FRACTURE TOUGHNESS INVESTIGATION OF METALLIC MATERIALS USING EXPERIMENT AND FINITE ELEMENT ANALYSIS

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SCHOOL OF ENGINEERING AND INFORMATION TECHNOLOGY
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THESIS SUBMITTED IN FULLFILLMENT FOR THE DEGREE OF DOCTOR OF PHILOSOPHY

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UNIVERSITI MALAYSIA SABAH

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DECLARATION

I hereby declare that the material in this thesis is my own except for quotations, excerpt, equations, summaries and references, which have been duly acknowledged.

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ABSTRACT

FRACTURE TOUGHNESS INVESTIGATION OF METALLIC MATERIALS USING EXPERIMENT AND FINITE ELEMENT ANALYSIS

This research was conducted to determine the plane stress and plane strain fracture toughness of various metallic materials. Compact Tension specimens of a wide range of constant thickness such as 5 mm, 10 mm, 15 mm, 20 mm and 25 mm and various materials used to make comparisons of AISI 1030, AISI 1045, AISI 4320, AISI 4340, Alu 2024-T3 ,Alu 2014-T6. Different thickness and width is the same as the main focus in this study. Specimens have been designed using Computer Aided Design and Computer Numeric Control (CNC) machining with an average surface roughness of 10 microns. Compliance method has been proposed to determine the fracture resistance measurement of metals in experimental work. Precracking is used to introduce the beginning of the crack before the test. Fracture toughness was evaluated by the graph of load and displacement and produced type I and type II curves, which were used for evaluation. Results for different materials have shown the value of 2014-T6-36 MPa is K_{IC} =36 MPa $\sqrt{m}$ and the value of cast iron is K_{IC} =23.3 MPa $\sqrt{m}$. This result shows both materials clearly indicate the failure of the current state of plane strain fracture tests at room temperature happen rapidly in the environment. The main contribution to the experimental work has shown that the fracture toughness of five different thicknesses with a constant width of the influence of fixed width over the thickness and increase the influence of plastic deformation region significantly in the early stages of crack growth. The load applied to the thickness of 5 mm 12500 N was compared with 25 mm maximum load of 50000 N to obtain fracture toughness in these materials. Similarly, the critical load increases as thickness increases. The result shows that the plane stress appeared to determine the influence of controlled constant width and thickness of the high plastic deformation around the crack tip generated. For this reason ASTM 399-90 suggested that the strength ratio should be calculated for all differences in thickness. Fracture surface with high magnification has been determined using scanning electron microscopic thickness to determine the effect of fracture surface essentially attributable to changes in the pattern of holes and rivers. This may appear at the crack tip necking material difference. Unstable crack propagation was observed during the exchange between the plane stress plane strain. The finite element analysis (FEA) found the stress distribution based on gradual of von Misses stress to predict the stress stage near to crack tip of the compact tension specimen is highest stress range at the notch tip region. It is seen that the contours of the difference stress range of Von Misses stress distribution along the symmetry plane of the specimen corresponding to maximum loading pin displacement of 0.5 mm for 5 mm and 20 mm. For future studies, metals with high heat resistance using the actual thickness of specimen can be tested. It is proposed that the mesh using less than 0.1 mm.

ABSTRAK

Dalam kerja penyelidikan ini, kajian telah dijalankan untuk menentukan keliatan patah, pelbagai bahan logam. Ketegangan spesimen lebar malar ketebalan pelbagai iaitu 5 mm, 10 mm, 15 mm, 20 mm dan 25 mm dan pelbagai bahan digunakan untuk membuat perbandingan iatu of AISI 1030, AISI 1045, AISI 4320,AISI 4340,Alu 2024-T3, Alu 2014-T6. Spesimen telah direka menggunakan pemesinan kawalan komputer angka (CNC) dengan purata kekasaran permukaan sebanyak 10 mikron. Kaedah pematuhan telah dicadangkan untuk menentukan patah pengukuran rintangan bahan logam di dalam kerja ujikaji. Retak pra-digunakan untuk memperkenalkan permulaan retak sebelum ujian. Patah akibat keliatan telah dinilai oleh graf beban dan anjakan dan jenis I dan jenis II lengkung yang digunakan untuk penilaian. Keputusan untuk bahan-bahan perbezaan telah menunjukkan nilai 2014-T6 adalah K_{IC} *=36MPa*$\sqrt{m}$ *dan nilai besi tuang adalah* K_{IC} *=23.3 MPa*$\sqrt{m}$ *. Ini menunjukkan kedua-dua bahan dengan jelas menunjukkan keadaan terikan satah kegagalan semasa ujian patah pantas dalam persekitaran suhu bilik. Bagi perbezaan ketebalan, hasilnya menunjukkan bahawa tekanan telah muncul untuk menentukan lebar malar menguasai pengaruh ketebalan dan ubah bentuk plastik yang tinggi dijana di sekeliling hujung retak. Atas sebab ini, ASTM 399-90 disyorkan bahawa nisbah kekuatan perlu dikira bagi semua perbezaan ketebalan. Permukaan patah dengan pembesaran yang tinggi menggunakan elektron mikroskopik imbasan untuk menentukan kesan ketebalan pada asasnya diagihkan kepada perubahan lubang-lubang dan corak sungai. Ini boleh muncul pada hujung retak necking bahan perbezaan. Perambatan retak yang tidak stabil telah diperhatikan semasa pertukaran antara tegasan satah terikan satah. Analisis unsur terhingga dengan jelas menunjukkan kemungkinan tegasan von Mises dan agihan tegasan dengan kontur warna tegasan maksimum di sekitar hujung retak dan ia menunjukkan bahawa ekanada menguasai di kawasan zon perbezaan ketebalan keplastikan. Walau bagaimanapun, Von terlambat Tekanan (VMS) adalah dianggap sesuai untuk bahan mulur-rapuh. Bagi bahan-bahan perbezaan, ia dilihat bahawa satah tegasan-terikan dan zon kontur ditunjukkan berhampiran takuk retak. Untuk kajian masa depan di atas bahan logam yang mempunyai rintangan haba yang tinggi dengan menggunakan spesimen ketebalan sebenar, analisis unsur terhingga, adalah dicadangkan itu bersirat menggunakan kurang daripada 0.1 mm dan analisis fractotography memberi penekanan atau tumpuan yang lebih kepada jenis ubah bentuk kecacatan dalam sifat bahan.*

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LIST OF SYMBOLS

P_Q	Applied load
α	Crack length, a divide by distance from the load line to far
W	Distance from the load line to far end of the specimen
$f(\alpha)$	Dimensionless geometry calibration or $f(a/W)$
R	Dugdale's plastic zone distance
K_{eff}	Effective fracture toughness
B	Specimen thickness
$P_{\max}$	Maximum load
K_{IC}	Plane strain fracture toughness
$\{u_i\}$	Local displacement
$[N(x_i)]$	Displacement shape of interpolation function
$\{u_i^e\}$	Nodal displacement
$[B]$	Matrix of coordinate positions of the nodes
$\{\varepsilon\}$	Element strain
U^e	Strain Energy
$[k^e]$	Elemental stiffness matrix
$[D]$	Matrix of elastic coefficient
$[K]$	Global stiffness matrix
$\{u\}$	Global nodal displacements
$\{F\}$	Nodal forces
$\{\sigma\}$	Stress at nodal point
U_E	Elastic strain energy per unit of plate thickness
a	Crack length
E	Young Modulus or Modulus of Elasticity
σ	Tensile stress
U_γ	Elastic surface energy
γ_S	Surface energy

U	Total energy
ν	Poisson's ratio
G	Energy release rate or crack driving force
R_{crack}	Crack resistance
$f(a/W)$	Dimensionless geometry calibration
K_C	Plane stress fracture toughness
G_C	Stored elastic strain energy
K_{IC}	Plane strain fracture toughness
r_Y	Plastic zone size by Irwin Approximation
$y(\theta)$	Plastic zone of plane stress condition from von Mises yielding criteria
$r(\theta)$	Plastic zone of plane strain condition from von Mises yielding criteria
σ_{YS}	Yield strength of material
γ_P	Plastic strain work
c	Initial crack length
K_I	Plane stress fracture toughness, K_C or plane strain fracture toughness, K_{IC}
a_{eff}	Effective crack length
$\%_{dif}$	Difference percentage
K_{FE}	Fracture toughness computed by finite element modeling
K_{math}	Fracture toughness computed by mathematical modeling
R_{SC}	Strength ratio
V_m	Crack mouth opening displacement in m
E'	Effective Young's Modulus
$r(\theta)$	Dimensionless plastic zone of von Mises yielding criteria
C	Stress intensity factor correction

δ_t	Crack Opening Displacement or COD
γ_S	Elastic surface energy
σ_f	Fracture stress
$\sigma_{\max}$	Theoretical cohesive strength

REFERENCE

Ainsworth,.A.A.,2000. Effects of Residual Stress on Fracture Behavior-Experimental Result and Assessment Method*, Journal of Strain Analysis*, **35**, (4): 307-316

Anderson,.T.L,1995. Fracture Mechanics: Fundamentals and Applications. 2nd Edition. United State of America:*CRC Press Inc*.

Anderson,.T.L,2005. Fracture Mechanics: Fundamentals and Applications. 3rd Edition. United State of America:*CRC Press Inc*.

ASTM E399-90,1990. Standard Test Method of Plain-Strain Fracture Toughness of Metallic Material*s. American Society for Testing and Materials.*

ASTM B 645-02, 1997. Standard Practice for Plane-Strain Fracture Toughness Testing of Aluminum Alloys. *American Society for Testing and Material.*

ASTM E647-00, 2000. Standard Test Method for Measurement of fatigue Crack Growth Rates. *American Society for Testing and Materials*

ASTM E1820-01, 2000. Standard Test Method for Measurement of Fracture Toughness. *American Society for Testing and Materials*

ASTM E1290-02, 2001. Standard Test Method for Crack Tip Opening Displacement Fracture Toughness Measuremen*t. American Society for Testing and Materials*

ASTM E8-01, 2001. Standard Test Method for Tension Test of Metallic Material, *American Society for Testing and Materials*

ASTM B647-78, 1978. Standard Test Method for Indentation Hardness of Aluminum Alloy, *American Society for Testing and Materials*

ASTM Bulletin, 1964*.* Reports of Special ASTM Committee on Fracture Testing of High-Strength Metallic Materials: 1st report: Fracture testing of high-strength sheet materials. *ASTM*

Asserin. A & Besson. J. 2004, Fracture of 6065 Alu. Sheet Material, Efeect of Specimen Thickness and Hardening Behaviour on Strain Locaization and Toughness*, Int.Journal. Material Science and Engineering ,Elservier*, **395**:186-194

ANSI/ASME. 1985. Instruments and Apparatus. Part I: Measurement Uncertainty. PTC *American Society of Mechanical Engineers*, New York.

Balart, M. J. & Knott J. F, 2006. Effects of geometry and flow properties on the fracture toughness of a C–Mn reactor pressure vessel steel in the lower shelf region, *International Journal of Pressure Vessels and Piping* **83**: 205–215

Barbagallo S, 2003. Evaluation of the K_{IC} and J_{IC} fracture parameters in a sand cast AZ91 magnesium alloy, *International Journal Engineering Failure Analysis*,Paragamon,**11**: 20-25.

Bhawesh K, 2011, Significance of K-dominance zone size and nonsingular stress field in brittle fracture Original Research Article*, Engineering Fracture Mechanics*, **78**, 2042-2051.

Bhargava and Hasan.S (2011), Crack opening displacement for two unequal straight cracks with coalesced plastic zones – A modified Dugdale model, *Applied Mathematical Modelling **35**, 3788–3796*

Okwon Lee,. 2003. Mode-1 Fracture Criterion and Finite Width Correction Factor for Notched Laminated Composite. *MSc. Thesis*,18-55: Hong Kong.

Boresi A.P S& Chmidt R. J, 2000. Advanced Mechanics of Material ,Fifth edition, John Willey and Son.

BS 7448-05,2005. Fracture mechanics toughness tests, Part 1, Method for determination of fracture toughness of metallic materials at rates of increase in stress intensity factor greater than 3.0 MPa·m$^{0.5}$s^{-1}, *British Standards Institution, :* London

BS, 7448-071997. Fracture mechanics toughness tests Part 4, Method for determination of fracture resistance curves and initiation values for stable crack extension in metallic materials , *British Standards Institution,*London

BS, 7448-91,1991. Fracture mechanics toughness tests Part 1,Method for determination of KIc, critical CTOD and critical J values of metallic materials, *British Standards Institution, ,*London

BS ISO 13586,2000.Plastic - Determination of Fracture Toughness (G_{IC} and K_{IC}) - Linear Elastic Fracture Mechanics (LEFM) approach*.2000. British Standards Institution, ,*London

Bulloch, J. H,2004. *A study concerning material fracture toughness and some small punch test data for low alloy steels*, Engineering Failure Analysis **11**: 635–653

Beer, F.P,2005, (2005) *Mechanics of materials*, 4th edn. McGraw-Hill International, Singapore, pp 360–378

Bertolino & PerezIpina 2006.Geometrical effects on lamellar grey cast iron fracture toughness, *Journal of Materials Processing Technology* **179**: 202–206

Broek D. 1982. Elementary engineering fracture mechanics. 3rd : *Columbus.*

Broek D.1984. Elementary engineering fracture mechanics. 4th Edition: *Columbus*

Bueckner H. F, 1958. The propagation of crack and energy of elastic deformation, Transaction of the *American Society of Mechanical Engineer*, **80** : 1225-1230.

Calister W,. 1994. Material Science and Engineering: An Introduction, 3rd Edition:194-196.

Calister W,. 1994. *Material Science and Engineering: An Introduction*, 3rd Edition,*John Wiley & Sons* :4-20.

CDM ,2000. Wire cut Manual user : Rovella Industry Press, *Italy*

Calister W, 1994. *Material Science and Engineering: An Introduction*, 3rd Edition, *John Wiley & Sons*

Cerolo.L & Tommaso A.D,. 1998, 2nd *Int. Ph.D Symposium in Civil Engineering*, Budapest.

Chow C. & Nho K.H ,1997. Effect of thickness on the fracture toughness of irradiated Zr-2.5Nb pressure tubes, *Journal of Nuclear Materials* **246** : 84-87

Cockeram B.V, 2006. The mechanical properties and fracture mechanisms of wrought low carbon arc cast (LCAC), molybdenum–0.5pct titanium–0.1pct zirconium (TZM), and oxide dispersion strengthened (ODS) molybdenum flat products, *Materials Science and Engineering*: A, **418**, 1-2, 2006, Pages 120-136

Debdulal.D, 2010. Influence of sub-zero treatments on fracture toughness of AISI D2 steel , *Materials Science and Engineering*: A, **2**, 528,

David Hutton, 2004. Fundamentals of Finite Element Analysis. USA: McGraw-Hill.

Degarmo E. P, J. T Black & Ronald A.K,2003,Material and Processes In Manufacturing, 9th Edition.McGraw-Hill

Dieter G. E, 1986. Mechanical Metallurgy. 3rd Edition. U.S.A., McGraw-Hill Inc.

Durelli,1970. Applied Stress Analysis, Prentice-Hall of India Private Limited, New Delhi:20-85.

Dugdale, D. S., 1960. Yielding of steel sheets containing slits, *J Mech.Phys*., **8** ,1960.

Duga J. J,.Fisher W.H.,& Buxbaum R.W.,1983, Fracture Costs Us $119 Billion A Year, Says Study By Battelle/Nbs, *Int.Journal of Fracture*. Elesiver