

FRACTURE ASSESSMENT OF NOTCHED 2099-T83 ALUMINUM-LITHIUM SPECIMENS UNDER TENSILE STATIC LOADING

BY

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A Thesis Presented to the
DEANSHIP OF GRADUATE STUDIES

KING FAHD UNIVERSITY OF PETROLEUM & MINERALS

DHAHRAN, SAUDI ARABIA

In Partial Fulfillment of the
Requirements for the Degree of

MASTER OF SCIENCE

In

MATERIAL SCIENCE AND ENGINEERING

SEPTEMBER 2020

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MATERIAL SCIENCE AND ENGINEERING

September 2020

KING FAHD UNIVERSITY OF PETROLEUM & MINERALS
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I dedicate the thesis to Allah, the creator, most merciful and the source of all knowledge, wisdom and understanding.

In addition, to the most important people in my life and mean all the world to me. First of all, to my beloved parents who were always there for me, supporting me through the toughest time and continuously encouraging me to be the best I can be, Thank you both for everything. Next, to my dear siblings, my brothers and sisters, who have taught me the value of hard work and guided me to reach my goals and objectives, I will always remember the valuable advise you passed on to me. Lastly, I also would like to dedicate this to my newly beloved wife and her unlimited emotional support, overlooking and accepting my absence especially during our precious as newlyweds and given me reassurance during trying times. In the end, I love you all and there are not enough words to express how much I appreciate your presence in my life. May Allah bless you all and grant you Janat Al-Fardos

ACKNOWLEDGMENTS

To begin, I would first like to thank Dr. Jafar Albinmousa who has continuously encouraged, supported and guided me during my journey, I have gained much experience working with you and learned value lessons in my personal life and professional life as well. In addition, I would like to thank Dr. Nesar Merah and Dr. Morsi Ahmed for their continues guides throughout this study work. Never to forget, my family and friends who provided support and motivations through my higher education journey.

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LIST OF ABBREVIATIONS

Al-Li	Aluminum-Lithium Alloy
AM	Area Method
ANSI	American National Standard Institute
APDL	ANSYS Parametric Design Language
ASTM	American Society for Testing and Materials
FEA	Finite Element Analysis
FEM	Finite Element Modeling
KFUPM	King Fahd University of Petroleum and Minerals
LM	Line Method
MTC	Material Testing Certificate
PM	Point Method
SED	Strain Energy Density
SEM	Scanning Electron Microscopy
TCD	The Theory of Critical Distance
VM	Volume Method

NOMENCLATURE

ε_x	Elongation
K_{IC}	Fracture Toughness
K_p	Notch Stress Intensity Factor
r_0	Distance Of The Origin Coordinates To The Notch Tip
T_{ef}	The Effective T-Stress
X_{ef}	The Effective Distance
σ_{ef}	The effective Stress
σ_o	Critical Distance
σ_{yy}	Maximum Principle Stress
G_c	Critical Energy Value
F_c	Critical Force Value
W_c	Critical Strain Energy
F	Force
R_c	Radius of Controlled Volume
W	Strain Energy
UTS	Ultimate Tensile Strength
$wt\%$	Weight Percentage
Y	Yield Strength
E	Young's Modulus
a	Crack Length
d	Distance
k	Elasticity Factor
K	Strain Hardening Coefficient
L	Critical Distance, Length
n	Strain Hardening Coefficient
P	Applied Force

S	Surface Energy
U	Stored Strain Energy
V	Volume
x	Displacement
α	Notch Opening Angle
δ'	Sigma Phase Precipitate
λ	William's Eigenvalue
ν	Poisson's Ratio
ρ	Notch Root Radius
σ	Ultimate Tensile Strength
Φ	Weight Function
T	Stress Triaxiality

ABSTRACT

Full Name : [Abdullateef Saleh Almutairi]
Thesis Title : [Fracture Assessment of Notched 2099-T83 Aluminum-Lithium Specimens Under Tensile Static Loading]
Major Field : [Material Sciences & Engineering]
Date of Degree : [September 2020]

Al-Li alloys attracted researcher's attention due to their widespread uses for high strength and stiffness accompanied with low density properties. Saudi Arabia 2030 vision is aiming toward a knowledge-based economy through localization of engineering industries especially in military and defense fields where Al-Li is playing a vital role in aerospace and aircrafts manufacturing. Engineering numerical modelling to predict load design capacity or evaluation of the remaining life of notched engineering member is essential however, it is a lengthy and costly process. Researchers and engineers developed and explored several methods to analyze and understand material failure mode under different type of loadings, design and operating-related discontinuities. One of the main methods that are explored for predicting materials behavior under static and cyclic loadings is the strain energy density (SED) criterion. The SED approach suggests that failure of a material occurs when total strain energy averaged over a critical controlled volume with a radius R_c surrounding a notch tip or crack reaches or exceeds its critical value $W > W_c$. The applicability and accuracy of the strain energy density (SED) was studied by assessing its predictability of static fracture for U and V notched specimens machined from AW2099-T83 Al-Li alloy. Smooth specimens were tested under static tensile load to understand the static fracture behavior of Al-Li alloy. Five U-notched specimens with different notch radius (1.5 mm, 3.0 mm, 4.0 mm, 5.0 mm and 6.0 mm) and six V-notch in which three are with 0.4 mm notch radius and distinctive different notch angle (35-degree, 60-

degree and 90-degree) and similarly for the remaining three with 0.8 mm notch radius. All specimens were machined and tested monotonically to failure. Strain energy for smooth specimen was calculated based on ultimate tensile stress and modulus of elasticity. On the other hand, the strain energy density for each notch geometry was evaluated using ANSYS finite element software. The critical radius was determined for AW2099-T83. The resulted fracture stress at notch area is almost similar to the same in experiment. The SED has shown high range of accuracy more than 85% for the predicted fracture loads against experiment. Effect of stress triaxiality on fracture load was evaluated using stress triaxiality equation and observed that, as the notch radius increases stress triaxiality decreases hence decreasing the fracture load required to break the specimens. Stress triaxiality is found to have an important role in fracture loading and need to be considered when analyzing the mechanical behavior for ductile materials.

[ملخص الرسالة]

الاسم الكامل: عبداللطيف صالح المطيري.

عنوان الرسالة: تقييم الكسر لعينات مسننة من الألومنيوم الليثيوم T83-2099 المعرض لحمل ساكن.

التخصص: هندسة وعلوم المواد.

تاريخ الدرجة العلمية: سبتمبر 2020

جذبت سبائك الألومنيوم الليثيوم انتباه الباحثين لصلابتها وقوتها العالية مصحوبة بخصائص منخفضة الكثافة وإمكانية استخدامها على نطاق واسع من التطبيقات الهندسية. وتزامنا مع رؤية المملكة العربية السعودية 2030 التي تهدف إلى تحقيق اقتصاد قائم على المعرفة من خلال توطيد صناعات التطبيقات الهندسية وخاصة في المجالات العسكرية والدفاعية حيث تلعب سبائك الألومنيوم الليثيوم دوراً حيوياً في صناعة الطائرات. تعد النمذجة الرقمية الهندسية للتنبؤ بقدرة تصميم الحمل أو تقييم العمر المتبقي للعضو الهندسي المحزوز أمراً ضرورياً؛ إلا أنها تعتبر عملية طويلة ومكلفة. وللحاجة لعملية أسهل، قام الباحثون والمهندسون بتطوير واستكشاف العديد من الطرق البسيطة لتحليل وفهم كيفية فشل المواد في ظل أنواع مختلفة من الأحمال والتصاميم والانقطاعات المرتبطة بالتشغيل. إحدى الطرق الرئيسية التي يتم استكشافها للتنبؤ بسلوك المواد في ظل الأحمال الثابتة والدورية هي معيار كثافة الطاقة. يوحى نهج معيار كثافة الطاقة بما يلي: يحدث الفشل في المواد عندما يصل متوسط الطاقة المبذولة الإجمالية على حجم معروف متحكم فيه. يمكن استخلاص القيمة الحرجة لكثافة طاقة السلالة تحليلياً باستخدام خصائص المواد مثل؛ قوة الشد المطلقة للمادة غير المحززة، ومتانة كسر الانفعال، ومعامل "يونج" للمادة المراد دراستها. في هذا البحث تمت دراسة قابلية تطبيق ودقة معيار كثافة الطاقة من خلال تقييم قدرتها على التنبؤ بالكسر الساكن للعينات المحززة على شكل U و V والتي تم تشكيلها من سبيكة الألومنيوم الليثيوم T83-2099 AW. في البداية تم اختبار العينات الملساء تحت حمل الشد الثابت لفهم سلوك الكسر الساكن لسبائك الألومنيوم الليثيوم. تمت دراسة خمس عينات مسننة على شكل حرف U بنصف قطر قطع مختلف (1.5 مم، 3.0 مم، 4.0 مم، 5.0 مم، 6.0 مم) وستة مسننة على شكل حرف V ثلاث منها بنصف قطر قطع 0.4 مم وزاوية قطع مختلفة (35 درجة، 60 - درجة و 90 درجة) وبالمثل للثلاثة المتبقية بنصف قطر درجة 0.8 مم. تم تشكيل جميع العينات واختبارها حتى الانكسار. تم حساب طاقة الإجهاد للعيينة الملساء بناءً على إجهاد الشد النهائي ومعامل المرونة. من ناحية أخرى، تم تقييم كثافة طاقة الإجهاد لكل قطع باستخدام برنامج

ANSYS ومن ثم تم تحديد نصف القطر الحرج لـ AW2099-T83. إجهاد الكسر الناتج في منطقة القطع مسلوي تقريبًا لنفس قيمة الإجهاد المستوحاة من التجربة العملية. أظهر معيار كثافة الطاقة نطاقًا عاليًا من الدقة يزيد عن 85% لأحمال الكسر المتوقعة مقابل القيم المستوحاة من التجربة العملية. تم تقييم تأثير ثلاثي محاور الضغط على حمل الكسر باستخدام معادلة الإجهاد ثلاثي المحاور، ولوحظ أنه كلما زاد نصف قطر القطع الهندسي، تنخفض قيمة ضغط ثلاثي المحاور وبالتالي ينخفض حمل الكسر المطلوب لكسر العينات. تم التحقق من أن ضغط ثلاثي المحاور له دور مهم في قيمة الحمل المطلوب لكسر العينات ويجب أخذه في الاعتبار عند تحليل السلوك الميكانيكي للمواد المطواعة.

CHAPTER 1

INTRODUCTION

1.1 Fracture of Materials

The fundamentals of material fracture and strength has long been analyzed to prevent and predict material behavior before failures occur. Fracture is defined as separation of material or object into two or more segments under the action of stress. In solid objects it occurs usually due to the initiation and growth of displacement and discontinuity of surfaces within the material itself. Type and direction of applied stress defines the nature of displacement. When the developed stress is perpendicular to the surface of the material it is called a conventional tensile crack. On the other hand, when the displacement develops tangentially to the surface it is known as dislocation, shear crack or slip band [1]. There are two types of fracture based on material strength and nature, ductile fracture and brittle fracture as shown in Figure (1).

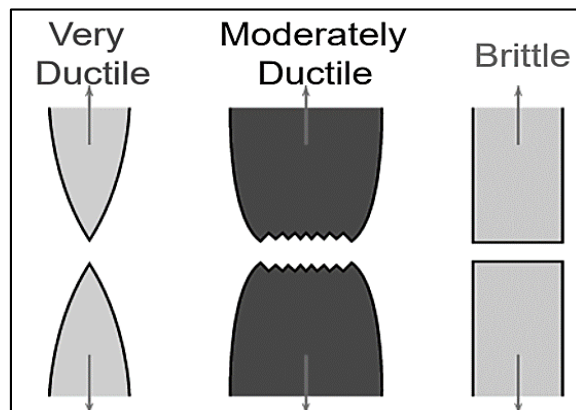


Figure (1): Fracture characteristics of brittle and ductile material [1].

Ductile material can absorb higher energy than brittle material in which ductile material will deform plastically before fracture take place. Ability of energy absorption which is represented by the area under stress-strain curve varies for different materials depending on metallurgical aspect and stain rates [2]. Materials with fine grains will deform plastically prior fracture, in which energy

will be absorbed by the micro-voids during loading. Such deformation will act as a warning and can be detected before fracture. However, In the case of brittle materials the failure is sudden and more catastrophic as the amount of absorbed energy is much less due to the large grains in material microstructure.

Fracture strength is the stress at which fracture of materials take place. For a given sample, this is typically determined by monotonic tensile testing. American Society for Testing and Materials (ASTM) described the method of tensile testing in ASTM E8. Stress–strain curve shown in Figure (2) is produced that typical contains ultimate tensile strength UTS , yield strength Y and fracture stress F . For ductile material fracture strength is commonly lower than the ultimate tensile strength [1]. On the other hand, fracture strength is equivalent to the ultimate tensile strength in brittle material.

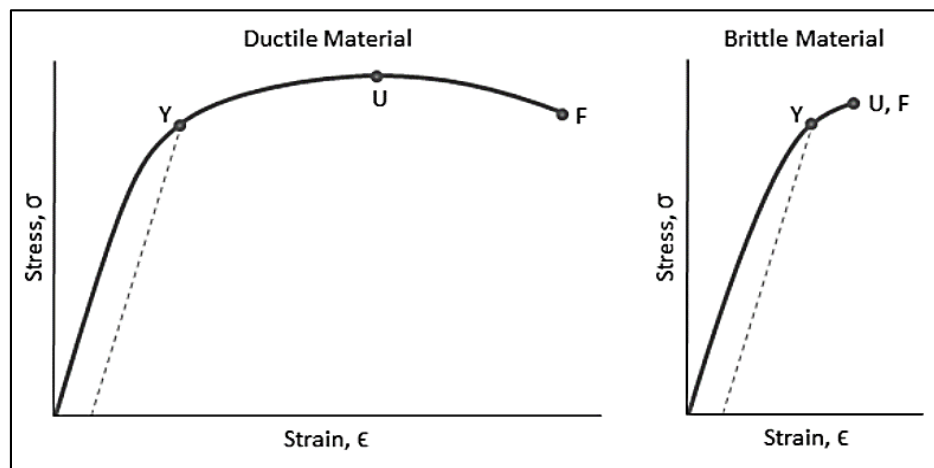


Figure (2): UTS and fracture stresses for ductile and brittle materials [2].

1.2 Strain Energy Density

When a load is applied to a material deformation will occur. Energy is the product of force (F) and distance (d). Hence, by exerting a load that deforms the material we are imposing energy into the loaded material. The energy introduced into the material due to the applied load is known as “strain energy” [3]. Therefore, strain energy density is the strain energy per unit volume. In correlation

with section 1.1 the strain energy measured up to the yielding point is known as modulus of resilience in which represents the amount of internal strain-energy per unit volume that the material can absorb elastically without resulting in any permanent damage. In stress-strain diagram Figure (3) it is calculated by the area of the triangular under the curve [4].

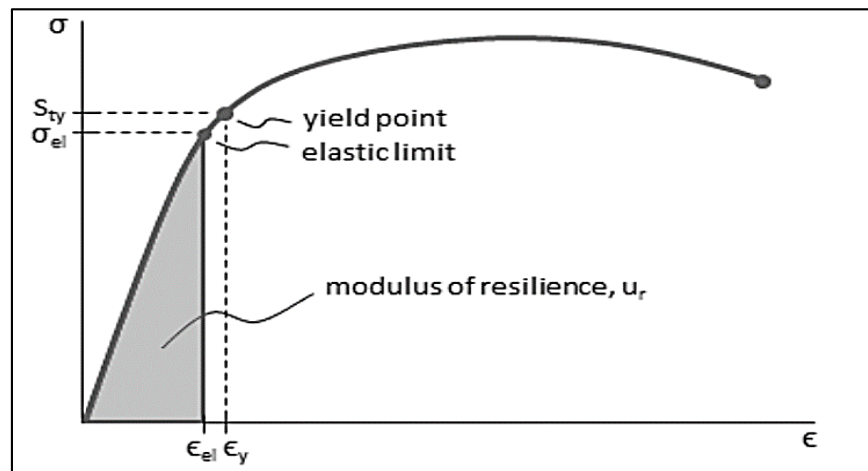


Figure (3): Modulus of resilience [4].

Furthermore, when strain energy reaches to its maximum value that material can absorb before it fractures material will deform plastically and permanently as illustrated in Figure (4). It is known as fracture toughness or modulus of toughness. Its value is equivalent to the total area under stress strain curve [5].

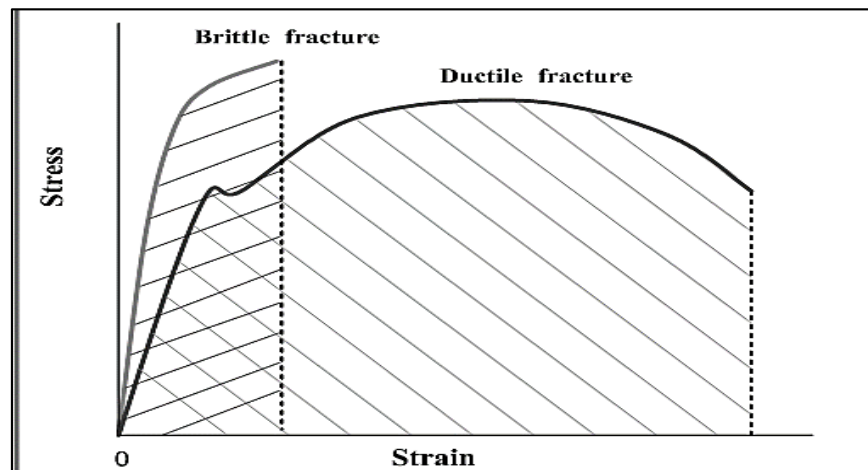


Figure (4): Modulus of toughness [4].

1.3 Aluminum-Lithium Alloy Overview

Industrial revolution was enormous in the last decades, aiming towards production of efficient and green engineering applications. This revolution has promoted excellency in material development and manufacturing processes resulting in fine, state-of-art products. This transition phase involved a constructive change from handmade production methods to mechanized, automated factory production systems. Material Scientists and field researchers contributed in the industrial phase transition by development of new materials and exploring innovative chemical and mechanical enhancement methods of the existing materials. Starting from the stone age to bronze and iron ages until reaching plastic age, materials development has improved and allowed for expanding the limits of successes and human endeavor [24]. Al-Li alloys attracted researcher's attention due to their widespread uses due to their high strength and stiffness accompanied with low density properties. Al-Li series alloys are member of Aluminum age-hardenable alloys family. In comparison to other alloys, higher specific strength, lower density and higher elastic modulus, in addition to the superior favorability in damage tolerance and excellent weldability can be achieved in Al-Li alloys [25]. Nowadays, Al-Li alloys application in military, aircraft and aerospace industries has grown tremendously, as optimizing structural components is an essential approach to increase the payload, reduce total weight and improve fuel efficiency. The enhancements of specific strength and density are not the only factors of performance measurement for aerospace materials. Residual strength and fatigue crack growth damage tolerance, in addition to material durability, fatigue and crack resistance durability generally imposes control of aerospace and aircraft component dimensions such as fuselage, wing, empennage [24].

1.3.1 Al-Li Alloys Development History

The use of Aluminum-Lithium alloys has a long history. Lithium was used as an alloying element since 1924 and commercialized in mid of 1940 [26]. In between it went through progressive development due to the promising result for various engineering applications and its potential for further properties enhancement as shown in Table (1). It worth to divide Al-Li developed alloys into three generations [27] based on the change in the chemical composition and material processing.

1.3.1.1 First Generation

During 1950s, researchers spotted significant improvement in the stiffness (elastic modulus) of Al alloy due to the addition of Li in the structure matrix any several alloys were generated [27]. In 1957, Al-Cu-Li high-strength alloy 2020 was industrialized and commercialized as it possessed high creep and high strength resistance at 150-200 °C temperature range [27]. The 2020 alloy was used for more than 20 years in wings manufacturing of United States Navy's RA-5C Vigilante jets without any single documented fracture due to cracking or corrosion issues during its service life [26]. However, in the middle of 1960s, 2020 alloy production was stopped from being used for commercial applications due to manufacturing issues attributed to material's poor ductility and high brittleness [27]. The ductility issue is caused by the presence of high *wt%* of Fe and Si used in aircraft alloys and during solidification, Fe and Si particles precipitate in the matrix as insoluble components in which these particles may initiate cracks and disturb the uniformity of strain distribution [28].

1.3.1.2 Second Generation

To overcome the earlier mentioned issues, researches continued and 2nd generation of Al-Li alloys were developed with intending of achieving alloys that are stiffer and lighter than traditional Al

alloys. Consequently, in the period of 1970s and 1980s, attempts were focused on reducing Fe and Si contents to obtain a high toughness and ductility [25], in addition to enormous efforts were directed to replace some alloying elements with others to produce grain reinforcement precipitates in order to positively affect toughness, ductility and nucleating voids. Although reduction in density is appealing in the second generation, Al-Li alloys had few undesirable characteristics such as high anisotropy of mechanical properties and Low short-transverse properties, therefore their applications were restricted [27].

1.3.1.3 Third Generation

In the beginning of 1990s, third generation of Al-Li alloys were commercialized with a reduction in Li *wt%* concentration to less than 2 *wt%* in order to minimize the undesirable characteristics observed in the former Al-Li [29]. Physical and mechanical properties of produced alloys in the 3rd generation were greatly enhanced fulfilling the future aircraft requirements including performance, weight savings and reduced maintenance cost. Thus, third generation alloys replaced traditional Al alloys due to their low density, high stiffness, excellent weldability, superior damage tolerance and corrosion resistance.

1.4 AW-2099 T83 Alloy

1.4.1 Chemical Composition

Major advancement of 2099 alloy is attributed to the modification of alloy compositions, in which, controlling the weight-percent of alloying elements helped in increasing the superiority of 2099 alloy over other Al-Li alloys [30] as listed in Table (2). Following is list of major alloying elements and their contribution in overall improvement:

- Lithium (Li): strengthen the alloy, forms coherent Al_3Li precipitate which cause, decrease the density inhomogeneity, dislocation and planer slip. 1 wt% of Li, decreases density by approximately 3% [25].
- Copper (Cu): strengthen the alloy, forms Al_2CuMg precipitate which provides barrier to dislocation and homogeneity.
- Magnesium (Mg): strengthen the alloy, forms Al_2CuMg & Al_2CuLi precipitate which provides barrier to dislocation and homogeneity. In addition, in controlling recrystallization [27].
- Chromium (Cr): control recrystallization and grain size.
- Zirconium (Zr): control recrystallization and grain size.
- Scandium (Sc): control recrystallization and grain size.
- Iron (Fe): considered as impurity as it impairs fracture toughness.
- Silicon (Si): considered as impurity as it impairs fracture toughness.

Table (1): Chemical compositions of AW 2099 alloy [25].

Element	Cu	Li	Ti	Zr	Be	Al	Mg	Zn	Mn
wt%	2.74	1.77	0.05	0.10	0.0001	Bal.	0.32	0.72	0.34

1.4.2 Properties and Characteristics

As per American National Standard Institute (ANSI) for aluminum alloys and temper designation systems (ANSI H35.1), digit numerical system for designation is used to classify aluminum and aluminum alloys for casted produced alloys [31]. In the case of 2099-T83, the first digit which is “2” indicates that the main alloying element is copper. In addition, “T” letter is referred to precipitation hardening tempering treatment, where “83” indicates that, alloy is undergone solution heat-treatment and cold working, following by artificial aging to improve their strength [31].

Table (2): Al-Li alloys compositions of 1st, 2nd and 3rd generations [27].

Alloy	Li wt%	Cu wt%	Mg wt%	Ag wt%	Zr wt%	Sc wt%	Mn wt%	Zn wt%	Al wt%	Density ρ (g/cm^2)
First generation										
2020	1.2	4.5					0.5		Bal.	2.7
1420	2.1		5.2		0.11					2.47
1421	2.1		5.2		0.11	0.17				2.47
Second generation (Li ≥ 2 wt%)										
2090	2.1	2.7			0.11				Bal.	2.59
2091	2.0	2.0	1.3		0.11					2.58
8090	2.4	1.2	0.8		0.11					2.54
1430	1.7	1.6	2.7		0.11	0.17				2.57
1440	2.4	1.5	0.8		0.11					2.55
1441	1.95	1.65	0.9		0.11					2.59
1450	2.1	2.9			0.11					2.60
1460	2.25	2.9			0.11					2.60
Third generation (Li < 2 wt%)										
2195	1.0	4.0	0.4	0.4	0.11				Bal.	2.71
2196	1.75	2.9	0.5	0.4	0.11		0.35 max	0.35 max		2.63
2297	1.4	2.8	0.25 max		0.11		0.3	0.5 max		2.65
2397	1.4	2.8	0.25 max		0.11		0.3	0.10		2.65
2098	1.05	3.5	0.53	0.43	0.11		0.35 max	0.35		2.70
2198	1.0	3.2	0.5	0.4	0.11		0.5 max	0.35 max		2.69
2099	1.8	2.7	0.3		0.09		0.3	0.7		2.63
2199	1.6	2.6	0.2		0.09		0.3	0.6		2.64
2050	1.0	3.6	0.4	0.4	0.11		0.35	0.25 max		2.70
2296	1.6	2.45	0.6	0.43	0.11		0.28	0.25 max		2.63
2060	0.75	3.95	0.85	0.25	0.11		0.3	0.4		2.72
2055	1.15	3.7	0.4	0.4	0.11		0.3	0.5		2.70
2065	1.2	4.2	0.5	0.30	0.11		0.4	0.2		2.70
2076	1.5	2.35	0.5	0.28	0.11		0.33	0.30 max		2.64

1.4.2.1 Strength

The presence of Li in Al matrix helps in a relatively minor degree of the resulted solid solution strength [25], that is mostly achieved by the total variation of the size of Li and Al atoms and elastic modulus. However, in Al-Li alloys the key strengthening factor is largely achieved from the presence of an enormous volume fraction of Al_3Li phase, that is considered the core reason for higher elastic modulus in those alloys, as Al_3Li itself is bulky in intrinsic modulus [26]. Degree of strength achieved from such mechanisms varies with the ageing condition and chemical composition of the alloy. Furthermore, the solid solution and grain size at different ageing conditions resulted in marginal difference with different strengthening mechanisms [28].

1.4.2.2 Crack Resistance and Fracture Toughness

Existence of grain-boundary brittle phases, segregation at grain-boundaries of lithium and contribution of impurity elements potassium and sodium, strain localization at grain-boundaries in addition to the segregation of lithium to grain boundaries are primarily accountable for the low-short transverse fracture toughness and brittle intergranular fracture characteristic [13].

1.4.2.3 Extrusion Effect

After extrusion process, formation of large noticeable elongated recrystallized-grains among surface layer was observed of the extruded alloy with an approximate measured thickness of 200 μm of the recrystallized layer [10] as shown Figure (5). Such formation is attributed to the severe deformation that took place at the surface layer.

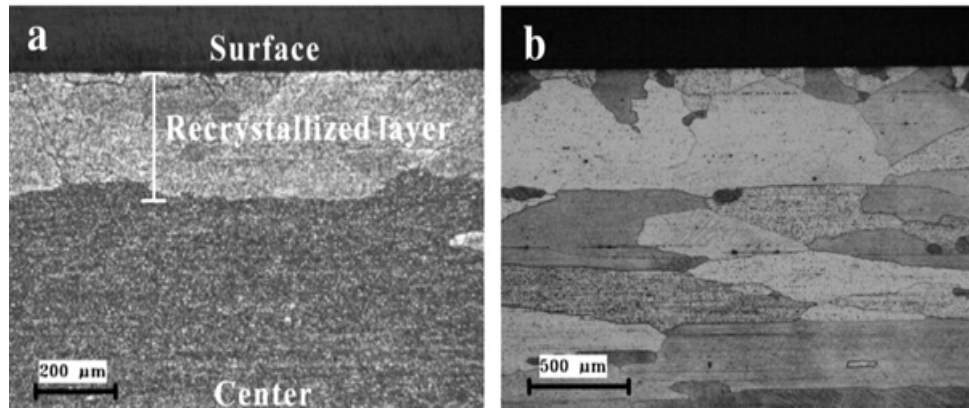


Figure (5): Grain characteristic in the surface zone of (a) Extruded alloy (b) treated alloy [10].

[CHAPTER 2

LITERATURE REVIEW

2.1 Notch Fracture Assessment Overview

Every machine and structural member are designed to withstand different kinds of cyclic and static loadings. Several catastrophic failures could be avoided if material's failure behavior and loading capacity were well analyzed and understood for the maximum loading that member can tolerate, hence designed with proper safety margin. Understanding loading capacity and failure behavior also help in material selection during design phase for load-bearing and high cost avoidance. Notches are very significant geometry with widespread applications in the field of engineering structural components. Presence of notches cannot be avoided in several structures and machines which significantly affects the load-bearing capacity of engineering structural members and play as crack initiation sites. For this reason, notch effects have been a crucial problem in fracture toughness studies being a source of stress concentration which plays essential role for safe design [6]. The study of notch effect in materials is important for assessing materials sensitivity to grooves, notches, holes or other geometrical discontinuities [7]. An extensive research has been done in the past decades to assess the structural integrity of engineering components that contains notch type defects. Several methods were proposed to understand and predict material behavior in the presence of notches such as the two-parameter fracture criterion, the theory of critical distance and the strain energy density method [8]. The evaluation of the stress distributions before of notches and cracks through engineering numerical methods is widely used for safe designing of structural members against fracture and fatigue. Accurate precise calculations strains and stresses by finite-element methods and rigorous analytical are expensive and lengthy. A major

disadvantage of numerical modelling for stress concentration regions is the extremely refined meshes requirement to get reliable results of local stresses and strains.

2.1.1 Two-Parameter Fracture Criterion

The two-parameter fracture criterion were developed to predict notched material behavior under fracture mode. This criterion includes two critical parameters effective T-stress and critical notch stress intensity factor. The effective T-stress T_{ef} is defined as the average T-stress distribution value ahead of notch tip with critical effective distance X_{ef} [9]. On the other hand, notch stress intensity factor K_p represents notched material's fracture toughness with notch radius of ρ . These parameters were derived from the volumetric method of notch fracture mechanics [10]. The volumetric method was used to estimate the effective T-stress and calculate notch fracture toughness. The volumetric method is a mesomechanical method in which, a physical volume is required for fracture [9]. The method is supported by the fact that, material resistibility for fracture is affected by scale effect, specimen geometry and loading mode [11]. Maximum stress at notch tip alone is not enough to explain the influence of scale effect, specimen geometry and loading mode on fracture toughness. Stress gradient and value in fracture volume is necessary in evaluating the influence on fracture toughness [10]. A quasi-cylindrical shape is assumed to be the fracture volume with a diameter known as effective distance X_{ef} . Fracture stress within fracture volume is estimated by computing average stress values within this zone. Hence, local fracture criterion depends on two parameters: effective stress σ_{ef} and effective distance X_{ef} [12]. Within fracture zone, the average weighted stress is defined as the effective stress σ_{ef} defined in equation (2.1):

$$\sigma_{ef} = \frac{1}{X_{ef}} \int_0^{X_{ef}} \sigma_{yy}(r) \Phi(r) dr \quad (2.1)$$

The notch stress intensity factor K_p presented in equation (2.2) is a function of the effective stress and the effective distance:

$$K_p = \sigma_{ef} \sqrt{2\pi X_{ef}} \quad (2.2)$$

The effective T-stress T_{ef} in the fracture zone is determined in equation (2.3) and using equation (2.4) through averaging stress distribution over the effective distance X_{ef} [9]:

$$T_{ef} = \frac{1}{X_{ef}} \int_0^{X_{ef}} T_{xx}(r) \Phi(r) dr \quad (2.3)$$

$$T_{xx}(r) = (\sigma_{xx}(r) - \sigma_{yy}(r))_{\theta=0} \quad (2.4)$$

2.1.2 The Theory of Critical Distance

The theory of critical distance is a group of linear elastic analytical methods with a defined constant critical distance L [13]. These methods are: the point method (PM), the line method (LM), the area method (AM) and the volume method (VM). These methods were established independently over a very long time starting in 1930 by different researchers [14]. To predict material behavior two parameters are required: critical distance and critical stress σ_o . The common features of all the four methods are the approach of linear-elastic behavior and continuum mechanics [13]. There is a theoretical correlation between the theory of critical distance (TCD) and linear elastic fracture mechanics (LEFM) in which materials constants such as fracture toughness K_c and ultimate tensile stress (UTS) are used to obtain constant critical distance L [15]. The theory of critical distance has been used over years to predict brittle fracture and fatigue with relatively excellent accuracy for different stress concentration modes of different materials especially composite materials [16]. Following is a brief definition and discussion of each methods.

2.1.2.1 Point Method (PM)

The simplest form of the theory of critical distance is the point method. It states that, failure occurs when the stress at half of the critical distance L from the notch root reaches the value of critical stress σ_o [13], demonstrated in equation (2.5):

$$\sigma(L/2) = \sigma_o \quad (2.5)$$

It assumes that stress is liner-elastic and is directly proportional to the applied load. By assuming the linearity and knowing the critical distance L , fracture load can be calculated by scaling stress-distance curve [8]. The critical distance L can be calculated as shown in equation (2.6) using material's fracture toughness and ultimate tensile stress:

$$L = \frac{1}{\pi} \left(\frac{K_c}{\sigma_u} \right)^2 \quad (2.6)$$

2.1.2.2 Line Method (LM)

With using the same concept for point method (PM), line method states that failure occurs when the averaged stress over a critical distance d from the notch root reaches fracture stress σ_o [17].

The critical distance d can be obtained for brittle fracture as shown in equation (2.7):

$$\frac{1}{d} \int_0^d \sigma(r) dr = \sigma_o \quad (2.7)$$

By using fracture mechanics and material's constants, the critical distance d can be therefore rewritten as in equation (2.8) which is equal to $2L$:

$$d = \frac{2}{\pi} \left(\frac{K_c}{\sigma_u} \right)^2 \quad (2.8)$$

2.1.2.3 Area Method (AM) and Volume Method (VM)

These methods suggest that, failure occurs when the averaged stress over a defined area reaches fracture stress σ_o , and a defined volume in the case of volume method [18]. Predicting notch

failures using both methods are a bit complicated depending on the shape of the defined area and volume. As shown in the line method (LM) the critical distance L was also used to find the critical distance d and similarly it can be used to obtain the intended area and volume in the case of AM and VM [13]. To illustrate, in the case of sharp crack the radius of the defined area is $1.32L$ and $1.54L$ for the defined volume [19].

To conclude, the TCD was used for several decades in different materials and stress modes. The four methods show almost a similar prediction for notch materials in comparison with experimental values [20]. The critical distances L can be derived from materials constants as derived in equation (2.6) and can be used in all the four methods. The majority of the predictions are conducted using point method (PM) and line method (LM) due to simplicity and higher accuracy in comparison to area method (AM) and volume method (VM) [11], whilst all are capable of valid prediction.

2.1.3 Strain Energy Density Method (SED)

Fracture assessment concepts were introduced long time ago by Neuber through structure support length and elementary volume definitions [44]. It states that static strength parameter is the notch stress averaged over a defined distance not the theoretical maximum notch stress. It was applicable for static loading until later where Radaj extended Neuber concept to include fatigue assessment [45]. The fundamental of critical distance is that crack propagates when stress at that defined distance reaches a critical value. Erdogan and Sih in 1963 proposed that, crack growth is perpendicular to the maximum tangential stress from crack tip [14]. Improvement was made to include T-stress contribution in maximum tangential stress criterion by Ayatollahi. Core region concept by Sih was proposed for the area around crack tip and made a great contribution in developing the concept of strain energy density [20]. The main idea of core region concept is that

at a distance from the crack tip, continuum mechanics stops providing the concept of core region radius [17]. From point of singularity at a critical distance the product of strain energy density is the factor S as Sih's criterion is a point-wise criterion. S -factor was thought to control the failure and direction of crack was defined by imposing minimum condition on S . Absorbed Specific Fracture Energy (ASFE) is the required energy in a unit volume for crack initiation was measured by Gillemot [46]. Development considering fracture energy by Elices as of cohesive zone model for various materials weakened by notches and cracks [47]. By combining the concepts of elementary volume by Neuber and local mode I by Erdogan and Sih, average strain energy density was proposed which is volume based unlike the point-wise criterion by Sih [14]. Berto [16], Lazzarin [17], and other researchers presented a comprehensive overview of the volume-based strain energy density (SED) criterion method. Fracture assessment of notched and cracked components using strain energy based (SED) approach discovered to be the most robust in fracture assessments of several materials [20]. In depth discussion of the history and fundamentals of SED is presented in Chapter 3 in this thesis, however following is a brief overview. The SED approach suggests that failure of a materials take place when the total strain energy W averaged over a critical controlled volume with a radius R_c surrounding a notch tip or crack reaches its critical value $W > W_c$ [21]. The value of the critical strain energy density can be analytically derived using material properties such as ultimate tensile strength σ of un-notched material, fracture toughness K_{IC} and Young's modulus E of the examined material. The critical value W_c of the total strain energy for un-notched specimen is determined in equation (2.9):

$$W_c = \frac{\sigma^2}{2E} \quad (2.9)$$

2.2 Mechanical Behavior of Al-Li Alloy

In the past decades, Al-Li alloys attracted researcher's attention due to their high strength and stiffness accompanied with low density properties. Such properties are essential for widespread engineering applications especially in the field of aerospace and aircrafts manufacturing where AW2099 alloy plays a vital role. Existence of geometrical discontinuities such as crafted notches or manufacturing induced cracks are essential, however, they are widely reported to cause a reduction of both fatigue and tensile strength [32]. Tremendous effort was placed by researchers to understand and predict Al-Li behavior under different modes of loading. Due to the frequently reported issues in aerospace structural members, R.J.H. Wanhill in (1994) studied the damage tolerance engineering properties of aerospace aluminum alloys through analyzing aerospace failures and conducting flight simulations to understand fracture and fatigue crack initiation and growth [26]. In (2006), J. Jabra, M. Romios and others studied the effect of thermal exposure on the mechanical strength and other properties of aluminum-lithium alloy AW2099-83 through experimental analysis and determined that, alloy strength decreases at higher temperature and longer exposure time [33]. Yi Lin, Zheng, Ye Han and others in (2012), evaluated AW2099 Al-Li alloy's microstructure and mechanical properties during thermo-mechanical processing. AW2099 underwent five different manufacturing processes and mechanical investigation was done after completion of each process to study the effect imposed on alloy strength [34]. In (2012), Nikolaos D. Alexopoulos, Evangelos Migklis and others studies fatigue and tensile mechanical behavior of 2198-T351 alloy through experimental fatigue analysis. Fatigue endurance limit was found to be 9% below yield stress, dynamic stiffness and absorbed energy per fatigue cycle are decreasing due to micro-cracking and hardening effect for high applied stress regimes [32]. Jing Zhong, Shen Zhong and others in (2013) studied Al-Li 2A97 for fatigue crack initiation and propagation

behavior through experimental and metallurgical analysis [35]. Crack initiation was found predominantly at coarsen secondary phase and inclusions, whilst propagation is influenced by persistent slip bands and the interaction between dislocations and grain structure. In (2015), Franck Armel Tchitembo Goma, Daniel Larouche and others evaluated the AW2099-T83 crack growth behavior and had simulated the impact of load fluctuation during airplane service at different temperatures and analyzing the potential effect of processing history [36]. Muhammed J. Adinoyi, Nesar Merah and Jafar Albinmousa in (2018) investigated AW2099-T83 shear fatigue behavior for strain-controlled and monotonic cyclic loading [37]. Al-Li examined alloy initially observed hardened under monotonic shear loading, however, it softened along the few fatigue cycles. Plastic deformation observed for 0.7% strain amplitude and higher in the case of torsion shear loading. Coffin-Manson relation was used to determine the shear fatigue constants of the material. Crack paths were investigated and were observed in the longitudinal direction at low strain amplitudes. In (2018), A.R. Cisko, J.B. Jordon and others conducted experiments and modeled rolled AA2099 to quantify the microstructure fatigue properties through reversed shear and monotonic testing [38]. Crack initiation observed at copper-rich sites in alloy's microstructure and fatigue cracking is influenced by the size of these sites.

Another Important factor in fracture mechanism of metallic alloy is the stress state triaxiality, it is a quantitative parameter in evaluating plastic damage, stress constraint and failure mode. There have been many experimental and study works done to evaluate the effect of stress triaxiality in fracture assessment [39]. Chandan et al, studies the correlation of notch geometries such as notch size and notch type on the fracture toughness and strength. Chandan found that, notch depth is greatly affecting plastic constraint of the alloy and subsequently effecting fracture toughness and strength (2018) [40]. In 2015, Wen observe that stress triaxiality is affecting the failure strain and

effect of loading was significant at lower stress triaxiality. Kato experimented three tensile specimens for plastic deformability assessment and found that plastic strain and ductility at the fracture tip decreased with increasing triaxiality (2016) [41]. Bridgman has evaluated the stress distribution at the necked section as a function of the negative surface curvature. In 2017, Zhang found that the development of void volume fraction is significantly affecting load parameter and stress triaxiality [42]. In 2018, Yu found that change of stress triaxiality is being insensitive considered in the constitutive equation under axisymmetric tensile loading. Keshavarz, load angle and triaxiality correlation with the failure strain was extracted for alloy material (2014) [43].

The effect of load parameter and stress triaxiality on alloys and metals plastic behavior has been the interest of many researchers. When dealing with failure and damage, stress triaxiality is a significant factor. Stress triaxiality can contribute to material rupture generally by either postponing plastic deformation or producing a void growth inside the tested specimen [39]. Postponing plastic deformation results in stress level increase hence, reaching the rupture stress by cleavage. The other mechanism is that micro-voids originate inside the material due to the pre-existence of inclusions, which are enlarged due to plastic straining until void coalescence, and ductile rupture occurs [40]. Stress triaxiality is related to the ratio between the hydrostatic pressure and the von Mises stress. Local triaxiality under a given load configuration is affected by the local and the change in geometry [41]. Stress triaxiality can be defined as follows:

$$T = \frac{1}{3} + \ln\left(1 + \frac{a}{2R}\right) \quad (2.10)$$

where a is the width of the necking section and R is the local radius of the groove.

CHAPTER 3

THESIS WORK BACKGROUND

Al-Li fatigue and monotonic behavior and related properties were thoroughly investigated by many researchers and metallurgists in the past due to the widespread applications of Al-Li in cyclic-operating conditions. However, to the best of author knowledge none have approached the applicability of strain energy method for predicting fracture behavior of AW2099-T83 under monotonic loading. The intend of this report is to study and examine SED criterion method to predict static behavior of Al-Li AW2099-T83 alloy to confirm the applicability of the strain energy density (SED) method for analyzing the monotonic behavior of Al-Li specimens that are weekend by different notch geometries. Finite elements analysis modeling is utilized to verify the reliability of SED approach in fracture assessment under static loading.

3.1 Motivation

Al-Li alloy is an attractive material for its high strength and stiffness accompanied with low density properties. In line with Saudi Arabia 2030 vision that aiming toward a knowledge-based economy through localization of engineering application industries especially in military and defense fields, Al-Li is playing a vital role in aerospace and aircrafts manufacturing. Such applications are prone for different kinds of cyclic and static loadings. Several catastrophic failures can be avoided if material's failure behavior and loading capacity are well analyzed and understood. Understanding loading capacity and failure behavior also help in material selection during design phase for load-bearing and high cost avoidance. As it was discussed in the literature review up to the best of author knowledge the effect of U and V notches on the fracture of Al-Li AW2099-T83 has not been investigated. As notches cannot be avoided in the field of AW-2099 alloy application which significantly affects the load-bearing capacity and play as crack initiation sites. The study of

different notches effect is important for assessing fracture behavior and sensitivity to geometrical discontinuities. It is important to predict static behavior of Al-Li AW2099-T83 alloy and examine the applicability of using a well-known reliable method such as strain energy density (SED) method for Al-Li specimens that are weekend by different notch geometries

3.2 Thesis Objective

The main aim of this research is to investigate and model the fracture behavior of AW-2099 T83 Aluminum-Lithium V and U-notched specimens under static tensile loading. The specific of the objectives are:

1. To design and machine different U and V-notched specimens from AW-2099 T83 Al-Li extrusion.
2. To perform tensile testing and analyze the results for all specimens.
3. To determine the critical radius based on the strain energy density method for AW-2099 T83 Aluminum-Lithium.
4. To develop finite element subroutine using Ansys Parametric Design Language (APDL) in order to predict the static fracture load for all specimen using strain energy density method (SED).
5. To verify the numerical prediction using the experimental results.
6. Analyze obtained data and the effect of stress triaxiality.

3.3 Thesis Overview

This thesis is divided into seven main chapters, the first chapter contains fundamentals needed to understand material fracture and related material properties, in addition to strain energy concept. Furthermore, history of Al-Li alloys especially AW-2099 T83 are presented discussing the main characteristics and properties to understand the major enhancement in Al-Li over the years and

discussed the key properties related to load bearing capability and the effect of alloy processing. The second chapter is summarizing the literature review done to understand notch effect on material's strength and briefly discuss different methods that were established to predict fracture occurrence and the mechanical behavior of Al-Li alloys. Third chapter is explaining the background of thesis and motivation to select this subject. Forth chapter is discussion of strain energy density method fundamentals, In depth elaboration of the use and application of strain energy density in fracture prediction. Experimental and numerical work is presented in chapter five, where the finite modeling and the monotint testing for thesis intended work is presented. Results and experiment data were discussed in chapter six to validate applicability of strain energy density method. Conclusion and recommendation are presented in chapter seven in this thesis.

CHAPTER 4

STRAIN ENERGY DENSITY METHOD

The SED approach suggests that failure of a materials take place when the total strain energy W averaged over a critical controlled volume with a radius R_c surrounding a notch tip or crack reaches its critical value $W > W_c$ [8]. Strain energy density critical value can be analytically derived by using material properties such as ultimate tensile strength σ of un-notched material, fracture toughness K_{IC} and Young's modulus E of the examined material [48]. The critical value W_c of the total strain energy for un-notched specimen is determined by below equation:

$$W_c = \frac{\sigma^2}{2E} \quad (3.1)$$

In case material is deformed by external loading, the load applied is considered an external work in which the material will stored as internal energy called strain energy W [4]. Strain Energy Density (SED) is strain energy per unit volume.

To understand the theoretical background of strain energy density method using stress strain curve shown Figure (6), the strain energy U at any point in stress strain curve is:

$$U = \int_0^x P dx \quad (3.2)$$

$$U = \int_0^x kx dx \quad \text{where } P = kx \text{ for elastic region} \quad (3.3)$$

$$U = \frac{1}{2} kx^2 = \frac{1}{2} Px \text{ (N.m)} \quad (3.4)$$

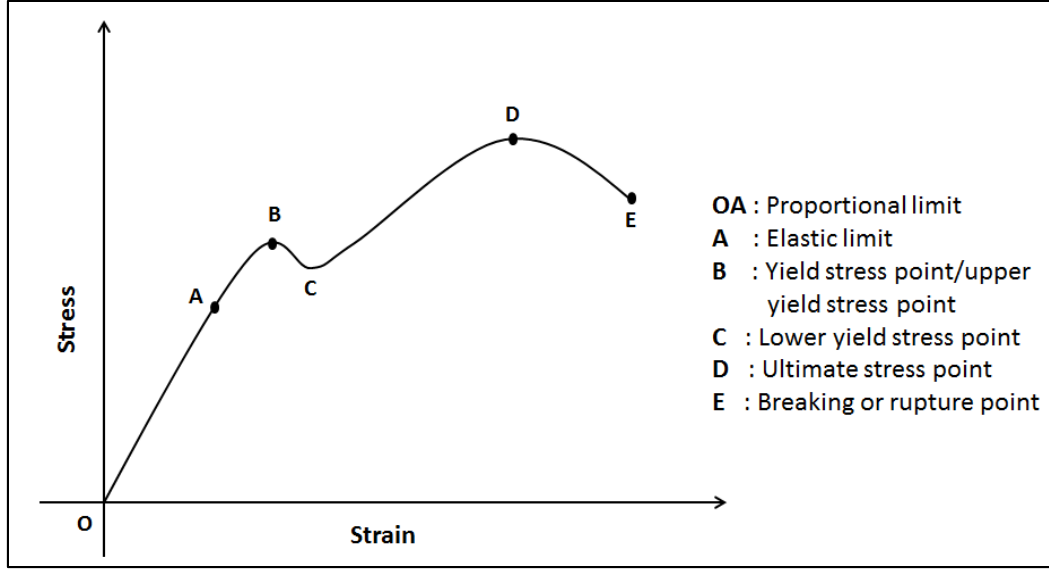


Figure (6): Stress strain curve [18].

Strain energy density is the strain per unit volume, in order to obtain the strain energy density of above formula, divide strain by volume:

$$\frac{U}{V} = \int_0^x \frac{Pdx}{V} \quad (3.5)$$

$$\frac{U}{V} = \int_0^x \frac{Pdx}{AL} \quad \text{where } V = \text{area (A)} \times \text{length (L)} \quad (3.6)$$

Below considerations to be reflected in (3.6) formula:

- Strain energy density W is the strain per unit volume $W = \frac{U}{V} \quad (3.7)$

- Change in material length is represented by elongation $\epsilon_x = \frac{x}{L} \quad (3.8)$

- Stress σ is the applied force over area $\sigma = \frac{P}{A} \quad (3.9)$

- From Hook's low, strain ϵ_x can be derived as $\epsilon_x = \frac{\sigma}{E} \quad (3.10)$

By substituting above considerations in the strain energy density equation (3.6):

$$W = \int_0^{\epsilon_x} \sigma d\epsilon_x = \int_0^{\epsilon_x} E d\epsilon_x^2 = \frac{1}{2} E \epsilon_x^2 = \frac{1}{2} E \left(\frac{\sigma}{E}\right)^2 = \frac{\sigma^2}{2E} \quad (3.11)$$

Finally, the final equation for strain energy density method is:

$$W = \frac{\sigma^2}{2E} \quad (3.12)$$

4.1 Determination of Critical Volume

In case of static loading, critical volume for strain energy density method depends only on the mechanical properties of the examined material such as fracture toughness K_{IC} , Young's Modulus E , the ultimate tensile strength σ and Poisson's ratio ν [19]. Radius of the critical volume R_c is calculated based on the shape of material notch in which:

For V-notched specimens, in the case of cracks or pointed V-notch, the controlled volume as shown Figure (7) becomes a circular sector or a circle with a critical radius (R_c). Under plain-strain, critical radius can be written as follow [20]:

$$R_c = \left[\frac{(1 + \nu)(5 - 8\nu)}{4\pi} \right] \left(\frac{K_{IC}}{\sigma} \right)^2 \quad (3.13)$$

If the notch stress intensity factor critical value is determined of specimens with $2\alpha \neq 0$, where, 2α is the opening angle and λ William's eigenvalue which controls the sharp solution for zero notch radius as discussed deeply by Berto F and Ayatollahi M.R in [14]. The critical radius can then be estimated through [20]:

$$R_c = \left[\left(\frac{I \cdot K_{IC}}{4\lambda (\pi - \alpha) E \cdot W_c} \right) \right]^{1/2-2\lambda} \quad (3.14)$$

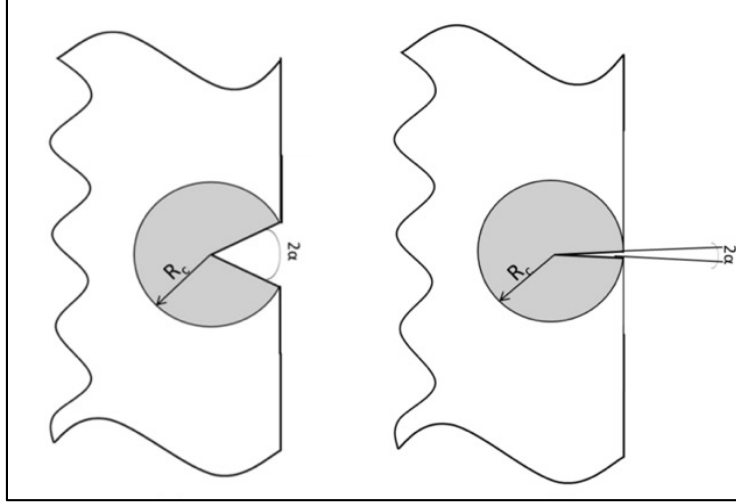


Figure (7): Critical radius for crack and V-notch [20].

For blunt V-notch and U-notch specimens, in the case of blunt V-notch and U-notch: controlled radius shown Figure (8), R_c is the measured depth alongside the bisector line. The outer radius of crescent is equal to $r_0 + R_c$, where r_0 is the measured distance between the origin of the local coordinate system and the notch tip [21].

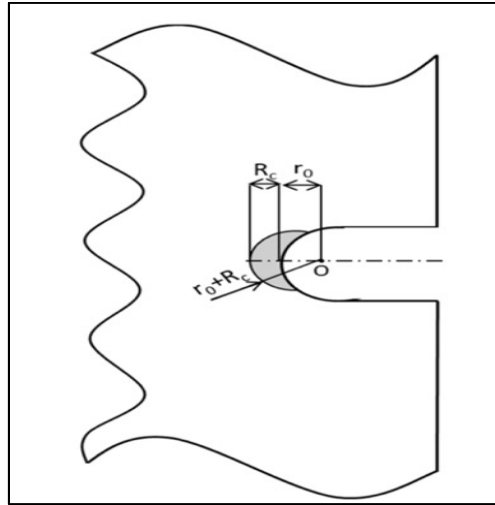


Figure (8): Critical radius for blunt V-notch and U-notch [20].

r_0 is dependent on two main parameters: notch-opening angle 2α and notch root radius ρ [16] and

It is calculated by:

$$r_0 = \rho \frac{(\pi - 2\alpha)}{(2\pi - 2\alpha)} \quad (3.15)$$

Where notch-opening angle 2α is equal to zero in case of U-notch and it depends on the straight parallel lines of the opening illustrated Figure (9). However, in case of inclined lines, the notch-opening angle is greater than zero.

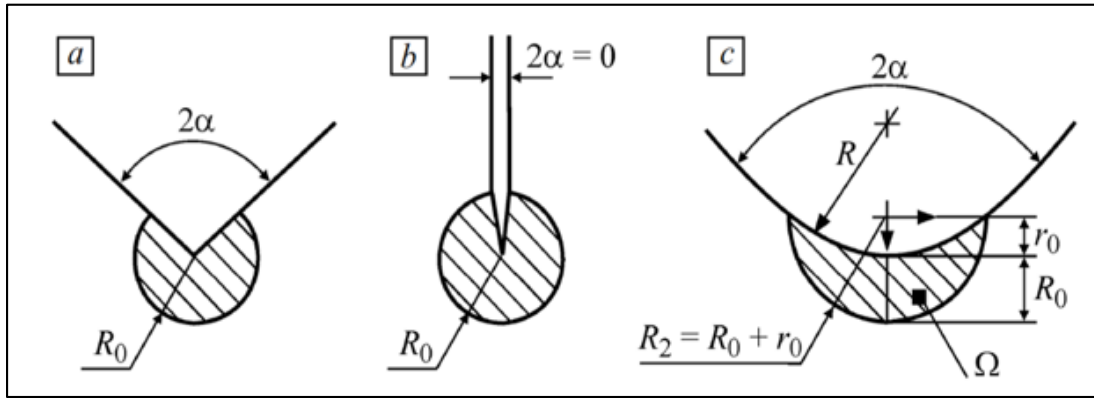


Figure (9): Notch-opening angle and critical value determination [17]

CHAPTER 5

MATERIALS AND EXPERIMENTAL DETAILS

5.1 Material

Aluminum-Lithium samples that will be experimentally investigated are manufactured by Alcoa Extrusions Hannover company under commercial designation AW 2099 T83. Testing samples were machined with different type of notches and various notching dimeters. The chemical compositions of AW 2099 T83 according to the supplied Material Testing Certificate (MTC) is listed below in Table (3).

Table (3): Chemical composition of the tested Al-Li.

Element	Si	Fe	Cu	Mn	Mg	Zn	Ti	Be	Li	Zr
wt%	0.02	0.02	2.70	0.03	0.29	0.70	0.03	0.00	1.80	0.10

5.2 Monotonic Tensile Behavior

Samples of the received AW 2099 T83 material was machined with 25.0 mm and a diameter of 6.0 mm for monotonic testing to failure as shown Figure (10) at KFUPM Material-Lab using Instron-5569 tensile testing machine in atmospheric condition at 37°C with a strain rate of 2 mm/min according to ASTM E8-08 Standard. Extensometer with 12.5 mm to measure strains was used up to 1% then test was switched to displacement-controlled condition [37].

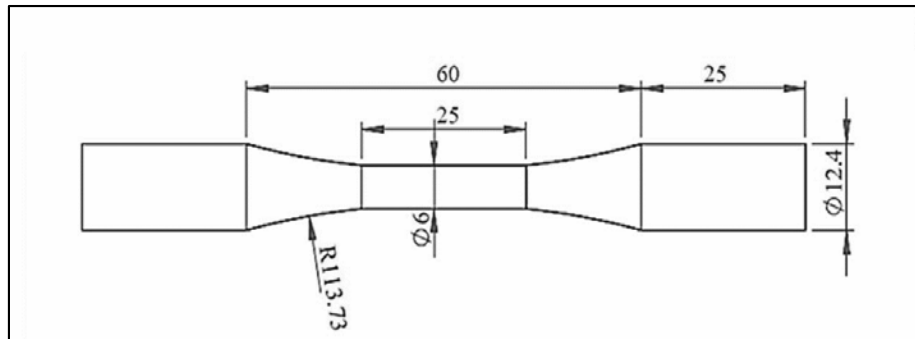


Figure (10): Dimension of the tested sample [37].

Engineering stress-strain curve shown Figure (11) was obtained for the conducted monotonic tensile test that was automatically recorded during the testing by the connected computer to determine the tensile properties. The mechanical monotonic properties is listed in Table (4).

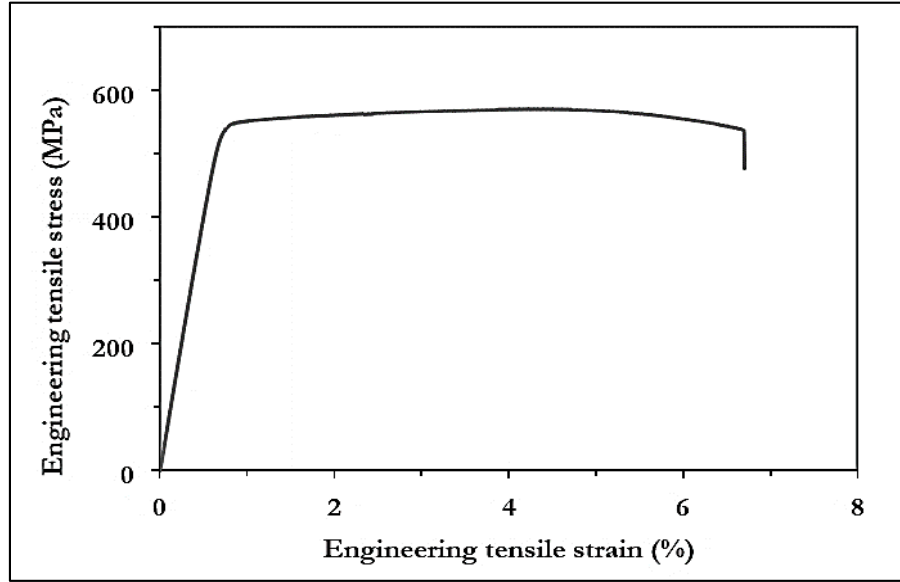


Figure (11): Engineering stress-strain curve [37].

Table (4): Mechanical monotonic properties [37].

Engineering Tensile Property	Value
Tensile strength (MPa)	567 ± 10.11
0.2% Yield stress (MPa)	549 ± 9.26
Elastic Modulus (GPa), E	80 ± 0.84
Strain Hardening Coefficient, K (MPa)	680 ± 15.76
Strain Hardening Exponent, n	0.0437 ± 0.01
Reduction in area (%)	8.0 ± 0.02
Elongation (%)	2.5 ± 0.22
Fracture stress (MPa)	530 ± 4.95
Fracture strain (%)	6.58 ± 0.7

5.3 Notched Specimens

Experiment matrix was set to study the effect of different notch geometries on fracture toughness and tensile properties. Specimens were divided into two groups based on the machined axisymmetric discontinuities (V and U notches). First and second group consist of 12 and 10 samples respectively, in which each two samples were made with distinctive radii and opening angles of V-notch and U-notch to ensure repeatability and comprehensive view for the effect of different size of discontinuity in fracture load. Below Table (5) and Figure (12 and 13) represent samples dimensions and quantity to serve thesis intent:

Table (5) Experiment matrix.

Type	Cylinder diameter (mm)	Notch radius (mm)	Depth (mm)	Net section diameter (mm)	Number of samples
U-R1.5	12	1.5	3	6	2
U-R3	12	3	3	6	2
U-R4	12	4	3	6	2
U-R5	12	5	3	6	2
U-R6	12	6	3	6	2
V-35	12	0.4	3	6	2
V-35	12	0.8	3	6	2
V-60	12	0.4	3	6	2
V-60	12	0.8	3	6	2
V-90	12	0.4	3	6	2
V-90	12	0.8	3	6	2

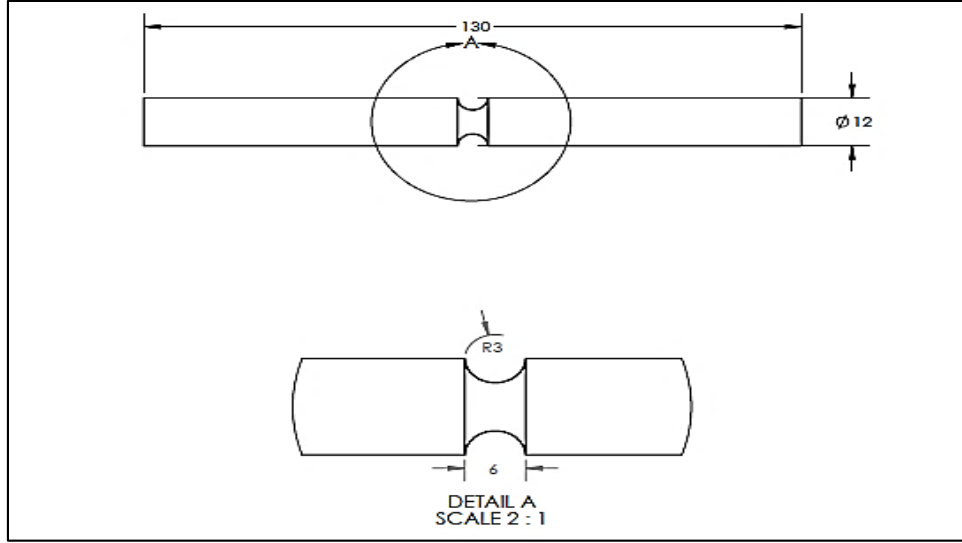


Figure (12): Modeling of U-notched sample.

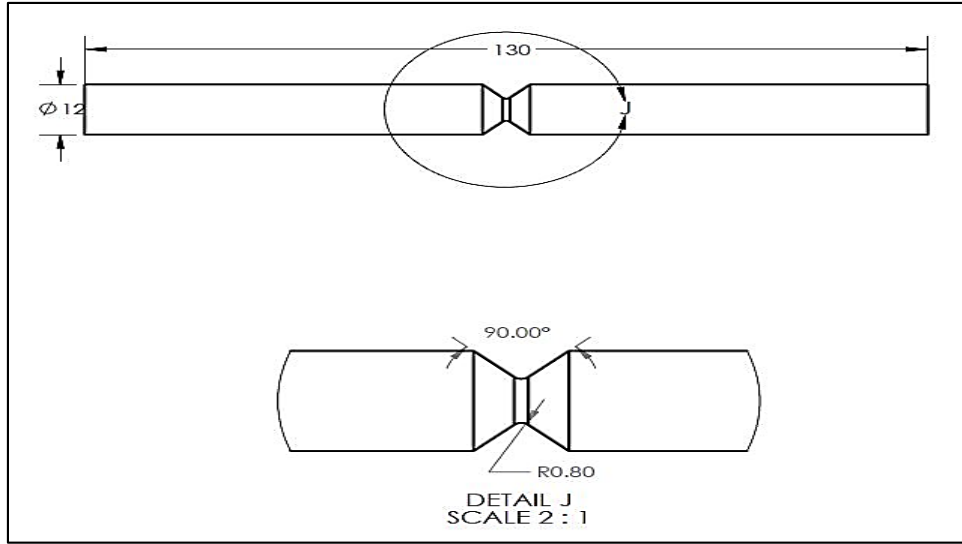


Figure (13): Modeling of V-notched sample.

5.4 Finite Element Analysis

Finite element codes were generated for each notch type after analyzing the samples geometries in order to accurately locate the controlled volume. The geometry was meshed using 183 solid element with 8 nodes. Material properties were set as liner elastic-isotropic with $E= 80.84$ GPa and $\nu=0.34$. Model was meshed as shown in Figure (14) with refined mesh around the control volume to enhance the accuracy of the results.

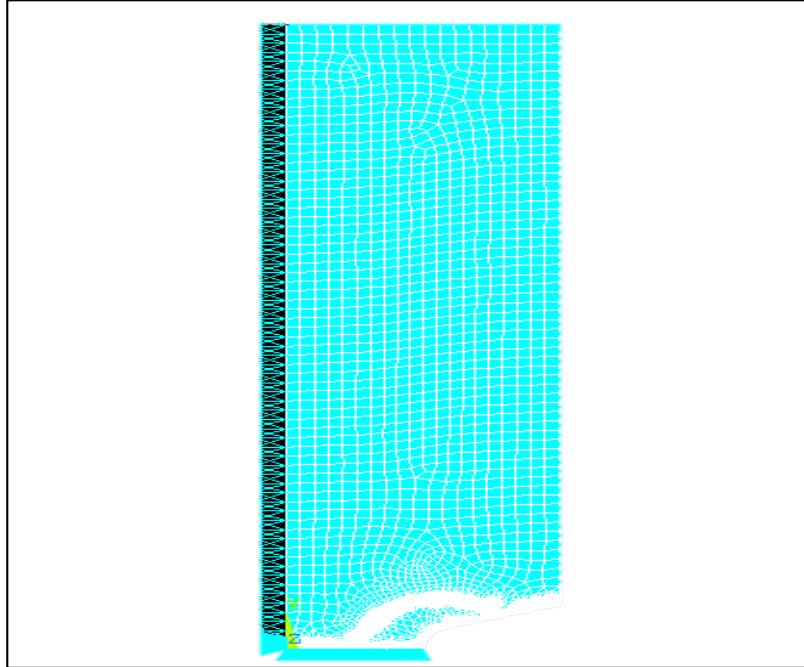


Figure (14): Model after refined meshing.

Symmetric boundary conditions shown in Figure (15) was applied in the horizontal and vertical symmetry lines to simulate tensile testing in addition to the applied loading at top side of the model.

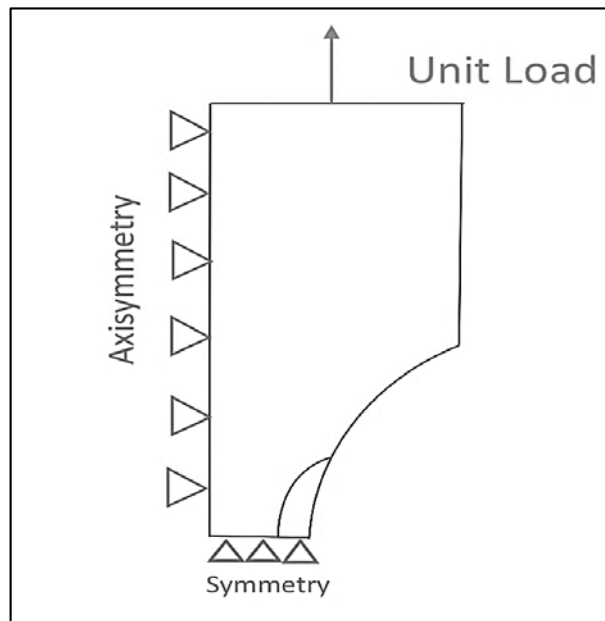


Figure (15): Simulations of the boundary conditions and loading.

5.4.1 Determination of Controlled Volume Radius

Controlled volume radius was determined for Al-Li alloy through trial and error method by knowing the material properties and the nominal stress where fracture occurs. Strain energy density was calculated for the smooth specimen using equation (3.1) and W_c found to be $2.009 \frac{MJ}{m^3}$. U-R6 sample was modeled in APDL and the experimental nominal tensile stress was applied 178.16 MPa to solve for Strain energy density. The critical radius R_c was initially set as 1.32 mm and the model was solved for SED. The critical radius was then changed in order for U-R6 SED to be equal to the strain energy density for smooth specimen $2.009 \frac{MJ}{m^3}$. After multiple analysis, the critical radius R_c found to be 1.39 mm where the SED at fracture surface of U-R6 is equal to $2.002 \frac{MJ}{m^3}$. The accuracy of the SED method found to be 99.61% for the modeled U-R6 specimen against smooth specimen strain energy density. As the critical radius R_c is purely a material property dependent, 1.39 mm can be used for all samples to calculate the fracture stress. Values of the controlled volume is summarized Table (6). Critical volume was used to anticipate the required stress at which samples will fracture.

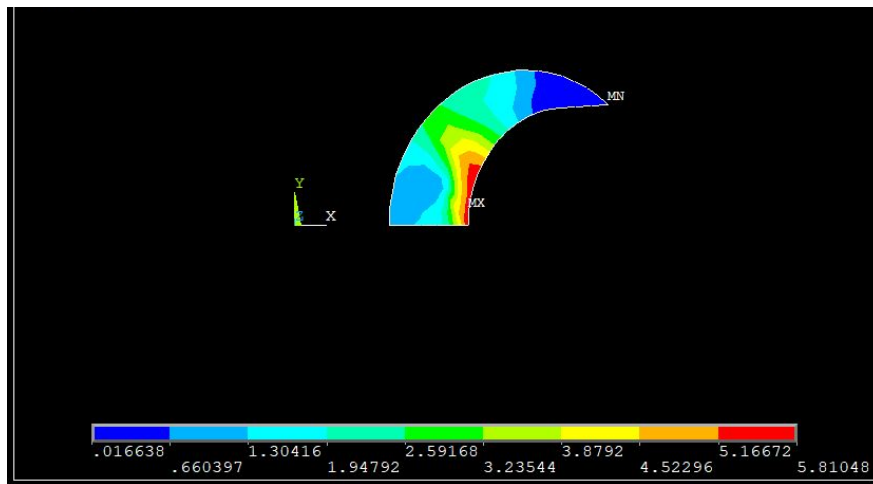


Figure (16): FEA modeling for U-notch sample's critical volume.

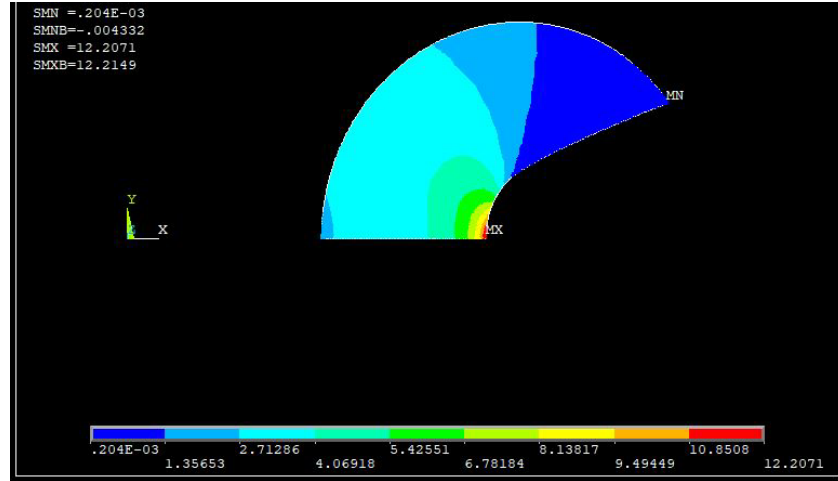


Figure (17): FEA modeling for V-notch sample's critical volume.

The critical radius R_c was determined using the above method for one sample as the critical radius is a material property and independent of geometry.

Table (6): Summary of the sample's critical volumes.

Specimen Type	R_c (mm)	r_0 (mm)	$R_{c0} = r_0 + R_c$ (mm)	Controlled Volume (m ³)
U-R1.5 mm	1.39	0.75	2.140	72.433
U-R3.0 mm		1.50	2.890	69.702
U-R4.0 mm		2.00	3.390	73.122
U-R5.0 mm		2.50	3.890	76.947
U-R6.0 mm		3.00	4.390	74.353
V35-R0.4 mm		0.178	1.568	54.125
V35-R0.8 mm		0.357	1.747	56.995
V60-R0.4 mm		0.160	1.550	48.098
V60-R0.8 mm		0.320	1.710	50.490
V90-R0.4 mm		0.133	1.523	41.233
V90-R0.8 mm		0.267	1.657	43.128

5.4.2 Numerical Prediction

After identifying the critical radius R_c , all samples were modeled in APDL with tension load of 1 Mpa and solved for strain energy density at fracture surface W_{c1} in order to compare it with the maximum stress obtained from the experiment. The maximum stress is the stress at which the fracture surface was bearing at the moment of fracture initiation. The values of W_{c1} at fracture surface is listed Table (7).

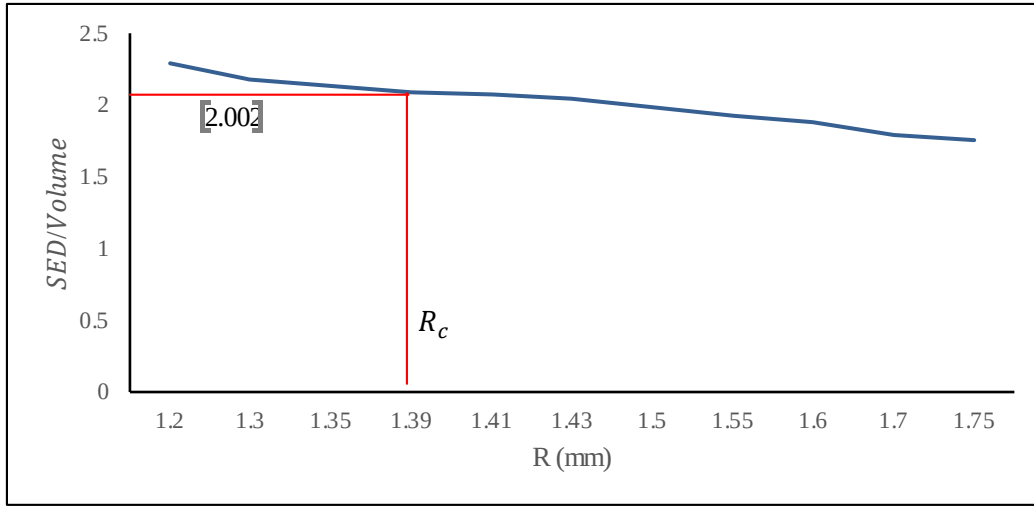


Figure (18): Determination of critical radius

A synthesis in terms of the square root value of the local energy averaged over the control volume (of radius R_c), normalized with respect to the critical energy of the material as shown in equation (5.1) was used to obtain the fracture stress σ_f at notch surface from APDL. The resulted fracture stress then were compared to the actual fractures stress at the notched surface from the experiment.

$$\sigma_f = \sqrt{\frac{w_c}{W_{c1}}} \left(\frac{D^2}{d^2} \right) \quad (5.1)$$

Table (7): List of W_c values at fracture surface.

Specimen Type	SED at 1 MPa Tensile Load (MJ)	The Controlled Volume (m^3)	W_{c1} At Fractured Surface (MJ)
U-R1.5 mm	3.27E-03	72.433	4.51E-05
U-R3.0 mm	4.06E-03	69.702	5.83E-05
U-R4.0 mm	4.53E-03	73.055	6.21E-05
U-R5.0 mm	4.95E-03	76.920	6.43E-05
V35-R0.4 mm	2.43E-03	54.125	4.49E-05
V35-R0.8 mm	2.69E-03	56.995	4.72E-05
V60-R0.4 mm	2.42E-03	48.098	5.02E-05
V60-R0.8 mm	2.66E-03	50.490	5.27E-05
V90-R0.4 mm	2.41E-03	41.233	5.84E-05
V90-R0.8 mm	2.62E-03	43.128	6.071E-05

5.5 Static Fracture Test

The 22 machined samples underwent monotonic testing to failure. The aim of testing was to obtain stress-strain curve for yield, ultimate tensile and fracture stresses. Result of representative samples is shown in Figure (19 and 20) and result is summarized Table (8):

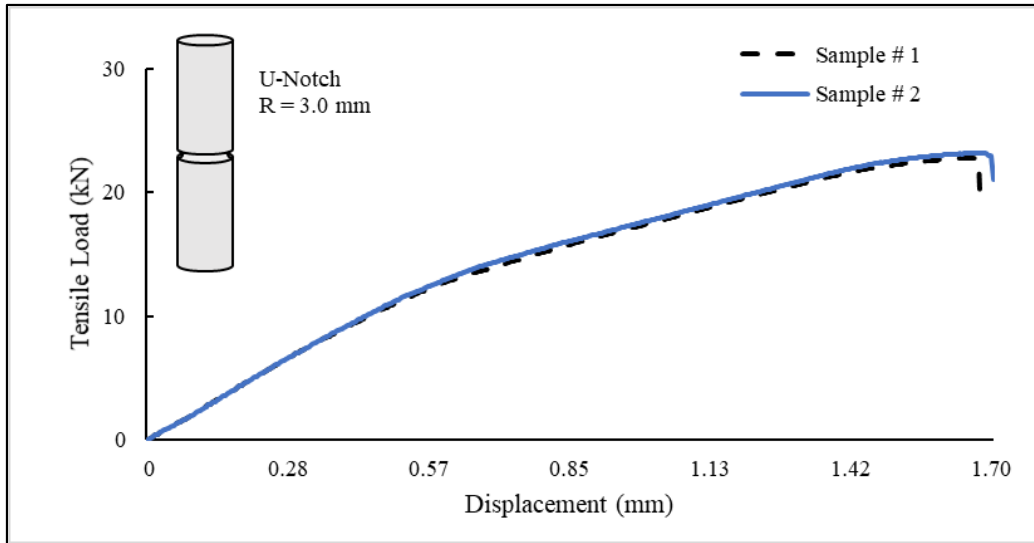


Figure (19): Stress-strain curve for U-notch with 3.0 mm notch radius.

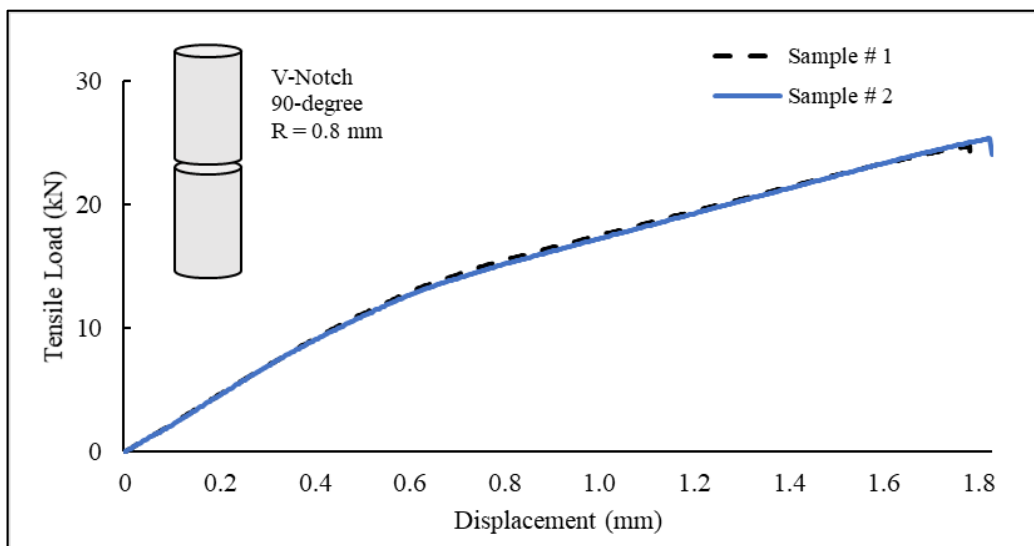


Figure (20): Stress-strain curve for V-notch with 0.8 mm notch radius and 90-degree notch angle.

Table (8): Maximum load for the tested samples.

Serial #	Specimen Type	Maximum Load (kN)	Average Maximum Load (kN)
1	U-R1.5 mm	22.62	22.67
2	U-R1.5 mm	22.72	
3	U-R3.0 mm	22.78	22.99
4	U-R3.0 mm	23.19	
5	U-R4.0 mm	19.76	20.06
6	U-R4.0 mm	20.35	
7	U-R5.0 mm	19.96	19.80
8	U-R5.0 mm	19.64	
9	U-R6.0 mm	19.38	20.14
10	U-R6.0 mm	20.89	
11	V35-R0.4 mm	22.19	22.62
12	V35-R0.4 mm	23.05	
13	V35-R0.8 mm	22.47	22.87
14	V35-R0.8 mm	23.26	
15	V60-R0.4 mm	23.55	23.11
16	V60-R0.4 mm	22.67	
17	V60-R0.8 mm	24.38	24.30
18	V60-R0.8 mm	24.22	
19	V90-R0.4 mm	24.77	25.21
20	V90-R0.4 mm	25.64	
21	V90-R0.8 mm	24.70	25.01
22	V90-R0.8 mm	25.33	

CHAPTER 6

RESULT AND DISCUSSION

Table (9) shows the summarized result for the conducted experiment, maximum load at which fracture had occurred. Average nominal stress at the gripping section, in addition to the maximum stress at notch cross-sectional area of each distinctive samples:

Table (9): Average stresses for the tested samples.

Specimen Type	Average Fracture Load (kN)	Average Nominal Fracture Stress (MPa)	Average Maximum Fracture Stress (MPa)
U-R1.5 mm	22.67	200.57	802.30
U-R3.0 mm	22.99	203.36	813.45
U-R4.0 mm	20.06	177.44	709.78
U-R5.0 mm	19.80	175.18	700.71
U-R6.0 mm	20.14	178.16	712.65
V35-R0.4 mm	22.62	200.13	800.53
V35-R0.8 mm	22.87	202.27	809.10
V60-R0.4 mm	23.11	204.44	817.76
V60-R0.8 mm	24.30	214.93	859.73
V90-R0.4 mm	25.21	222.99	891.98
V90-R0.8 mm	25.01	221.28	885.12

List of σ_f for each distinctive sample listed Table (10) were calculated through (5.1). Experimental fracture stresses were compared against the predicted stresses from strain energy density method. The aim is to investigate the range of accuracy of SED fracture assessments for the intended Al-Li specimens tested under tensile loading. It can be shown in Table (10) that, SED method level of accuracy is high for the majority of the specimens and moderately high for the rest of the specimens. Hence, SED can be used for materials with known critical radius R_c .

Table (10): List of experimental fracture stresses at notch surface and comparison with SED method prediction.

Specimen Type	Experimental Fracture Stress (MPa)	Predicted σ_f (MPa)	Δ %
U-R1.5 mm	802.30	843.86	4.92
U-R3.0 mm	813.45	742.61	8.71
U-R4.0 mm	709.78	719.76	1.39
U-R5.0 mm	700.71	707.01	0.89
V35-R0.4 mm	800.53	846.03	5.38
V35-R0.8 mm	809.10	824.88	1.91
V60-R0.4 mm	817.76	800.05	2.17
V60-R0.8 mm	859.73	781.16	9.14
V90-R0.4 mm	891.98	741.67	16.85
V90-R0.8 mm	885.12	727.54	17.80

Table (11) shows the stress triaxiality for each distinctive specimen calculated using equation (2.10). As the notch radius increases stress triaxiality decreases hence decreasing the fracture load required to break the specimens.

$$T = \frac{1}{3} + \ln\left(1 + \frac{a}{2R}\right) \quad (2.10)$$

Table (11): List of stress triaxiality values.

Specimen Type	$\sigma_{y \max}$ (MPa)	a (mm)	R (mm)	T
U-R1.5 mm	7.0	6.0	1.5	1.43
U-R3.0mm	5.7	6.0	3	1.02
U-R4.0mm	5.3	6.0	4	0.89
U-R5.0mm	5.0	6.0	5	0.80
U-R6.0mm	4.9	6.0	6	0.73
V35-R0.4 mm	12.2	6.0	0.4	2.47
V35-R0.8 mm	9.0	6.0	0.8	1.89
V60-R0.4 mm	12.2	6.0	0.4	2.47
V60-R0.8 mm	9.01	6.0	0.8	1.89
V90-R0.4 mm	12.0	6.0	0.4	2.47
V90-R0.8 mm	9.0	6.0	0.8	1.89

In Table (11) it can be shown that the required perpendicular stress to fracture the specimens increases as stress triaxiality increase at unit load. For U-notched specimens as shown in Figure

(21) and Figure (22), fracture stress decreases with increasing notch radius and reduced stress triaxiality.

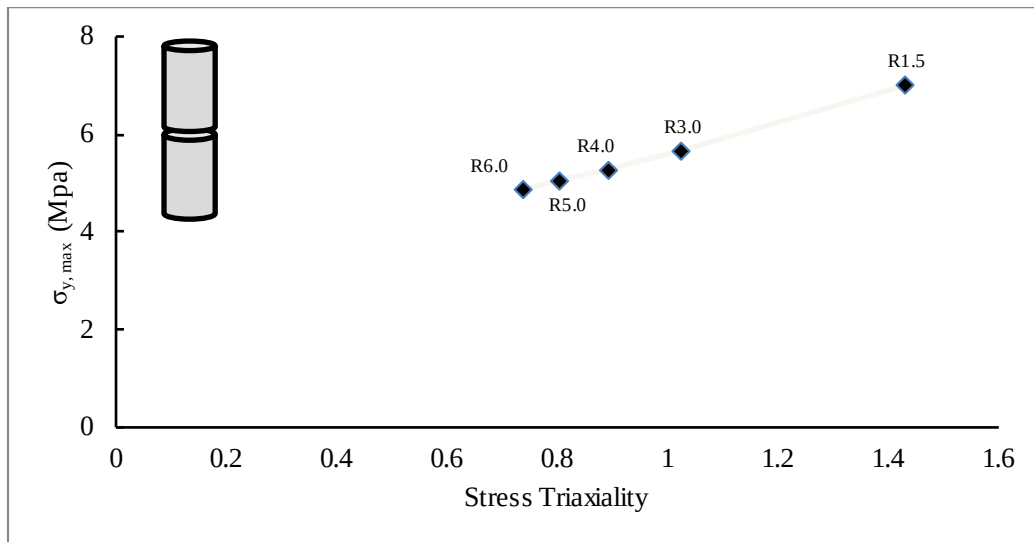


Figure (21): Stress triaxiality vs perpendicular stress for U-Notch specimens.

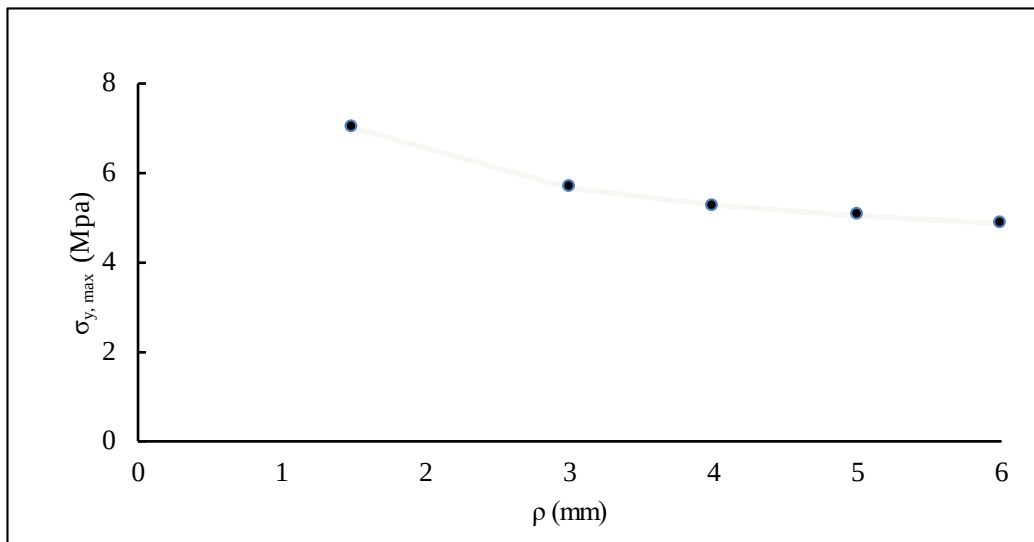


Figure (22): Stress vs notch radius for U-notch specimens.

For V-notch specimens as the geometry change will affect stress triaxiality and fracture load, each distinctive opening angel were compared with each other for proper analyzing as shown in Figure

(23) Figure (24). It can be shown that as the notch radius increases stress triaxiality decreases hence decreasing the fracture load required to break the specimens.

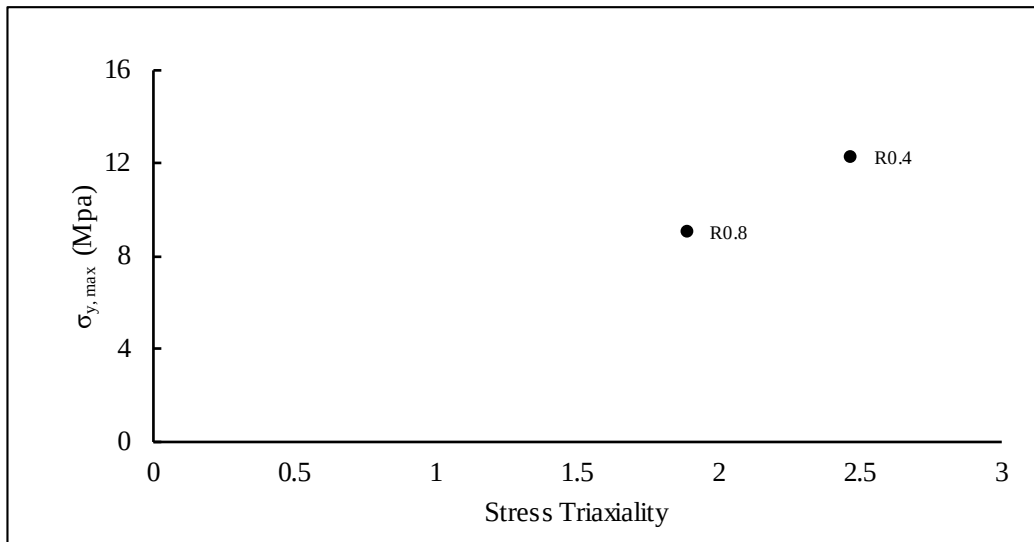


Figure (23): Stress vs stress triaxiality for V-notch with 35-degree opening angel.

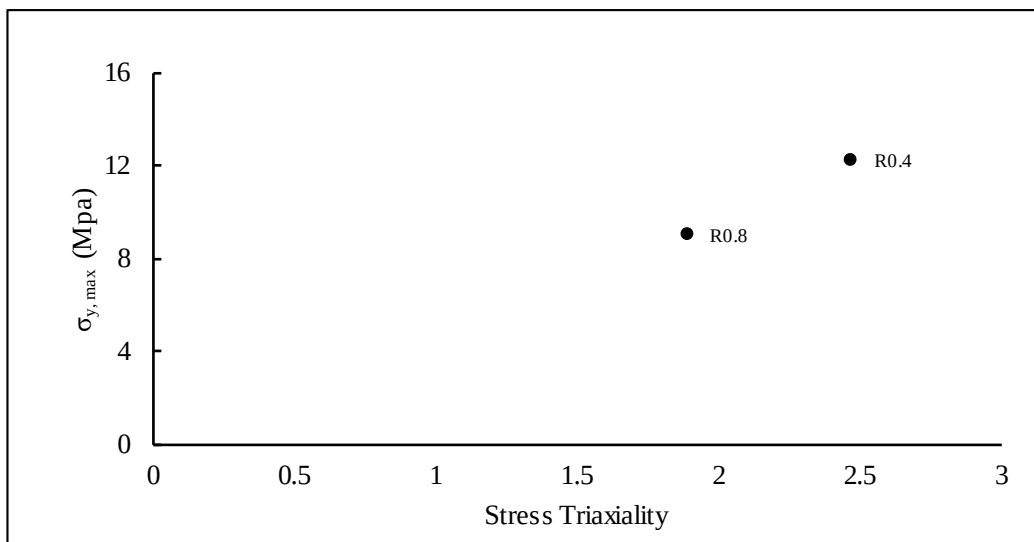


Figure (24): Stress vs stress triaxiality for V-notch with 60-degree opening angel.

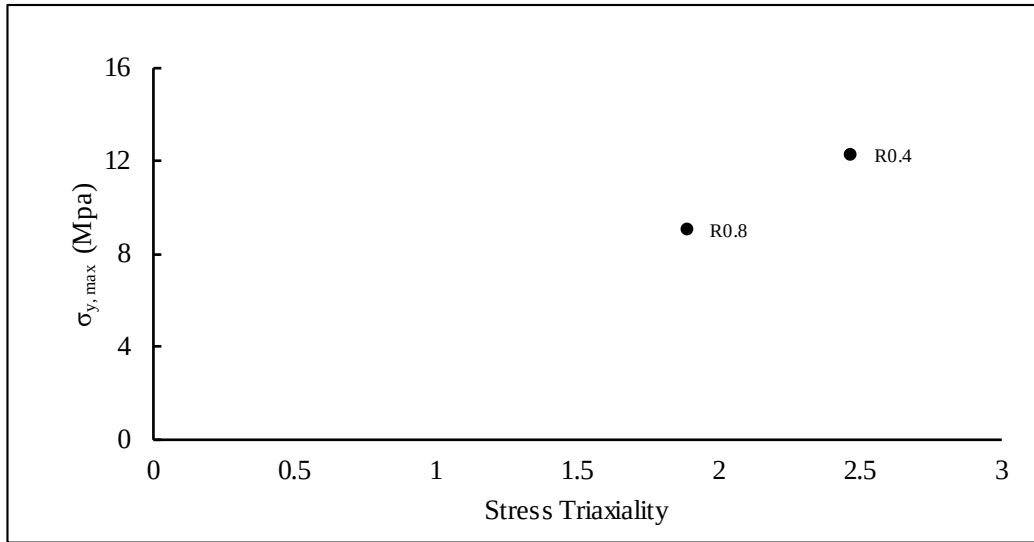


Figure (25): Stress vs stress triaxiality for V-notch with 90-degree opening angle.

Stress triaxiality plays a key factor in material rupture and loading effect, as it was shown above plastic damage and stress constraint are elevated with the increase in stress triaxiality hence, higher fracture load.

CHAPTER 7

CONCLUSION AND RECOMMENDATIONS

7.1 Summary and Conclusion

Al-Li alloys are well-known for their strength to density high ratio such characteristic is essential for widespread engineering applications especially in the field of aerospace and aircrafts manufacturing. Existence of geometrical discontinuities such as crafted notches or manufacturing induced cracks are unavoidable in several structures which significantly affects the load-bearing capacity and play as crack initiation sites. For this reason, notch effects have been a crucial problem in fracture toughness studies for assessing fracture behavior and sensitivity to geometrical discontinuities. It is important to predict static behavior of Al-Li AW2099-T83 alloy through a reliable and accurate method, hence the applicability of using strain energy density (SED) method was investigated for Al-Li specimens that are weakened by different notch geometries. The applicability and accuracy of the strain energy density (SED) was studied by assessing its predictability of static fracture for U and V notched specimens machined from AW2099-T83 Al-Li alloy.

Smooth specimens were tested under static tensile load to understand the static fracture behavior of Al-Li alloy. Five U-notched specimens with different notch radius (1.5 mm, 3.0 mm, 4.0 mm, 5.0 mm and 6.0 mm) and six V-notch in which three are with 0.4 mm notch radius and distinctive different notch angle (35-degree, 60-degree and 90-degree) and similarly for the remaining three with 0.8 mm notch radius. All specimens were machined and tested monotonically to failure. Strain energy for smooth specimen was calculated based on ultimate tensile stress and modulus of elasticity. On the other hand, the strain energy density for each notch geometry was evaluated using ANSYS finite element software. The critical radius was found to be 1.39 mm. Hence, the

critical volume for each geometry was determined accordingly. The resulted fracture stress at notch area is almost similar to the same in experiment. The SED shown high range of accuracy more than 85% for the predicted fracture loads against experiment.

Stress triaxiality is a quantitative parameter in evaluating plastic damage, stress constraint and failure mode. Effect of stress triaxiality on fracture load was evaluated using stress triaxiality equation and observed that, as the notch radius increases stress triaxiality decreases hence decreasing the fracture load required to break the specimens. Stress triaxiality is found to have an important role in fracture loading and need to be considered when analyzing the mechanical behavior for ductile materials.

7.2 Recommendations

As Al-Li alloy is a key material in aerospace applications, it is subjected to different modes of cyclic loading. Many studies were conducted to examine SED applicability for predicting fatigue behavior of the material. However, efforts is to be exerted to investigate the applicability of SED to estimate the fracture load in mixed mode loading and cyclic loading. In addition, effect of stress triaxiality on fracture loading to be studied to understand its effects on ductility, stress constraint and fracture toughness.

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Vitae

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APPENDIX 1
FRACTURE RESULT OF U-NOTCHED SPECIMENS

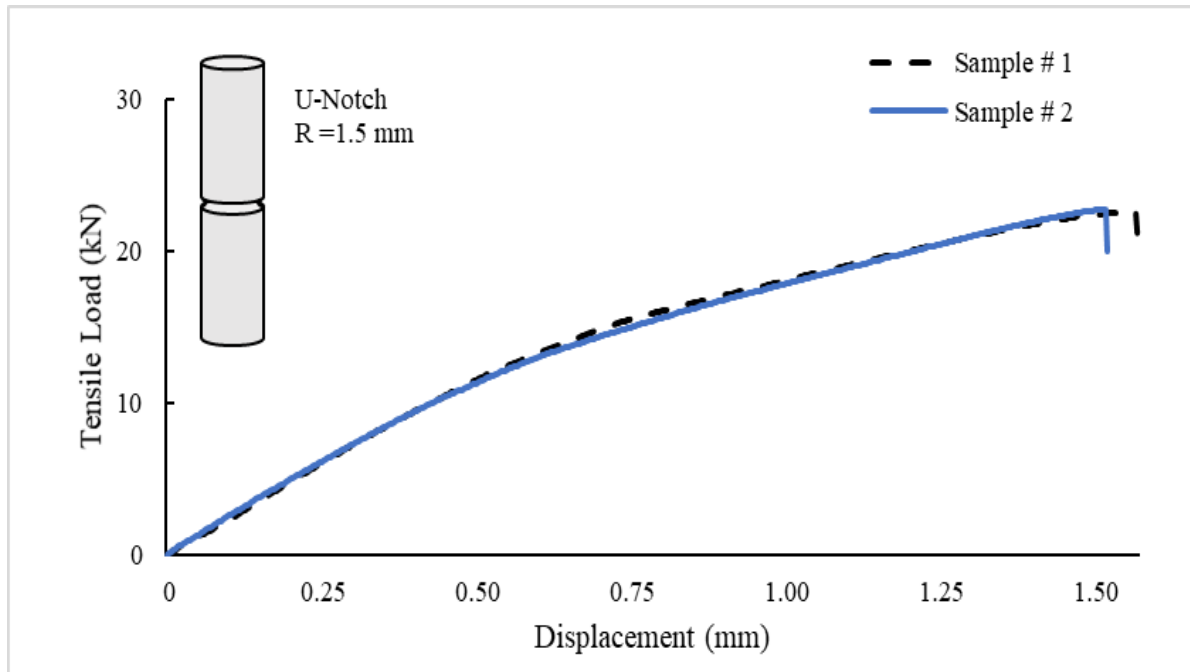


Figure (26): Stress-strain curve for U-notch with 1.5 mm notch radius.

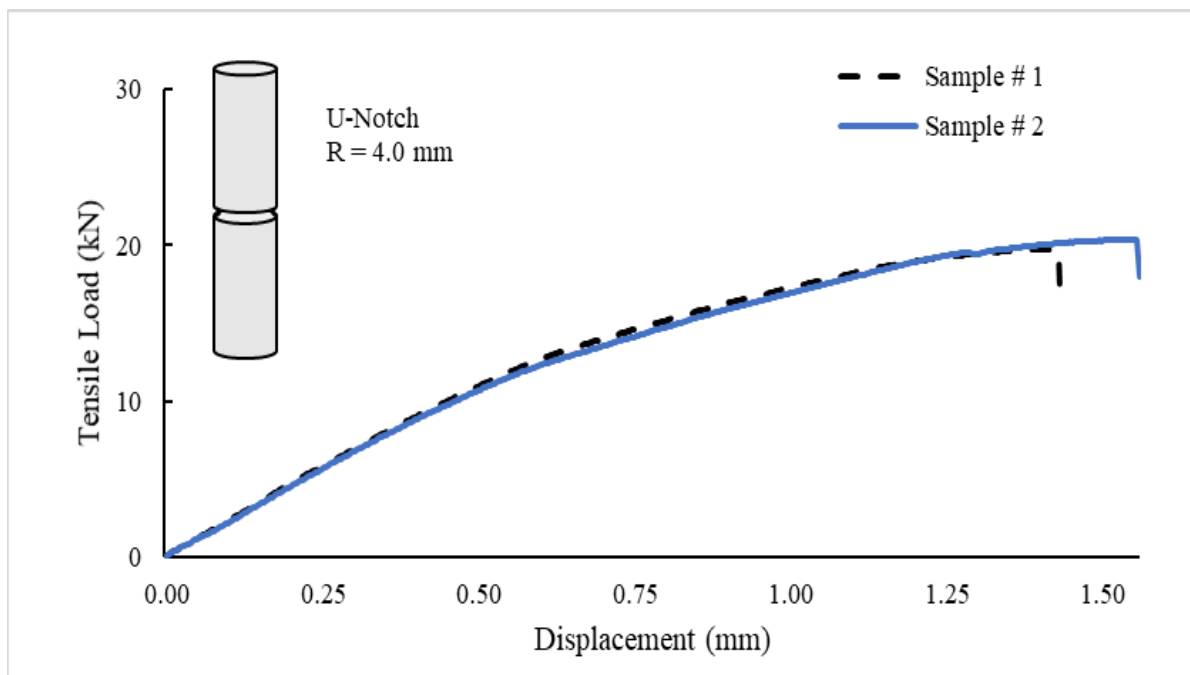


Figure (27): Stress-strain curve for U-notch with 4.0 mm notch radius.

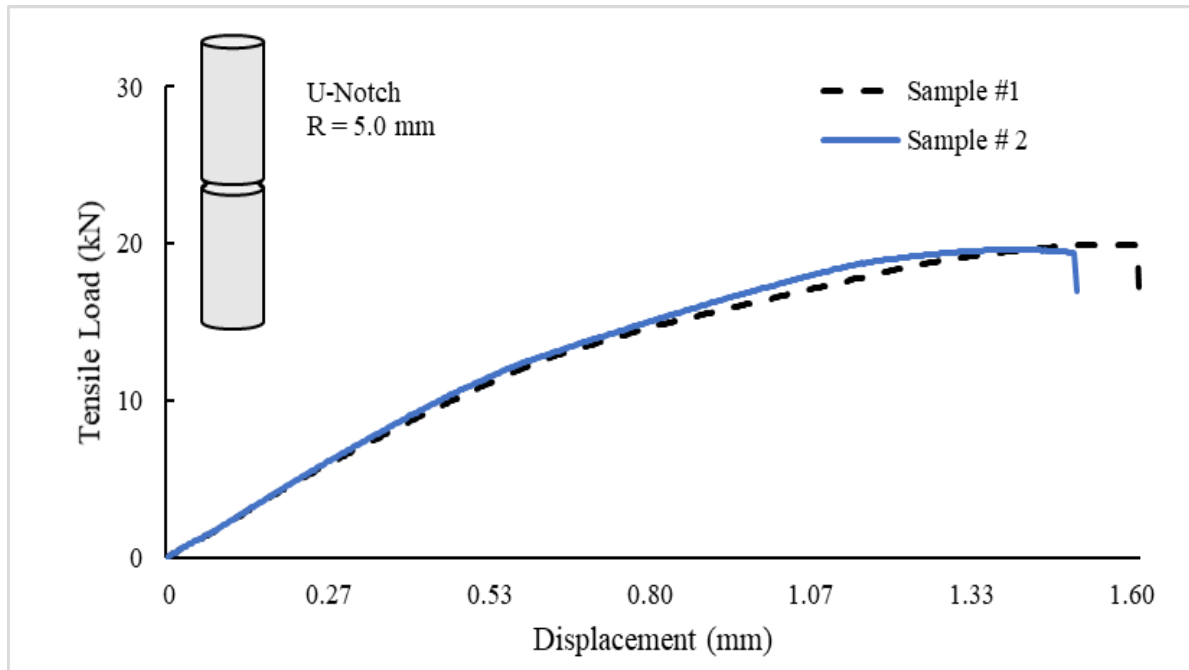


Figure (28): Stress-strain curve for U-notch with 5.0 mm notch radius.

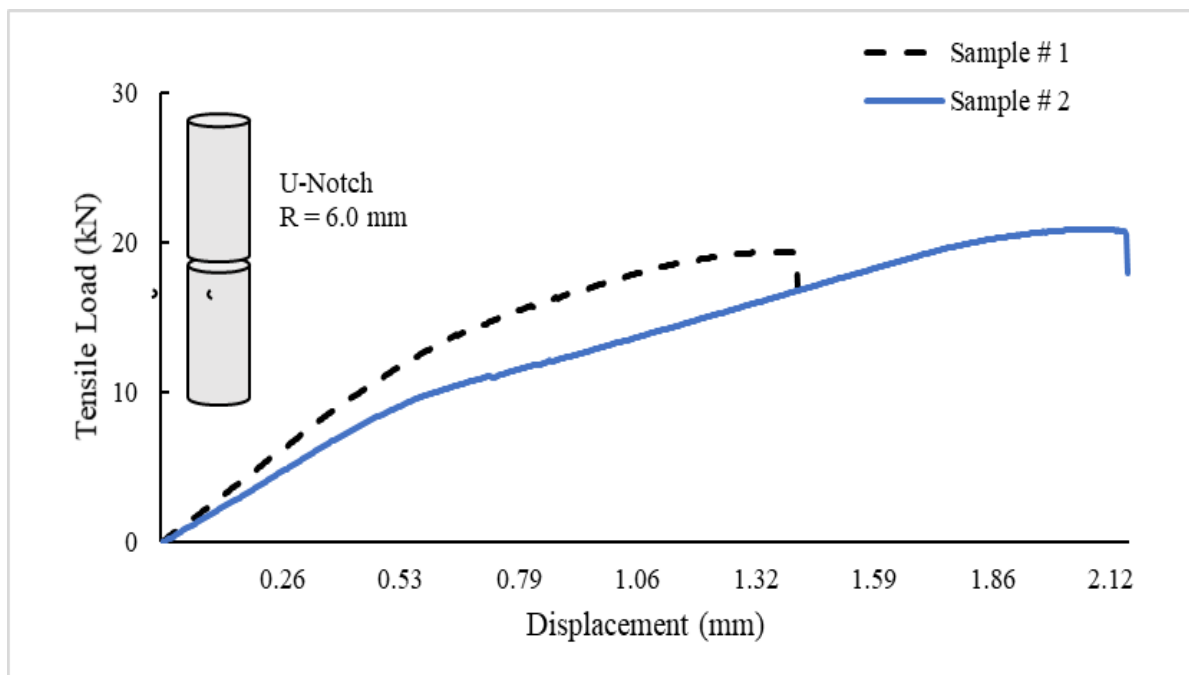


Figure (29): Stress-strain curve for U-notch with 6.0 mm notch radius.

APPENDIX 2
FRACTURE RESULT OF V-NOTCHED SPECIMENS

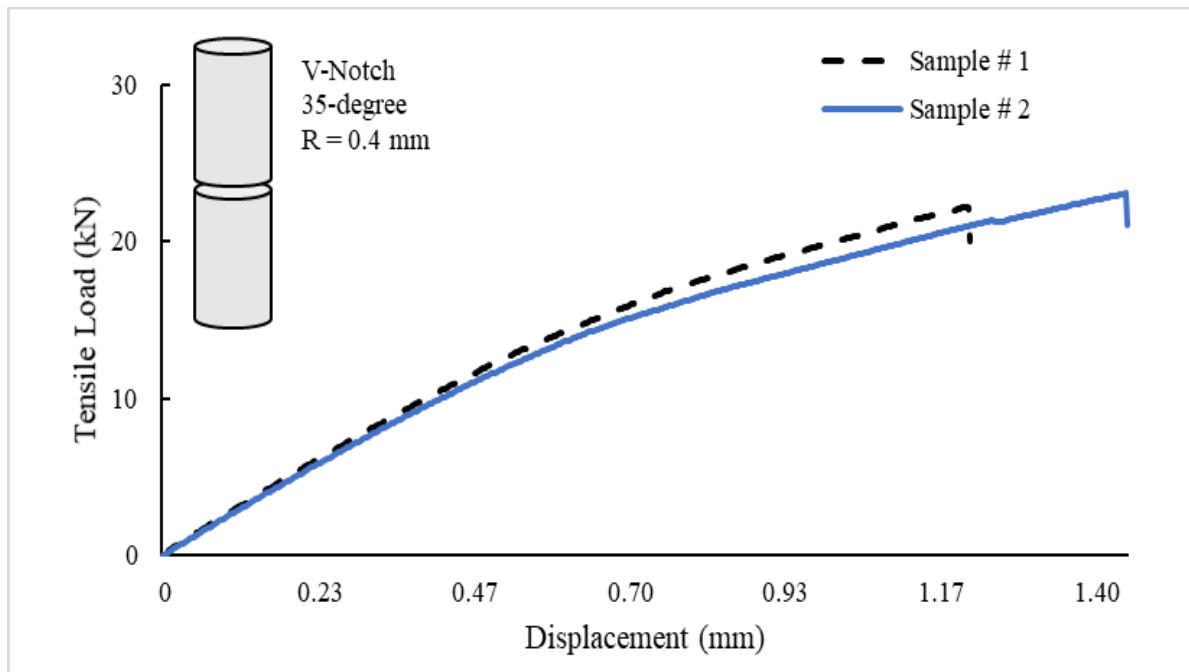


Figure (30): Stress-strain curve for V-notch with 0.4 mm notch radius and 35-degree notch angle.

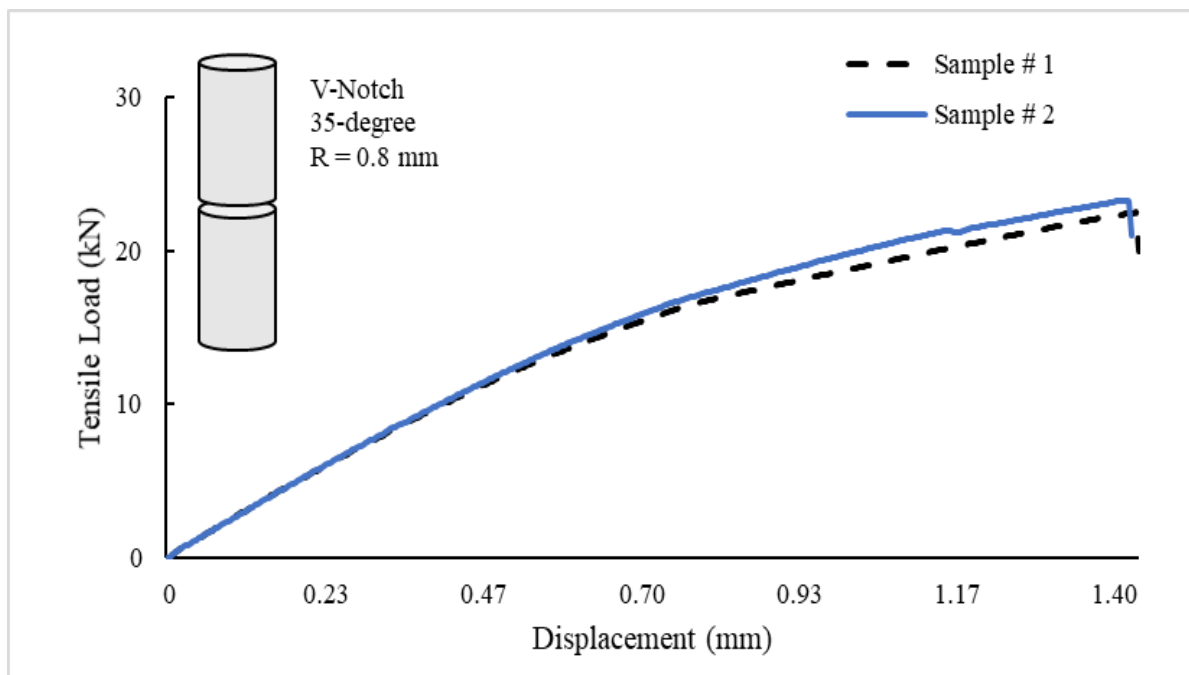


Figure (31): Stress-strain curve for V-notch with 0.8 mm notch radius and 35-degree notch angle.

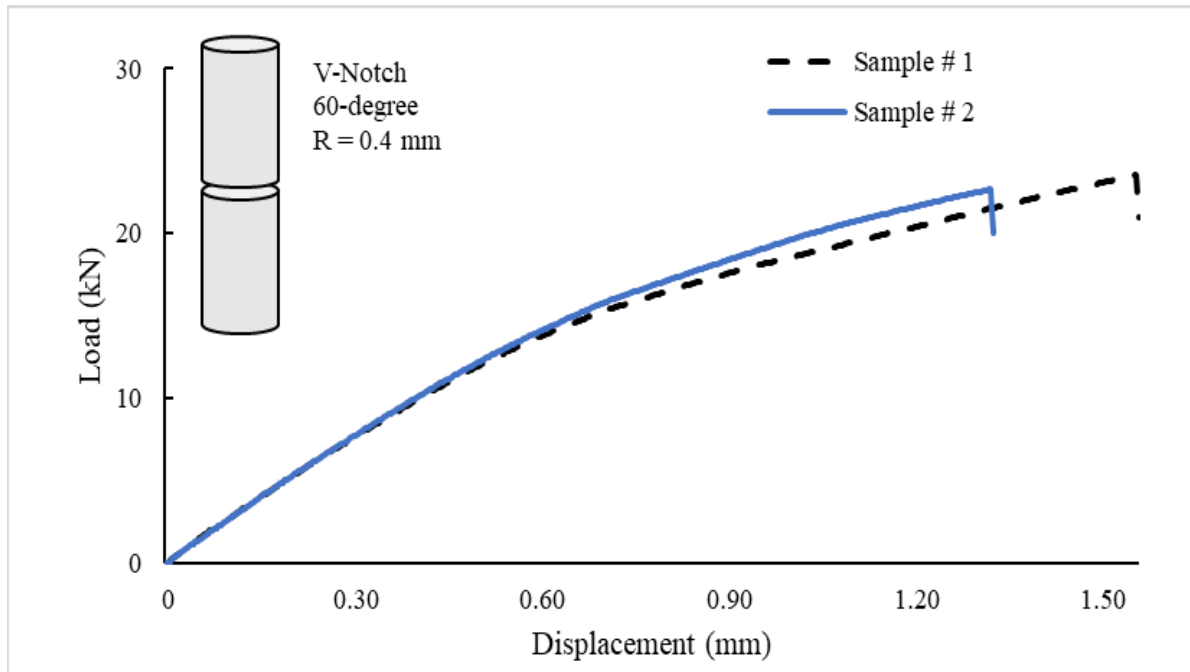


Figure (32): Stress-strain curve for V-notch with 0.4 mm notch radius and 60-degree notch angle.

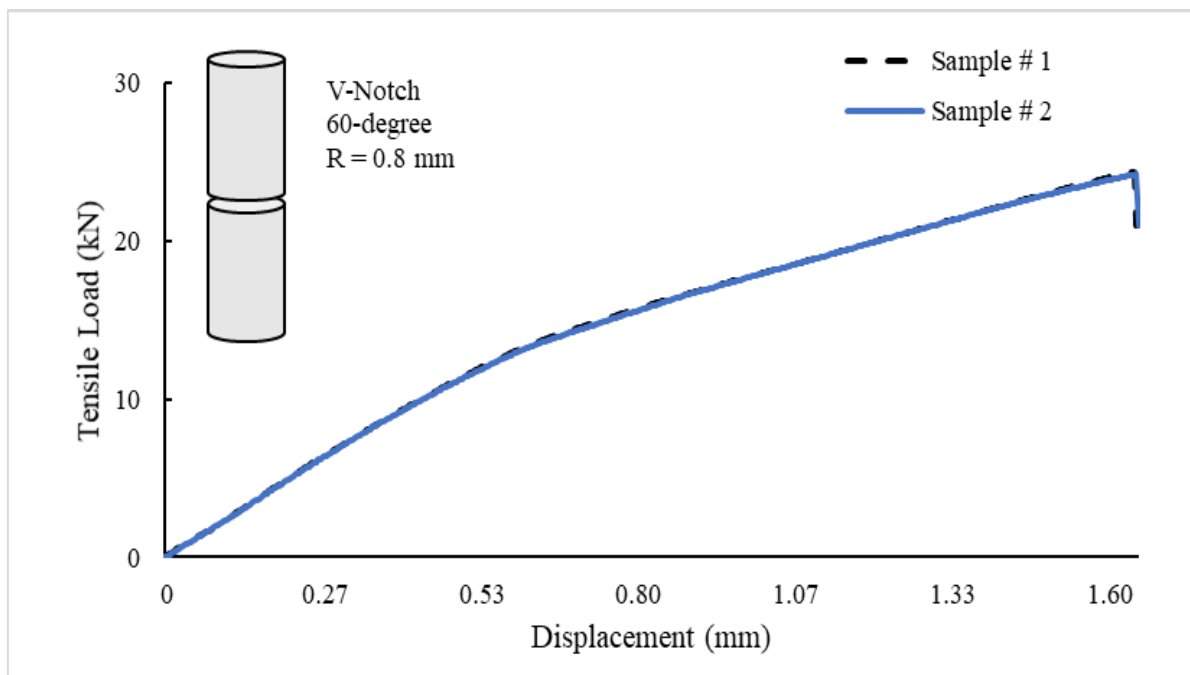


Figure (33): Stress-strain curve for V-notch with 0.8 mm notch radius and 60-degree notch angle.

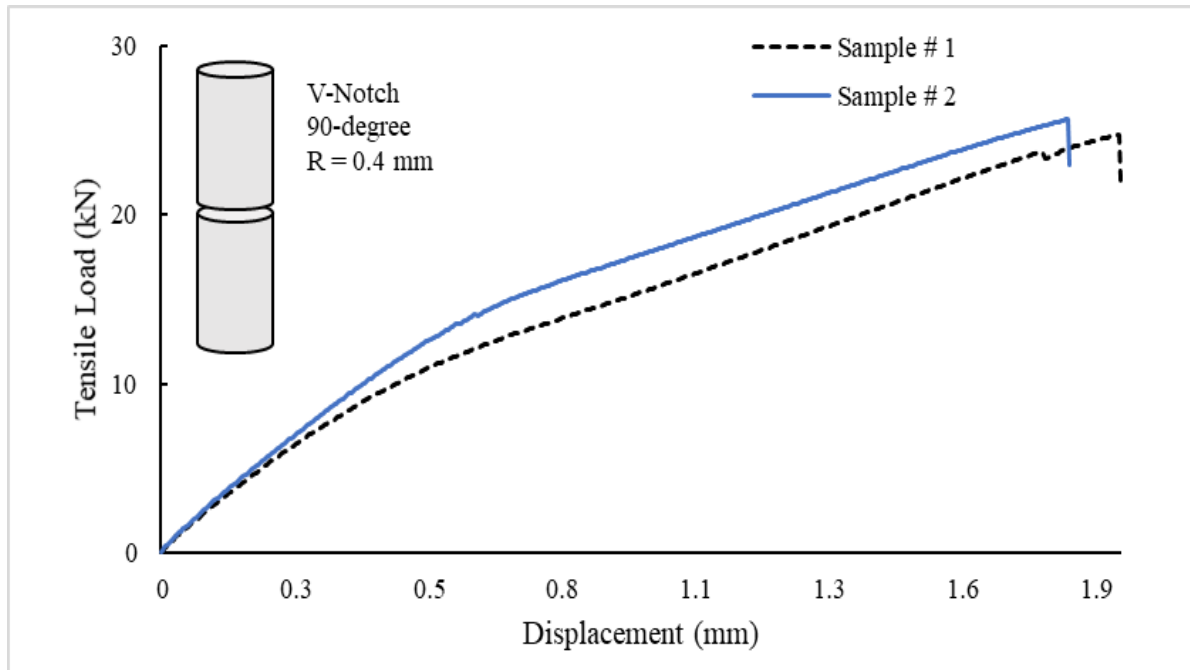


Figure (34): Stress-strain curve for V-notch with 0.4 mm notch radius and 90-degree notch angle.