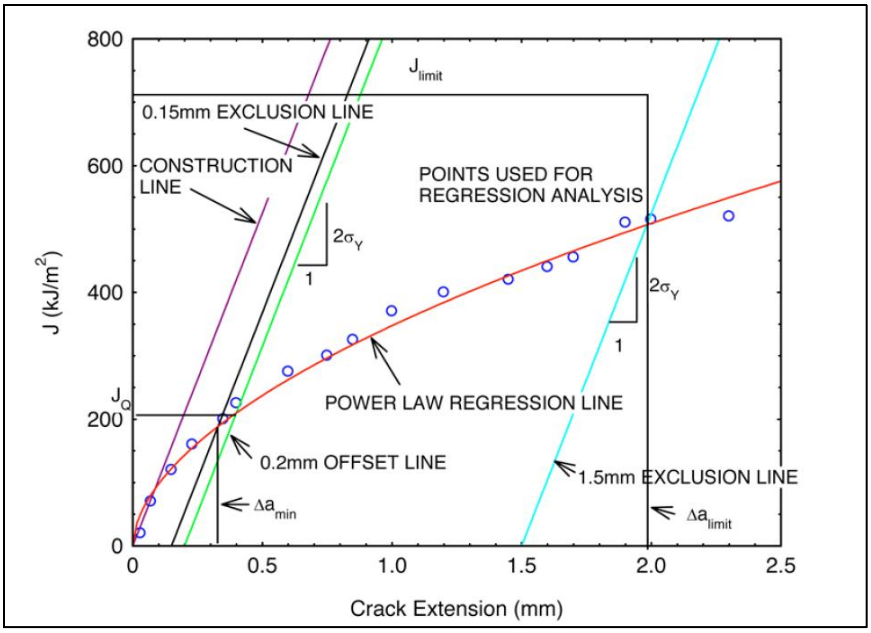

Figure 13: Definition of Construction Lines for Data Qualification [19]