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

LIM ENG HAR

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

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

Tarikh: 4 Julai 2008

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CERTIFIED BY

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

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

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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 33MPa.m$^{1/2}$, beyond a critical thickness of 22mm. Through the microscopic works, the bandwidth of crack initiation zone has been identified at 10μm 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.

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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 kebolehgunaan 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 Bukaan 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 kebolehgunaan 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.

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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

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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
eff	effective
kN	kilo Newton
max	maximum
min	minimum
mm	millimeter

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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
υ	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

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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

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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).

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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

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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.

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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.

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(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,

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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

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