

**DETERMINATION OF K_{IC} FRACTURE TOUGHNESS
BY CRACK INITIATION OF A COMPACT
TENSION STEEL SPECIMEN**

LIM ENG HAR

PERPUSTAKAAN
UNIVERSITI MALAYSIA SABAH

**THESIS SUBMITTED IN FULFILMENT FOR THE
DEGREE OF MASTER OF ENGINEERING**

**SCHOOL OF ENGINEERING AND INFORMATION
TECHNOLOGY
UNIVERSITI MALAYSIA SABAH
2008**



UMS
UNIVERSITI MALAYSIA SABAH

UNIVERSITI MALAYSIA SABAH

BORANG PENGESAHAN STATUS THESIS®

JUDUL : DETERMINATION OF K_{IC} FRACTURE TOUGHNESS BY CRACK INITIATION OF A COMPACT TENSION STEEL SPECIMEN

IJAZAH : SARJANA KEJURUTERAAN (MEKANIK RETAKAN)

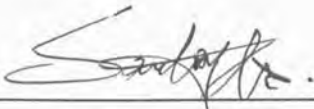
SESI PENGAJIAN : 2004-2007

Saya, LIM ENG HAR mengaku membenarkan tesis Sarjana ini disimpan di Perpustakaan Universiti Malaysia Sabah dengan syarat-syarat kegunaan seperti berikut:

1. Tesis adalah hakmilik Universiti Malaysia Sabah.
2. Perpustakaan Universiti Malaysia Sabah dibenarkan membuat salinan untuk tujuan pengajian saya.
3. Perpustakaan dibenarkan membuat salinan tesis ini sebagai bahan pertukaran antara institusi pengajian tinggi.
4. TIDAK TERHAD

PERPUSTAKAAN
UNIVERSITI MALAYSIA SABAH

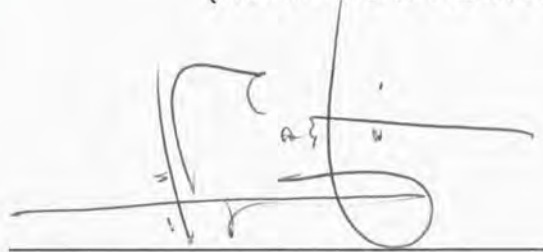
Disahkan oleh



(Penulis: LIM ENG HAR)

Alamat:
42D Kampung Baru,
Semeling,
08100 Bedong,
Kedah, MALAYSIA

(TANDATANGAN PUSTAKAWAN)



(Penyelia: Prof. Dr. Yeo Kiam Beng @ Abdul Noor)

Tarikh: 4 Julai 2008

Tarikh: 10 July 2008

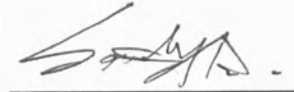
CATATAN : ® Tesis dimaksudkan sebagai tesis Ijazah Doktor Falsafah dan Sarjana secara penyelidikan atau disertasi bagi pengajian secara kerja kursus dan penyelidikan, atau laporan Projek Sarjana Muda (LPSM)



DECLARATION

I hereby declare that the material in this thesis is the sole work of mine except for quotations, excerpts, equations, summaries and references, which have been duly acknowledged.

04 July 2008



LIM ENG HAR
PS04-008-024

PERPUSTAKAAN
UNIVERSITI MALAYSIA SABAH



CERTIFICATION

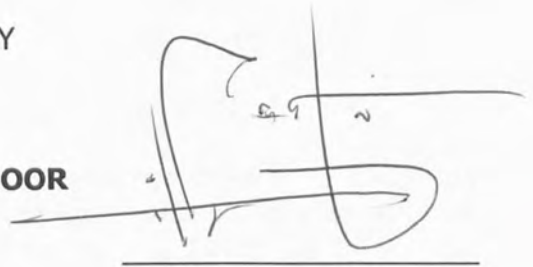
TITLE : **DETERMINATION OF K_{IC} FRACTURE TOUGHNESS BY CRACK INITIATION OF A COMPACT TENSION STEEL SPECIMEN**

DEGREE : **MASTER OF ENGINEERING (FRACTURE MECHANICS)**

VIVA DATE : **16 JUNE 2008**

CERTIFIED BY

1. **PROF. DR. YEO KIAM BENG @ ABDUL NOOR**
(MAIN SUPERVISOR)



2. **DR. MOHAMED HARIMI**
(CO-SUPERVISOR)



ACKNOWLEDGEMENTS

I would like to thank the Universiti Malaysia Sabah - UMS, supervisors, colleagues and families who have made this completion of thesis happen. My deepest gratitude goes to Prof. Dr. Yeo Kiam Beng @ A. N. for his patience in providing technical guidance, encouragement, advice and review on this research works. I am also very grateful to Dr. Mohamed Harimi for his kind support and contribution throughout the thesis writing. The financial assistance granted by the Universiti Malaysia Sabah through the Centre of Postgraduate Studies is highly acknowledged. My thanks also go to the School of Engineering and Information Technology for providing well-equipped laboratory in which to work. Alex, John and Panjiman were of invaluable help in the experimental works. A special mention is due to my colleagues and friends Choong, Aidy, Billy and Soo Ling who have made my stay in Sabah very enjoyable in addition to valuable discussion to accomplish my study.

My loving parents, with continuous moral support and motivation, supported my decision to achieve higher education. Many thanks go to my brother at China who has been working hard to support the living of my family so that I can concentrate on my study. I consider the completion of this thesis would be the best gift to appreciate their contributions. Finally, my devoted wife and life partner, Angeling, shared my joy and pain with her full encouragement and support without second thought. For that I want to thank her with all my love.



ABSTRACT

DETERMINATION OF K_{IC} FRACTURE TOUGHNESS BY CRACK INITIATION OF A COMPACT TENSION STEEL SPECIMEN

Fracture toughness parameter has been a critical concept in Fracture Mechanics (FM) analysis. In theory, the toughness parameter can generally be defined as the energy release rate, G , and the stress intensity factor, K . The latter fracture toughness parameter approach is applied in this research in which the plane-strain fracture toughness, K_{IC} , of a medium Carbon-steel is determined as to characterize the applicability of Linear Elastic Fracture Mechanics (LEFM) concepts. The experimental implementation of the K_{IC} fracture toughness evaluation is through the crack initiation approach by Crack Opening Displacement (COD) of highly constrained Compact Tension (CT) geometry-fabricated specimens, based on the ASTM Standard Test Method for Plane Strain Fracture Toughness of Metallic Materials, coded E-399, using the Instron Universal Testing Machine. Such geometry has been designed to constrain crack-tip sharpness and minimize negligible local crack-tip plastic zone for LEFM-concepts to be applicable, which is verified via the crack initiation zone measurement and the cleavage trademarks (river pattern and feather mark) identification using the Infinite Focus Microscope (IFM) and the Scanning Electron Microscope (SEM) alongside with the COD toughness characterization. In addition, a numerical analysis is carried out to provide comparative study to the experimental results using ANSYS version 9.0. This research found that the analyzed medium Carbon-steel with 0.33%C, 43% pearlite structure, hardness 183HB and Yield strength 360.40MPa achieves the plane-strain fracture toughness of $33\text{MPa}\cdot\text{m}^{1/2}$, beyond a critical thickness of 22mm. Through the microscopic works, the bandwidth of crack initiation zone has been identified at $10\mu\text{m}$ and the fracture surfaces within the zone possess cleavage microstructure deformation. This has further proven the applicability of LEFM-concepts can be achieved through the determination of K_{IC} fracture toughness, the measurement of crack initiation zone and the identification of cleavage trademarks at the zone.



ABSTRAK

Parameter kekuatan retakan merupakan satu konsep yang kritikal dalam Mekanik Retakan (FM). Secara teori, parameter tersebut boleh umumnya ditakrifkan sebagai kadar pembebasan tenaga, G , dan faktor keamatan tegasan, K . Dalam penyelidikan ini, parameter K diaplikasikan di mana kekuatan retakan jenis tarikan satah, K_{IC} bagi "medium Carbon-steel" adalah ditentukan untuk mencirikan kebolegunaan konsep-konsep Mekanik Retakan jenis Lurus Elastik (LEFM). Pelaksanaan eksperimen bagi penilaian kekuatan retakan jenis tarikan satah, K_{IC} adalah melalui pendekatan pencetusan retak oleh Sesaran Buka Retak (COD) bagi spesimen-spesimen bergeometri Tegangan Mampat (CT), berdasarkan "ASTM Standard Test Method for Plane Strain Fracture Toughness of Metallic Materials" yang berkod E-399, dengan menggunakan "Instron Universal Testing Machine". Geometri seumpama ini telah direkabentuk khas untuk mengekang ketajaman hujung retakan dan meminimum saiz zon plastik hujung retak yang boleh diabai supaya konsep LEFM akan dapat digunakan, di mana ia akan disahkan melalui pengukuran saiz zon pencetusan retak dan pengenalpastian tanda-tanda unik rekahan (corak sungai dan bulu) dengan menggunakan "Infinite Focus Microscope (IFM)" dan "Scanning Electron Microscope (SEM)" di samping pencirian kekuatan retakan melalui COD. Tambahan pula, satu analisis berangka dijalankan bagi menyediakan kajian perbandingan untuk kerja-kerja eksperimen dengan menggunakan ANSYS versi 9.0. Kesimpulannya, kajian ini telah mendapati bahawa "Carbon-steel" dengan kandungan 0.33%C, 43% struktur pearlite, kekerasan 183HB dan kekuatan pembentukan secara plastik 360.40MPa telah mencapai kekuatan retakan jenis tarikan satah, K_{IC} , sebanyak 33MPa.m^{1/2} dengan syarat melebihi ketebalan kritikal pada 22mm. Melalui kerja-kerja mikroskopik, lebar jalur zon pencetusan retak telah dikenalpasti kepada 10µm dengan permukaan-permukaan retak di dalam zon menunjukkan pembentukan tanda-tanda mikrostruktur rekahan. Ini selanjutnya membuktikan kebolegunaan konsep-konsep LEFM boleh dicapai melalui penentuan kekuatan retakan jenis tarikan satah, K_{IC} , pengukuran saiz zon pencetusan retak dan pengenalpastian tanda-tanda mikrostruktur rekahan pada zon tersebut.

TABLE OF CONTENTS

TITLE	i
DECLARATION	ii
CERTIFICATION	iii
ACKNOWLEDGEMENTS	iv
ABSTRACT	v
ABSTRAK	vi
TABLE OF CONTENTS	vii
LIST OF TABLES	x
LIST OF FIGURES	xi
LIST OF ABBREVIATIONS	xiv
LIST OF SYMBOLS	xvi
CHAPTER 1: INTRODUCTION	
1.1 INTRODUCTION OF RESEARCH	1
1.2 RESEARCH OBJECTIVE	1
1.3 RESEARCH BACKGROUND	1
1.4 SCOPE OF RESEARCH	3
1.5 RESEARCH METHODOLOGY	4
1.6 THESIS ORGANIZATION	5
CHAPTER 2: LITERATURE REVIEW	
2.1 INTRODUCTION	8
2.2 FERROUS METALS AND PROPERTIES	8
2.3 FRACTURE MECHANICS	11
2.3.1 A Historical Overview	12
2.3.2 LEFM Concepts and Applications	14
2.4 STANDARD TESTS FOR METALS	16
2.4.1 Profile of Test Specimen	17
2.4.2 Cutting Orientation	19
2.5 MICROSTRUCTURE ANALYSIS OF FRACTURE SOLID	20
2.5.1 Ductile Fracture by Coalescence of Microvoids	21
2.5.2 Brittle Fracture	23
2.6 COMPUTATIONAL FRACTURE MECHANICS	26



CHAPTER 3: COD FRACTURE TOUGHNESS THEORY	
3.1 INTRODUCTION	27
3.2 GENERAL MODES OF FRACTURE	27
3.3 LOCAL CRACK-TIP STRESSES	28
3.3.1 Stress Intensity Factor	30
3.3.2 Crack-Tip Yielding	30
3.4 PLANE-STRESS AND PLANE-STRAIN	31
3.5 MODE-I LINEAR-ELASTIC FRACTURE TOUGHNESS	33
3.6 MODE-I FRACTURE TOUGHNESS of C(T) SPECIMEN	34
CHAPTER 4: EXPERIMENTAL WORKS	
4.1 INTRODUCTION	36
4.2 MECHANICAL TENSILE TEST	38
4.3 CRACK OPENING DISPLACEMENT (COD) TEST	39
4.3.1 Preparation of COD Specimen	39
4.3.2 Testing and Data Collection	43
4.3.3 Validation Monitoring	43
4.4 POSTMORTEM TECHNIQUES	48
4.4.1 Determination of K_{IC}	48
4.4.2 Microstructure Analysis	49
CHAPTER 5: MATERIAL AND TOUGHNESS CHARACTERIZATION	
5.1 INTRODUCTION	54
5.2 TENSILE PROPERTIES	54
5.3 FRACTURE TOUGHNESS	55
CHAPTER 6: MICROSTRUCTURE ANALYSIS	
6.1 INTRODUCTION	59
6.2 MICROSTRUCTURE ON CLEAVED SURFACE	59
6.3 MICROSTRUCTURE ANALYSIS OF CARBON-STEEL	60
6.4 FRACTURED SURFACE ROUGHNESS PROFILE	61
6.5 FRACTOGRAPHIC MICROSTRUCTURE CHARACTERISTIC	63
6.5.1 Pre-Crack Zone	64
6.5.2 Post-Crack Zone	65
6.5.3 Crack Initiation Zone	66
CHAPTER 7: FINITE ELEMENT ANALYSIS	
7.1 INTRODUCTION	69
7.2 MODELING APPROACH	69
7.3 FINITE ELEMENT ANALYSIS PROCEDURES	71
7.3.1 Preprocessor	72
7.3.2 Processing	74
7.3.3 Postprocessor	74
7.4 RESULTS OF ANALYSIS	76
CHAPTER 8: RESULT AND DISCUSSION	
8.1 INTRODUCTION	79
8.2 DETERMINATION OF MATERIAL PROPERTIES	79
8.3 LINEAR ELASTIC FRACTURE BY K_{IC} CHARACTERIZATION	81

8.4 LINEAR ELASTIC FRACTURE BY YIELD ZONE CHARACTERIZATION	82
8.5 LINEAR ELASTIC FRACTURE BY FRACTOGRAPHY INVESTIGATION	83
8.6 FINITE ELEMENT ANALYSIS	84
CHAPTER 9: CONCLUSIONS AND FUTURE WORKS RECOMMENDATION	
9.1 CONCLUSION	86
9.2 FUTURE WORKS RECOMMENDATION	88
REFERENCE	89



LIST OF TABLES

	Page
Table 2.1 Mechanical properties of several pure metals at room temperature	9
Table 2.2 Chemical composition of selected steels	10
Table 2.3 Mechanical properties of selected steels at room temperature	11
Table 2.4 Expression of $f(a/W)$ for selected basic crack configurations	16
Table 2.5 Fracture modes in metals	21
Table 3.1 Stress components ahead of a crack-tip	29
Table 4.1 Dimension details of all fabricated test specimens B06 mm	45
Table 4.2 Dimension details of all fabricated test specimens B10 mm	46
Table 4.3 Dimension details of all fabricated test specimens B16 mm	46
Table 4.4 Dimension details of all fabricated test specimens B20 mm	47
Table 4.5 Dimension details of all fabricated test specimens B26 mm	47
Table 5.1 Tensile properties	55
Table 5.2 Distribution of $f(a/W)$ according to the measured a/W	57
Table 5.3 Calculation of fracture toughness values from P-COD data	57
Table 7.1 Results for varying crack-tip local mesh characteristics	76
Table 7.2 Sum of error to verify optimal crack-tip local mesh characteristics	77
Table 8.1 Hypothesis and experimental material properties	80

LIST OF FIGURES

	Page	
Figure 2.1	Variations in average material properties of carbon steel as a function of carbon and pearlite contents	10
Figure 2.2	A plate with small crack under uniform remote loading	14
Figure 2.3	Configurations of general fracture test specimen	18
Figure 2.4	ASTM notations for cutting orientation of Compact Tension specimen	20
Figure 2.5	Ductile fracture by microvoids coalescence	22
Figure 2.6	Micrograph of ductile microvoids coalescence fracture	22
Figure 2.7	Micrograph of cleavage	24
Figure 2.8	Types of grain boundaries orientation	24
Figure 2.9	Features of cracking path	25
Figure 3.1	Modes of fracture: I-Opening, II-Sliding and III-Tearing	28
Figure 3.2	Stress state at a tip of a central crack in an infinite body	28
Figure 3.3	Irwin's yield zone model	31
Figure 3.4	Deformation of crack-tip yield zone under Mode-I stress	32
Figure 3.5	Distribution of Mode-I fracture toughness at varying thicknesses	34
Figure 3.6	C(T) specimen configuration	34
Figure 4.1	Flow of research methodology	37
Figure 4.2	Typical geometric dimensions of a tensile test specimen	38
Figure 4.3	Tensile test with Instron Universal Testing Machine	39
Figure 4.4	Compact tension specimen with proportional dimensions	40
Figure 4.5	ASTM notation for T-L and S-L orientations	41

Figure 4.6	Precrack profile viewed by 10x magnification traveling microscope	42
Figure 4.7	Actual compact tension geometry specimen	42
Figure 4.8	COD test with Instron Universal Testing Machine	43
Figure 4.9	Deviation constraint of pre-cracking path (Magnification x20)	44
Figure 4.10	Measurement of pre-crack length (R: Magnification x7)	44
Figure 4.11	Three types of load-displacement (P-COD) curve	48
Figure 4.12	Microstructure analysis using stereomicroscope	50
Figure 4.13	3D microstructure analysis using infinite focus microscope	51
Figure 4.14	Areas for SEM micrographic investigation	52
Figure 4.15	Principle of images and signals in Electron Microscopy	53
Figure 5.1	Measurement of tensile properties for Sample 1	55
Figure 5.2	Mode-I P-CODs for specimens at varying thicknesses	56
Figure 5.3	Characteristic fracture toughness with respect to various thicknesses	58
Figure 6.1	Microstructure features on cleavage surfaces	60
Figure 6.2	Layered microstructures of pearlite (light) and ferrite (dark)	61
Figure 6.3	Pre-crack, crack initiation and post-crack fractured zones	62
Figure 6.4	3D fractured surface profile in pseudo colour mode	62
Figure 6.5	Variations of surface roughness along fracture path	63
Figure 6.6	Fractured surface of a COD specimen	63
Figure 6.7	Striations patterns at pre-crack zone	64
Figure 6.8	Small micro-voids at 1000x and zoomed in at 3000x (Top right)	65
Figure 6.9	Large pre-drawn dimples created by large particles at 500x magnifications	65
Figure 6.10	Crack front of initiation along the width of a COD specimen (doted in red)	66

Figure 6.11	“River” patterns magnified at 3000x and 5000x	67
Figure 6.12	“River” patterns magnified at 10,000x	67
Figure 6.13	“Closed-feather” marks magnified at 1000x and 5000x	68
Figure 6.14	“Open-feather” marks magnified at 1000x and 3000x	68
Figure 7.1	Half model local mesh of compact tension geometry	70
Figure 7.2	“PLANE2” elements around a crack-tip	70
Figure 7.3	Finite element analysis procedures	71
Figure 7.4	Finite element model of half compact tension geometry	72
Figure 7.5	Local mesh with fine element concentration at crack-tip region	73
Figure 7.6	Displacement constraints and load application	73
Figure 7.7	Selected solution options	74
Figure 7.8	Crack path definition and local coordinate system	75
Figure 7.9	Contour plot of fracture model	75
Figure 7.10	Characteristics of crack-tip local mesh	77
Figure 7.11	Numerical crack-tip stress intensity factor at varying thicknesses	78
Figure 8.1	Characteristic material properties and phase composition of Carbon-steel	80
Figure 8.2	Toughness characteristic with respect to thickness effect	81
Figure 8.3	Comparison of micrograph. L: adapted from Anderson (1992) and R (Top and bottom): from observation	83
Figure 8.4	Cleavage patterns as indicators to locate crack origin	84
Figure 8.5	Combined river patterns and feather marks directing to crack origin	84
Figure 8.6	Distribution of experimental and numerical critical stress intensity factor	85

LIST OF ABBREVIATIONS

A(B)	Arc-shaped (Bend)
A(T)	Arc-shaped (Tension)
ANOVA	Analysis of Variance
ASTM	American Society for Testing and Materials
BSI	British Standards Institution
CNC	Computer Numerical Control
COD	Crack Opening Displacement
COV	Coefficient of Variance
C(T)	Compact (Tension)
CTOD	Crack-Tip Opening Displacement
DOF	Degree of Freedom
DC(T)	Disk-shaped Compact (Tension)
EPFM	Elastic Plastic Fracture Mechanics
FEA	Finite Element Analysis
FM	Fracture Mechanics
GD-AES	Glow Discharge Atomic Emission Spectrometer
GPa	giga Pascal
HB	Brinell hardness
IFM	Infinite Focus Microscope
ISO	International Organizations for Standardization
J	Joule
JSME	Japanese Society of Mechanical Engineer
LEFM	Linear Elastic Fracture Mechanics

MPa	mega Pascal
MPa.m ^{1/2}	mega Pascal square-root meter
NC	Numerical Control
NRL	Naval Research Lab
SEM	Scanning Electron Microscope
SEN(B)	Single-Edge Notched (Bend)
UK	United Kingdom
US	United State
<i>eff</i>	effective
<i>kN</i>	kilo Newton
<i>max</i>	maximum
<i>min</i>	minimum
<i>mm</i>	millimeter

LIST OF SYMBOLS

$^{\circ}$	degree
μ	micron
$\%$	percent
γ_s	surface energy
Θ	radian
π	pi
σ	uniform stress
σ_f	fracture stress
σ_{ut}	ultimate tensile strength
σ_{ys}	yield strength
σ_{xx}	local crack-tip stress in x -direction
σ_{yy}	local crack-tip stress in y -direction
τ	shear stress
ν	Poisson's ratio
sec	secant
tan	tangent
A	area
B	thickness of specimen
B_{IC}	critical thickness
E	Young's modulus
G	energy release rate
G_{IC}	critical fracture toughness
K	stress intensity factor

K_{IC}	mode-I plane-strain fracture toughness
P	load
P_{IC}	critical @ fracture load
Q	internal strain energy
Q_o	internal strain energy of uncracked plate
S	span width
W	width of specimen
a	crack length
e	elongation
m	yielding constraint factor
r	distance of an arbitrary entity from a crack-tip
r_y	radius of crack-tip yield zone
w_t	total work

CHAPTER 1

INTRODUCTION

1.1 INTRODUCTION OF RESEARCH

Crack-induced fractures particularly in cleavage have been and continuously a matter of concern in the failure of various materials. The control of such failure phenomenon requires the understanding of the micro and macro mechanics of a defined material under specified loading condition. This research addresses the characteristic local crack-tip stress analysis under cleavage or Mode-I fracture toughness of metallic materials. The investigation focuses on the succession of modeling the Compact Tension (CT) geometry; Crack Opening Displacement (COD) test practices; fractographic analysis; and finite element analysis encircling the crack-tip stress at local-scale.

1.2 RESEARCH OBJECTIVE

The research objective aims to: (i) develop experimental technique for Mode-I fracture toughness analysis of metallic material using the stress intensity fracture toughness parameter (K_{IC}); (ii) identify the fracture mechanisms in cleavage failure by Mode-I loading via microstructure analysis; and (iii) investigate and compare the results between experiment and the finite-element analysis.

1.3 RESEARCH BACKGROUND

To current knowledge it is known that all materials fail at a critical load no more than the capacity they can bear. As yet, there are no complete and perfect answers to cross the limits, therefore, existing material design criteria has to be followed. Lawn (1993) has made this statement, "To make solids strong, we must first find out what make them weak". Therefore, the causes of failure have always been essential in developing appropriate criteria for the reliability assessment of a material. Conventional modeling assumes materials are free of defects and the maximum capacity is characterized by the yield strength (Griffith, 1920; Sanford, 2003).



In reality, structures have failed at much lower stress, especially at low temperature and for tougher/brittle building materials. Other researches had looked at the mannerism of how operating stress is transmitted to the inner regions, where fracture actually takes place and as a result led to the discovery of crack-induced fractures. Cracks or flaws can be easily formed during the mechanical works, such as machining, forging, rolling, and even at the earliest solidification process. Such defects must be incorporated for any real case studies of material failure, particularly in critical applications such as nuclear facilities, high rising structures, and transport facilities on land, air and sea.

The Fracture Mechanics is a well established failure criterion for modeling the sustainability of materials containing cracks. Fundamentally, the approach relies on three primary steps of works; determination of the stress distribution at the vicinity of cracks or crack tip, measurement of the crack size, and evaluation of crack resistance. The mechanical energy release rate G and stress intensity factor K are two general parameters developed to quantify the motive of fracture in terms of operating stress, specimen geometry, environmental condition, and etc. These are characterizing parameters of what happens at the crack-tip, which correlates to the stress field of any cracked system. At some critical value, these parameters become independent of any system geometry, so called the critical fracture toughness of material (G_{IC} or K_{IC}). This material parameter plays a critical role in designing materials for application. For a particular material with a known fracture toughness, maximum operating stress or tolerable flaw size in designing a component can be pre-determined, when either one of these condition is pre-stated.

Besides developing concepts, assumptions, and criterion for modeling fracture behaviour, translation into standard practical techniques for actual evaluation and investigation is equally needed. The American Society for Testing and Materials (ASTM) Standard coded E399-90 (1997) is one of the test standards developed for in lab evaluation of Mode-I fracture toughness of metallic materials under the plain strain condition, in order to induce elastic fracture behaviour. The geometric dimensions, testing conditions, constraints, and monitoring are specifically correlated and designed to meet the theoretical concept of the critical toughness parameter. Post fracture analysis is another important aspect that can provide enormous

important physical insights to the failure mechanisms. Commonly adopted techniques for post fracture evaluation are through macroscopic and microscopic investigation using optical and Scanning Electron microscopes. Behaviours and patterns of microstructure deformation on fractured surfaces and during crack propagation can be correlated to the fracture criterion, and the material characteristics.

1.4 SCOPE OF RESEARCH

The scope of this research can be elaborated in four main parts as in the following:-

- (i) The formulation of local crack-tip stress field based on linear-elastic fracture mechanics (LEFM) concepts is comprehensively covered for the standard compact tension model. The modeling of stress intensity factor includes the consideration of corresponding constraints, assumptions, geometry function, and the fractured related parameters.
- (ii) The COD method in ASTM Standard E399 is identified and implemented for the fracture toughness evaluation of carbon steel by crack initiation method. Production of test specimens is strictly according to the requirements of COD geometry. Test condition of sharp crack profile must be established by pre-cracking procedure before initiation of crack can be developed for the critical fracture toughness test.
- (iii) The characterization of critical fracture toughness condition is strengthened by the microstructure analysis. Post-test microstructure observation of cracked surface under Scanning Electron Microscope (SEM) is carried out to identify and investigate the type of fracture deformation evident of cleavage loaded and elastic fracture.
- (iv) Numerical modeling and prediction of critical fracture toughness by crack-tip stress field analysis using ANSYS 9.0 is also developed in order to compare with the experiment results.

1.5 RESEARCH METHODOLOGY

The research methodology involves the development of literature review, theoretical modeling, experimental technique, numerical modeling, and microstructure analysis of cleavage of carbon steel. The following elaborates on the research methodology:-

(i) Literature survey

Compilations and reviews on early preliminary investigation of fracture toughness for brittle materials such as metals were carried out. Publications on early developments of linear-elastic fracture mechanics, concepts of COD toughness characterization, experimental standards and numerical approaches, and microstructure analysis in crack-tip toughness analysis were reviewed.

(ii) Crack Opening Displacement -COD modeling

Basic fracture mechanics concept model was developed prior to the implementation of fracture model for COD investigation. The COD geometric configuration was identified based on ASTM Standard E399. The elastic stress field analysis was derived to model the crack-tip stress field in term of local parameter; stress intensity factor, K . The constraints and assumptions of COD geometry were pre-described for the purpose to obtain a linear-elastic toughness interpretation.

(iii) Experimental Method and Toughness Interpretation

The K_{IC} toughness test method was conducted to develop the experimental data for the calculation of fracture toughness under plane-strain conditions. The test procedures utilized complies with the ASTM Standard coded E-399. The specimen geometry fabrication and the production of sharp crack at the machined V-notch tip were developed. Pre-cracking by low frequency fatigue for fine hair line crack or sharp crack was also developed prior to the crack initiation testing by COD method.

(iv) Microstructure Analysis

Post-fracture testing by COD method was subsequently subjected to further microstructure observation in order to correlate the validity of Mode-I cleavage loading and plain strain failure of the specimen. Characteristic failure mechanisms by microstructure deformation trademarks were identify to validate the achievement of critical fracture characters of the carbon steel.

(v) Numerical analysis

The ANSYS-9.0 computational software was utilized for modeling the local meshing parameters before the optimization and analysis of the crack-tip zone. The significant constraints and parameters responsible for the extraction of numerical critical fracture toughness values were also identified. Finally, a correlation and comparison of the numerical prediction to the experimental toughness value was established using the ANOVA statistical analysis.

(vi) Thesis Writing

The steps of activities throughout the research are documented. The thesis writing presents the introduction to the research, overview of literature, mathematical modeling and analysis, experimental technique, fracture toughness characteristic, microstructure analysis, numerical simulation, discussions and conclusion were drawn.

1.6 THESIS ORGANIZATION

The thesis documentation of the research work is distributed into nine chapters. These chapters include the introduction, literature review, theoretical modeling, experimental techniques, microstructure analysis, finite element analysis, discussion and conclusion.

The Chapter 1 introduces the initiative of this research work. The corresponding objectives to be achieved were elaborated along with the scope of work to be covered. Methodology to accomplish the research work was also provided along with the thesis organization.

The Chapter 2 provides a comprehensive review on all earlier researchers' works relevant and useful for this research topic. Metallic materials and properties; fracture Mechanics principle, criterion, and its applications; standard test methods and Mode-I fracture toughness evaluation; fractured failure mechanisms and microstructure investigations of metallic materials; and finite element modeling of crack tip problems were systematically addressed.

In Chapter 3, a fundamental linear fracture mechanics theory concept and criterion for the derivation of fracture toughness model was presented. In particular,

the derivation of Mode-I stress intensity factor (K_{IC}) under plane-strain condition was developed for the standard compact tension test geometry by Crack Opening Displacement-COD method. Some attention was also drawn to relate the constraints and assumptions in the determination of K_{IC} for the experimental implementation.

The experimental technique for the development of Mode-I stress intensity fracture toughness evaluation was elaborated in Chapter 4. The basic tests to obtain the mechanical properties and chemical composition of material were first conducted. Subsequently, the standard COD geometry for Mode-I toughness evaluation was fabricated based on the ASTM standard E399. Specimens with various thicknesses were fabricated for plane strain and plane stress evaluation. The most critical part of the experimental work is the in lab implementation of COD testing, monitoring, and data collection on the universal testing machine. Pre-cracking by fatigue, actual COD test by crack initiation, and post fracture microstructure evaluation techniques were all presented in this chapter.

Chapter 5 presents the data collected during the experimentation, the reduction of data, and the computation of results, which were utilized for the calculation of the stress intensity factor or fracture toughness values. Data reduction and derivation for the toughness value calculation were conducted on the different specimen thickness. Fracture toughness characteristic with respect to different thicknesses was obtained for plain-strain and plain-stress identification before the critical value of K_{IC} could be ascertained.

The Chapter 6 provides a postmortem analysis of the post fracture surfaces of the COD specimen. Microstructure analysis on the fractured zones during pre-crack, crack initiation, and gross failure were all identified. Particularly, the failure mechanisms, the trademarks of microstructure deformation under Scanning Electron Microscopic analysis were conducted to validate the cleavage failure of materials. Unique microstructure deformations were classified and explained.

In Chapter 7, Finite Element Analysis (FEA) using ANSYS-9.0 computational software was carried out in order to develop an appreciation of the numerical prediction of the fracture toughness. The local stress characterization at crack-tip by

REFERENCES

- ASTM Standard E 8-01. 2002. Standard Test Method for Tension Testing of Metallic Materials. *Annual Book of ASTM Standards*. **1**(2): 1-22.
- ASTM Standard E 399-90. 1997. Standard Test Method for Plane Strain Fracture Toughness of Metallic Materials. *Annual Book of ASTM Standards*. **3**(1): 1-31.
- ASTM Standard E 1290-02. 2003. Standard Test Method for Crack-Tip Opening Displacement (CTOD) Fracture Toughness Measurement. *Annual Book of ASTM Standards*. **3**(1):1-13.
- ASTM Standard E 1820-01. 2001. Standard Test Method for Measurement of Fracture Toughness. *Annual Book of ASTM Standards*. **3**(1): 1-46.
- Anderson, T. L. 1995. *Fracture Mechanics: Fundamentals and Applications*. Boca Raton: CRC Press.
- Ashby, M. F. & Jones, D. R. H. 1980. *Engineering Materials I: An Introduction to their Properties and Applications*. Oxford: Pergamon Press.
- Askeland, D. R. & Phule, P. P. 2003. *The Science and Engineering of Materials*. (4th edition). California: Brooks/Cole-Thompson Learning.
- Bickford, W. B. 1993. *Mechanics of Solids – Concepts and Applications*. USA: Richard D. Irwin Inc.
- Broek, D. 1986. *Elementary Engineering Fracture Mechanics*. Dordrecht: Martinus Nijhoff Publishers.
- Brundle, C. R., Evans Jr. C. A. & Wilson, S. (eds.). 1992. *Encyclopedia of Materials Characterization*. Massachusetts: Butterworth-Heinemann.
- Collins, J. A. 1993. *Failure of Materials in Mechanical Design – Analysis, Prediction, Prevention*. (2nd edition). Toronto: John Wiley & Sons.
- Cotterell, B. 2002. The Past, Present, and Future of Fracture Mechanics. *Engineering Fracture Mechanics*. **69**(5): 533-553.
- Chung, D. D. L. 2001. *Applied Materials Science - Applications of Engineering Materials in Structural, Electronics, Thermal, and Other Industries*. New York: CRC Press.
- Creager, M. & Paris, P. C. 1967. Elastic Field Equations for Blunted Cracks with Reference to Stress Corrosion Cracking. *International Journal of Fracture Mechanics*. **3**: 247-252.

- Dasgupta, A. & Hu, J. M. 1992. Failure Mechanism Models for Brittle Fracture. *IEEE Transaction on Reliability*. **41**(3): 328-335.
- Dasgupta, A. & Hu, J. M. 1992 Failure Mechanism Models for Ductile Fracture. *IEEE Transaction on Reliability*. **41**(4): 489-495.
- David, H. 2004. *Fundamentals of Finite Element Method*. New York: McGraw-Hill.
- Dowling, N. E. 1993. *Mechanical Behaviour of Materials – Engineering Methods for Deformation, Fracture, and Fatigue*. New Jersey: Prentice-Hall Inc.
- Ewalds, H. L. & Wanhill, R. J. H. 1986. *Fracture Mechanics*. London: Edward Arnold Ltd.
- Feirer, J. L. & Lindbeck, J. R. 1999. *Metal – Technology and Process*. New York: Delmar Publishers.
- Gellerman, M. 1995. *Welding Fundamentals*. New York: Delmar Publishers.
- Griffith, A. A. 1920. The Phenomena of Rupture and Flow of Solids. *Philosophical Transactions of the Royal Society of London*. **221**: 163-198.
- Honeycombe, R. W. K. & Bhadeshia, H. K. D. H. 1995. *Steels: Microstructures & Properties*. (2nd edition). London: Edward Arnold.
- Hull, D. 1999. *Fractography: Observing, Measuring and Interpreting Fracture Surface Topography*. Cambridge: Cambridge University Press.
- Inglis, C. E. 1913. Stresses in a Plate Due to the Presence of Cracks and Sharp Corners. *Proc. Inst. Naval Arch.* **55**: 219-241.
- Irwin, G. R. 1957. Analysis of Stresses and Strains near the End of a Crack Traversing a Plate. *Journal of Applied Mechanics*. **24**: 361-364.
- Kinloch, A. J. & Young, R. J. 1983. *Fracture Behavior of Polymers*. New York: Elsevier Science Publishing Co.
- Knott, J. F. 1973. *Fundamentals of Fracture Mechanics*. London: Butterworths.
- Lawn, B. 1993. *Fracture of Brittle Solids*. (2nd edition). Cambridge: Cambridge University Press.
- Liebowitz, H. (ed.). 1971. *In Fracture, An Advanced Treatise*. New York: Academic Press.
- Matvienko, Yu. G. 1999. On the Cohesive Zone Model for a Finite Crack. *International Journal of Fracture*. **98**: 53-58.
- Meyers, M. A. & Chawla, K. K. 1999. *Mechanical Behaviour of Materials*. New Jersey: Prentice-Hall.

- Novozhilov, V. V. 1969. On a necessary and sufficient criterion for brittle strength. *Journal of Applied Mathematics and Mechanics*. **33**: 201-210.
- Orowan, E. 1948. Fracture and Strength of Solids. *Reports on Progress in Physics*. **12**: 185-232.
- Parnes, R. 2001. *Solid Mechanics in Engineering*. England: John Wiley & Sons.
- Reese, R. T. & Kawahara, W. A. 1993. *Handbook on Structural Testing*. Georgia: The Fairmont Press, Inc.
- Rossmannith, H. P. 1997. (ed.) *Fracture Research in Retrospect*. Rotterdam: AA Balkema.
- Rossmannith, H. P. Fracture Mechanics and Materials Testing: Forgotten Pioneers of the Early 20th Century. *Fatigue & Fracture of Engineering Materials & Structures*. **22**(9): 781-797.
- Sanford, R. J. 2003. *Principles of Fracture Mechanics*. New Jersey: Pearson Education.
- Sih, G. C. 1973. *Handbook of Stress Intensity Factors for Researchers and Engineers*. Bethlehem: Lehigh University.
- Smallman, R. E. & Bishop, R. J. 1999. *Modern Physical Metallurgy and Materials Engineering: science, process, applications*. (6th edition). Massachusetts: Reed Educational and Professional Publishing Ltd.
- Wells, A. A. 1961. Unstable crack propagation in metals: cleavage and fast fracture. *The Crack Propagation Symposium*. 210-230.
- Westergaard, H. M. 1939. Bearing Pressures and Cracks. *J. Appl. Mech. Trans. ASME*. **6**: A49-53.