Fracture mechanic analysis of multiple edge cracks in a finite plate using kerf to emulate crack interaction

by

Ahmad Faizal Bin Annuar
(1131410713)

A thesis submitted in fulfilment of the requirements for the degree of Master of Science (Mechanical Engineering)

School of Mechatronic Engineering
UNIVERSITI MALAYSIA PERLIS

2015

UNIVERSITI MALAYSIA PERLIS

DECLARATION OF THESIS

Author's full name : ……………………………………………………………………………………

Date of birth : ………………………………………

Title : ……………………………………………………………………………………

……………………………………………………………………………………

……………………………………………………………………………………

Academic Session : ………………………………………

I hereby declare that the thesis becomes the property of Universiti Malaysia Perlis (UniMAP) and to be placed at the library of UniMAP. This thesis is classified as :

☐ **CONFIDENTIAL** (Contains confidential information under the Official Secret Act 1972)*

☐ **RESTRICTED** (Contains restricted information as specified by the organization where research was done)*

☐ **OPEN ACCESS** I agree that my thesis is to be made immediately available as hard copy or on-line open access (full text)

I, the author, give permission to the UniMAP to reproduce this thesis in whole or in part for the purpose of research or academic exchange only (except during a period of _____ years, if so requested above).

Certified by:

_______________________	_______________________
SIGNATURE	**SIGNATURE OF SUPERVISOR**
_______________________	_______________________
(NEW IC NO. / PASSPORT NO.)	**NAME OF SUPERVISOR**
Date :_________________	Date : _________________

NOTES : * If the thesis is CONFIDENTIAL or RESTRICTED, please attach with the letter from the organization with period and reasons for confidentially or restriction.

ACKNOWLEDGEMENT

Praise to God, the most gracious, merciful, and forgiving, for his blessings, I have managed to found my feet to complete this thesis. First and foremost, I would like to thank my main supervisor, Dr. Muhamad Saifuldin Bin Abdul Manan, for his constant mentoring and technical support throughout the period of study. The same can be said to another prominent figure, my co-supervisor Dr. Haftirman, who greatly supplied extensive information and data that corroborate this study.

I would also wish to express my gratitude to the Postgraduate Chairman for School of Mechatronics, Dr. Cheng Ee Meng, for clearing mostly the administration procedures. Special thanks to Dr. Noorhafiza Binti Muhammad for being a great confidant. Other supporting casts that I would like to pay tribute to are the technicians, Mr. Aliff Mad Yusof, from UniMAP's solid mechanic lab, and Hj. Abdullah Mohd Shariff from Universiti Kebangsaan Malaysia (UKM) of Fakulti Kejuruteraan dan AlamBina.

I personally dedicate this thesis to the first person that encourages me to pursue postgraduate studies, my former superior, Mr. Zamani Asmat, who made strong points for me to further studies while at younger age. His support and advice made it easy for me to leave the lucrative manufacturing industry to join the noble academic world.

Last but not least, I reserve my special gratitude to both of my parents, Norhabibah Binti Lebai Isa and Annuar Bin Mohd Saffar, for standing by me during thick and thin and for their unconditional love.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

2D	Two dimensions
AA	Aluminum Alloy
CAE	Computer Aided Engineering
COD	Crack Opening Displacement
CPS8R	8-node bi-quadratic plane stress quadrilateral in reduced integration
LEFM	Linear elastic fracture mechanics
LM	Laser Machining
FEA	Finite Element Analysis
MRS	Multiple Reference State
SIF	Stress Intensity Factor
WEDM	Wire Electric Discharge Machining
WJM	Water Jet Machining

LIST OF SYMBOLS

a	Potential Crack length
a_1	Length of Crack 1
a_2	Length of Crack 2
a_x	Crack length along plane
b	Kerf length
c	Empirical material constant in Paris Equation
C_j	Coefficients of load case
d	Separation between kerf and crack or between two cracks
da/dN	Fatigue crack growth rate
E	Young's Modulus of material
J	*J*- integral value
K	Stress intensity factor (SIF)
K_I	SIF mode I
K_c	Fracture toughness
K_{a1}	SIF for crack 1
K_{a2}	SIF for crack 2
$m(a,x)$	SIF weight function
m	Empirical material constant in Paris Equation
N	Number of fatigue cycles in linear elastic fracture mechanics
r	Radius
T	Specimen width
U	External work
$u(a,x)$	Crack opening displacement
V	Strain energy
W	Strip length
W_{ij}	Coefficients of MRS Weight Functions calculations
x	Distance along potential crack plane
Y_a	Normalised SIF
Y_1	Solution for tension load case
Y_2	Solution for bending load case

ν	Poisson ratio
σ	Stress
σ_U	Ultimate tensile strength
σ_Y	Yield strength
σ_0	Remotely applied stress
σ_K	Stress distribution along uncracked plane from kerf length
$\sigma_1(x)$	Stress distribution along potential crack 1
$\sigma_2(x)$	Stress distribution along potential crack 2
Γ	Crack contour
τ	Shear stress
θ	Angle
ΔK	Stress intensity factor range
ΔK_{th}	Threshold stress intensity factor range

Kajian Dasar Analisa Mekanik Patah Pada Beberapa Retak Tepi Pada Plat Terhingga Menggunakan Alur Potongan Untuk Meneladani Interaksi Retak

ABSTRAK

Keretakan yang berbilang dengan perbezaan atau persamaan geometri pada satah yang sama akan mempengaruhi nilai kiraan Faktor Keamatan Tegasan (SIF) pada sesuatu retakan dan juga retakan di sebelahnya akibat dari kesan interaksi. Kesan interaksi banyak berkait dengan perubahan profil taburan tegasan yang dihasilkan retakan bersebelahan. Kajian ini telah dibuktikan benar melalui pelbagai perisian berasaskan Analisis Elemen Terhingga (FEA) dan pembangunan formula, akan tetapi, ujikaji sebenar dan hasilan data asli agak jarang didapati dalam sebarang penerbitan. Ini barangkali berlaku kerana proses penghasilan kajian retakan berbagai agak sukar untuk dihasilkan berbanding dengan kajian retakan tunggal. Tujuan kajian ini dilakukan adalah untuk mensimulasi dan mencari kemungkinan menggantikan interaksi retakan berikut kepada retakan utama menggunakan alur potongan, yang dipotong melalui pemotongan wayar dari Mesin Nyahcas Elektrik (WEDM), dengan penilaian komponen taburan tegasan secara longitud. Teknologi terkini yang mampu ditawarkan EDM di rantau ini untuk lebar alur potongan adalah 0.050mm. Khusus pada kajian ini, skop yang difokuskan adalah mengemulasi kajian interaksi dua retakan tepi sebagai permulaan. Melalui simulasi dalam perisian Kejuruteraan Bantuan Berkomputer (CAE) ABAQUS, nilai taburan tegasan tak seragam yang disebabkan oleh alur potongan telah dianalisis dan dibandingkan dengan taburan tegasan tak seragam dihasilkan oleh retakan sebagai pengesahan. Tabulasi ralat mutlak pada taburan tegasan dari alur potongan menunjukkan yang ia layak menggantikan retakan berikut untuk kajian interaksi retakan berbagai. Kaedah tak konvensional untuk menentukan Normalisasi SIF, Y_a, <u>Fungsi</u> Pemberat melalui kaedah Keadaan Pelbagai Rujukan (MRS) dipilih kerana kebolehan dalam komputasi kompleks pada geometri retakan dan merangkumi nilai taburan tegasan tak seragam dalam struktur terhad. Nilai Y_a yang diambil dari FEA dari pelbagai model dua retakan tepi, sebagai rujukan, menunjukkan keseragaman yang baik dari segi aliran garis data. Eksperimen yang dijalankan menggunakan specimen, diperbuat dari Aloi Aluminium 60603 T6, mengandungi satu retakan, *a*, pada pelbagai panjang dan satu alur potongan 10mm, *b*, pada permukaan tepi yang sama dan pemisahan, *d*, sepanjang 10mm untuk pemerhatian pertumbuhan retakan dibawah pengaruh alur potongan. Tiga keadaan spesimen adalah; i) $a \approx b$, ii) a=1.5b, dan iii) a=2b. Ini adalah untuk menyerlahkan kewujudan interaksi antara retakan dan alur potongan pada keadaan retak sedang bertumbuh dibawah keadaan yang berbeza-beza. Kajian ini menyumbang kepada pengetahuan mengenai tegasan tak seragam yang dihasilkan alur potongan dan pengaruh keatas pertumbuhan retakan utama dimana hasilan adalah setanding retakan berikut. Signifikan kajian ini adalah ia mendedahkan perwatakan interaksi alur potongan dan retakan dan membolehkan jangkaan terhadap kegagalan struktur dapat diatasi oleh jurutera dan pengkaji untuk mengelakkan sebarang bencana.

Fracture Mechanic Analysis of Multiple Edge Cracks In A Finite Plate using Kerf to Emulate Crack Interaction

ABSTRACT

Multiple cracks with different or similar geometries that coexist on the same plane will affect its neighbouring counterpart's Stress Intensity Factor (SIF) value due to interaction effect. The interaction effect is much related to the change of stress distribution profile that produced by neighbouring crack. The study had been proven true over the past years through various Finite Element Analysis FEA software packages and formulation, but an actual experiment and raw data acquisition is rather scarce in literature. This could well mean that the process to prepare multiple cracks study is hard to emulate physically as oppose to single crack study. The main intention of this study attempts to simulate and find a possibility to replace subsequent crack interaction to primary crack with kerf, incise in Electric Discharge Machining (WEDM) wire cut, by evaluating the longitudinal stress distribution component. Current regional technology of WEDM permits kerf gap machining at 0.050mm. This research, focuses on emulating two parallel edge cracks' interaction as initial attempt to prove that kerf provides similar interaction on primary crack's SIF. Through simulation using ABAQUS Computer Aided Engineering (CAE), values of non-uniform stress distributions produced by kerf within the potential primary crack region was analysed and compared to non-uniform stress distributions that produced by a crack as validation. Absolute error tabulation of stress distribution that produced by kerf suggests that it is fit to replace subsequent crack for further study of interaction in multiple cracks. A non-conventional method to determine Normalised SIF of crack, Y_a , using Multiple Reference State (MRS) Weight Function was chosen given its capability in complex computation of crack geometries that includes non-uniform stress distribution values in finite bodies. The Y_a values from FEA models of double edge cracks which were used as reference points exhibits decent agreement with data trend line from those conceived by MRS Weight Function Method. Experiments are carried out with three (3) specimens, made from Aluminium Alloy 6063 T6, which contains a crack, *a*, at varying length and 10mm kerf, *b*, each at similar edge surface at similar separation of 10mm to observe further growth of crack under presence of kerf. The three conditions of the specimens are designed as followed; i) $a \approx b$, ii) $a=1.5b$, and iii) $a=2b$. This is to highlight the existence of interaction between crack and kerf under circumstance where primary crack at different conditions attempts to grow under loading. This research contributes the knowledge of kerf's non-uniform stress distribution trend under tension loading and its influence to primary crack's growth in which the results are comparable to those produced by subsequent crack. The study of kerf in this research is significant as it disclose characteristic of kerf and crack interaction and allows anticipation in the events structural failure for engineers and research in order to avoid potential disasters.

CHAPTER 1

INTRODUCTION

1.1 Research Background

The word fatigue was derived from Latin word *fatigare* which utterly means 'to tire'. Cracks are commonly associated with fatigue since it involves weakening of structures. Cracks are undesirable feature that weakens the structure of a machine, vehicle, or buildings. Some cracks are known to develop through flaws in designs under considerable cyclic loadings, and some grew out of wear and tear after going through long period of time. The former is an interesting point of study as it has taken engineers, designers, and architects alike by surprise during the early days of the 20th century. One of the most fatalistic tragedy occurred due to fatigue in design was the one involving the De Havilland Comet, the world's first production commercial jet airliner introduced in 1949. After a few years of service, the comet airframes suffered catastrophic metal fatigue crashed during mid-air. After extensive test, the engineers discovered that the window frames contain cracks at each squared corners. Rapidly changing cabin pressure between the inside and outside during air cruising causes the crack and consequently, the inevitable crash in mid-flight. The solution was to build rounded edge window frame to reduce the stress concentration at four frame corners along with fuselage structural reinforcement. As a result of the investigation, the design is now adopted by all aircraft manufacturers until today.

Although research of fracture mechanics dates back as far as during Leonardo Da Vinci era, the studies of fractures or cracks extensively began during World War II after the Liberty ships disaster. The Liberty ships, used to carry supplies during the war, were supposed to be a technological breakthrough in vessel manufacturing and design. Led by Henry Kaiser, the program's construction engineer, who's famous for the Hoover Dam project, the ships had an all-welded hull instead of riveted technique which was used on traditional ships design. The all-welded hull was revolutionary as it reduced lead time in production. However, of 2700 built, 400 were found defected with fractures and 90 deemed severe. Three factors later revealed that, first, welding by semi-skilled workers contains crack like flaws. Second, fractures commence at squared hatch corners, similar to De Havilland Comet catastrophe, in which stress concentration is high. Third, Charpy impact test shows that the metal used for built had inferior toughness. Thus, the Naval Research Laboratory appointed DrG. R. Irwin to conduct theoretical studies on fracture mechanics for future military projects.

Irwin works are mostly influenced by works of Griffith and Orowan. Griffith developed energy theory of brittle fracture which later yielded the concept of Linear Elastic Fracture Mechanics (LEFM) in the 1920's. The knowledge of LEFM will be elaborated in Chapter 2. Following the works of Griffith, Orowan modified the theory by including plasticity effect of metal fracture. Irwin complimented the works of his research predecessor by adding energy release rate to better suit engineering applications. His work resulted in the introduction of Stress Intensity Factor in which he concluded that a single parameter can be used to express the applied stresses and displacement near crack tip area.

1.2 Problem Statements

The study is intended to emulate research on effects of Stress Intensity Factor (SIF) of multiple edge cracks. There are countless of research with the assist of Computer Aided Engineering (CAE) software using Finite Element Analysis (FEA) on multiple cracks simulation. However, the numbers for physical experiments on the subject are still far from matching simulative experiment. According to Abdul Manan (2008), this is due to several reasons:

i. The specimen preparation for multiple edge cracks was difficult especially to grow cracks at required length, location and crack separation. Crack arresting method for incumbent crack is necessary to allow subsequent crack(s) to grow to length.

ii. To grow a crack in LEFM characteristic, usually, low force and frequency is essential and requires long hours, depending on applied frequency. This could be difficult with materials that have an ultimate tensile strength in range of 200 to 500 MPa which would require high time consumption.

iii. Requires a lot of trial and error to obtain the right crack line for subsequent crack. The unpredictable nature of crack direction makes it difficult to acquire ideal straight crack path especially in subsequent crack(s).

Using precision cut, kerf is suggested as an able alternative to subsequent crack(s) in terms of interaction effect. However, due to unknown nature of kerf's incorporation into fatigue testing, concerns arose on these problem statements whether;

i. The characteristic of kerf stress distribution under loading would match and provide results similar to ones produced by a crack.

ii. The SIF value of a primary crack, in the presence of kerf, is affected in the same manner as it is by subsequent crack(s) interaction.

iii. That kerf will perform as proper as a subsequent crack in experimental mechanical fatigue testing in terms of its interaction effects on primary crack's growth.

The first two statements from above will require analysis through simulation work in order to justify the assertion. The third statement is to be rectified by observing potential reactions of kerf's interaction onto propagating crack via experimental work. This research, however, will experience shortcomings due to lack of literature references in the use of kerf in mechanical testing, moreover, associates with fracture mechanics.

1.3 Objectives

The main idea of study is to find the possibility of replacing subsequent edge cracks with precision cuts or specifically the kerf. In order to overcome disadvantages, the comparison of data was made using Finite Element Analysis (FEA) software ABAQUS and references on single and multiple edge cracks.

i. To investigate, analyze, and compare non-uniform stress distribution along the potential crack plane that affected by the kerf using Finite Element Analysis (FEA) software.

ii. To analyze and establish the interaction made by kerf to potential crack plane and use the data of non-uniform stress distribution to incorporate in Weight Function Method.

iii. To utilize fatigue experimental results to observe potential interaction between crack, a, and 10mm kerf, b, with 3 specimens in three conditions; (i) $a \approx b$, (ii) $a=1.5b$, and (iii) $a=2b$.

1.4 Scopes

Referring to the research objectives, the scope of research comprises of Finite Element Analysis (FEA) simulation and experimental works. For FEA simulation, specimens modelled were generated in two-dimensional (2D) crack growth solution under mode I or opening mode fracture loading.

In experimental works, three specimens made from Aluminium Alloy 6063 T6 plate metals, with each sized at 350mm × 50mm × 5mm. Specimens consists of one edge cracks and one kerf adjacent to one another at fixed separation were subjected under tensile loading test.

Both simulation and experimental works adhered to Linear Elastic Fracture Mechanics (LEFM) theory as guideline to measure the kerf and crack interaction limit. This is to determine the Stress Intensity Factor, *K*, of model and specimen under small scale yielding.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

In real life circumstance, failed structure usually contains more than a single crack at the end of its fail-safe cycle. The degree of a certain crack's significance is measured by its Stress Intensity Factor (SIF), provided that subjected body comply to Linear Elastic Fracture Mechanics (LEFM) approach. Multiple cracks commonly emerge from diverse sources, geometries and sizes. Under certain circumstances, taking consideration of cracks arrangement and applied loading, form of interactions may produce outcomes of stress shielding, or shielding effect and stress amplification (Kachanov, 1985).

In previous attempt of multiple crack analysis, to arrest the growth of incumbent crack, a solution known as 'toe weld technique' was employ in which a block of metal was welded on top of the first crack to allow growth for the second crack (M. S. Abdul Manan, 2008). A research conducted to probe interaction of two coplanar cracks in bending introduces a method known as 'ridged technique' (Soboyejo, 1989). In an effort to study crack growth direction (Gope and Thakur, 2011), jewellery saw of 0.1 mm thick blade was applied to slit the specimen to create concentration spot at the tip of the cut.

Chapter 2 discusses important aspects involved in fatigue crack growth study by reviewing past researches and methods involved in SIF computation of propagating primary crack under influence of another propagating crack in a finite body. Furthermore, research also discusses works inclined towards study of multiple cracks and the interaction effect that occurs in between these cracks at intervals by acknowledging the stress field disturbance. With the SIF value of primary crack normally affected by stress field due to presence of another crack, there is a possibility that a precision machining, in a form of kerf, could display similar stress field disturbance as those produced by subsequent crack. However, the kerf has to match characteristic of a crack particularly in size. Three precision machining processes were considered; (i) Water Jet Machining (WJM), (ii) Laser Machining (LM), and (iii) Wire Electrical Discharge Machining (WEDM) based on capability to yield thin kerf width and regional availability.

2.2 Linear Elastic Fracture Mechanics (LEFM)

The study of correlating fracture stress and flaw size was initiated by Griffith (1921) during the time energy-based theory for brittle fracture was proposed. Griffith's theory, however, was restricted to Hooke's law for plane strain and stress application. As mentioned in Chapter 1, Griffith's work was later revised by Irwin to include plasticity effects that comes across during metal fracture and later the energy release rate concept was conceived. Based on Westergaard (1939) stress function, Irwin proves that a single parameter is able to consolidate analysis of stresses and displacement near crack's tip to relate with energy release rate. The parameter is called Stress Intensity

Factor (SIF), K, and had since been used to measure the stress field in advance of the crack tip.

Linear Elastic Fracture Mechanics (LEFM) is a concept outlined by the assumption that a linear elastic material contains crack fracture produce small scale-yielding under loading. Even with the presence of fractural deformation or crack, subjected material remains to respond in linear elastic behaviour. To adopt LEFM theory, it is important in foremost to assume that linear elastic theory is applied to a body in the presence of crack in a distant singularity field. The singularity field forms a plastic deformation zone, as shown in Fig. 2.1 that surrounds the crack tip in which the body is actually structurally compromised above its yield stress limit. The theory of LEFM is commonly employed to characterize parameters of stress distribution and magnitude close to the crack tip in the form of load, crack geometry and material properties. LEFM is applicable when inelastic deformation at plastic zone is small in contrast to size of crack length.

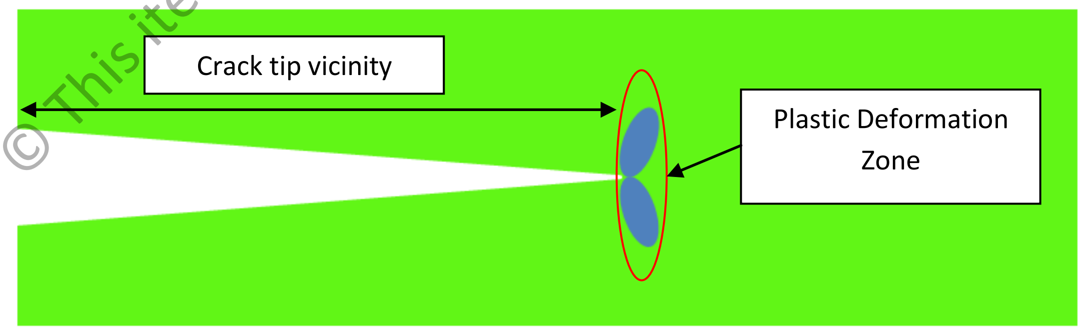

Figure 2.1: Plastic deformation zone at crack tip

In general, knowledge of fracture mechanics helps in forecasting life span of components in machine or structures for building on time-dependent basis. Over the years, crack-growth prediction has been developed to measure reliability range for cracked bodies under static or monotonic loading. To complement the SIF calculation under loading propagation, Paris and Erdogan (1963) developed a log-log plot of *da/dN* against ΔK to characterize the fatigue crack growth rate in metals. The relation of the rate is expressed in terms:

$$\frac{da}{dN} = C\Delta K^{m} \tag{2.1}$$

Where ΔK is SIF range, C and m are material constants which are determined by experiment. The sigmoidal curve introduced by Paris as shown in Fig. 2.2, is divided into three distinct regions to signify the stages of crack growth under cyclic loading. Region I is commonly referred to as crack threshold or crack initiation region where *da/dN* value starts at zero. The value of *da/dN* post-threshold stage starts to stabilise in approximately linear trend in Region II where fatigue growth is normally defined for groups of metal. The final stage of fatigue, Region III, is an acknowledgement stage where material is due to fully fracture. The studies of LEFM mainly revolve around Region II.

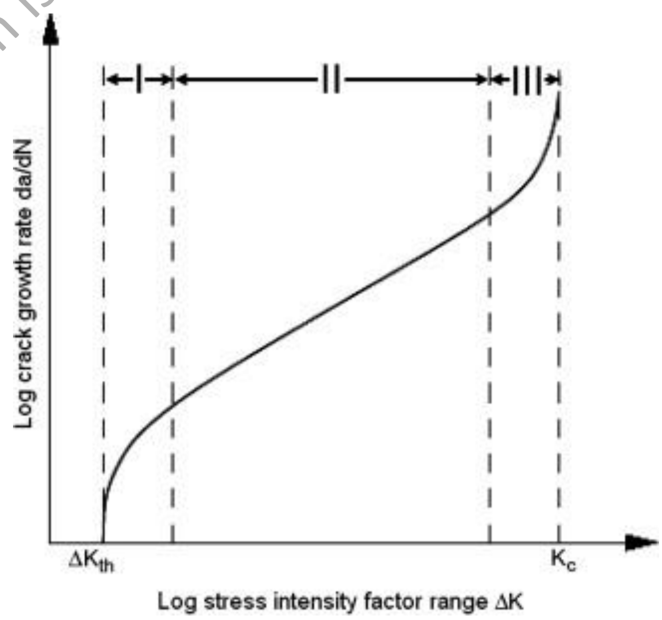

Figure 2.2: Paris law three regions plot