



**UNIVERSITI PUTRA MALAYSIA**

**SIMULATION OF FATIGUE CRACK GROWTH IN FRICTION**

**STIR-WELDED JOINTS OF 2024-T351 ALUMINUM ALLOY**

**AMIRREZA FAHIM GOLESTANEH**

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STIR-WELDED JOINTS OF 2024-T351 ALUMINUM ALLOY**

**By**

**AMIRREZA FAHIM GOLESTANEH**

**Thesis Submitted to the School of Graduate Studies, Universiti Putra  
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Science**

**November 2008**



## **DEDICATION**

**To my dear parents, that I owe them my life**

To my supervisor Dr. Aidy Ali who I learned a lot from

To my high school teacher Mr. Shirdavani who interested me in  
mechanical engineering field.

Abstract of thesis presented to the Senate of Universiti Putra Malaysia in fulfillment of the requirement for the degree of Master of Science

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**Faculty : Engineering**

The present work simulates and predicts the fatigue crack growth in the friction stir welded (FSW) joint of the 2024-T351 Al alloy. The simulation is used to estimate the fatigue life of this welded joint. The study is based on finite element method (FEM) and in the framework of Fracture Analysis Code for two-dimensional (FRANC2D/L), developed by Fracture Group of Cornell University. Fatigue crack behavior through the FSW joint is investigated under Linear Elastic Fracture Mechanics (LEFM) using the Paris' model. The work concentrated on a stable crack propagation regime, the obtained fatigue life shows good agreement with experimental and analytical results. The present work incorporates a few different types of loading which are 1) the cyclic fatigue loading for the case of  $R= 0.1$ , 2) the longitudinal tensile residual stress, 3) the crack closure concept and 4) the residual stress relaxation phenomenon. In the current work the stress intensity factor is calculated by applying displacement correlation technique, which is based on calculating the displacement field around the crack tip. The maximum circumferential tensile stress method was



used to predict the fatigue crack direction. In fact FRANC2D/L does not have the capacity to consider different Paris' constants for FSW zones and it predicts the crack propagation through the welded zones by considering the same values of Paris' constants. This work presents a strategy to investigate the crack growth based on the corresponding Paris' constants for each FSW zone. The numerical results are validated with the previous experimental and analytical work, which show a good agreement of 88% and 97%.

Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia sebagai memenuhi keperluan untuk ijazah Master Sains

**SIMULASI RAMBATAN RETAK OLEH KELESUAN DI DALAM  
KIMPALAN GESERAN 2024-T351 AL LOGAM CAMPURAN**

Oleh

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**November 2008**

**Pengerusi : Aidy Ali, PhD**

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Kerja penyelidikan yang dibentangkan adalah simulasi dan jangkaan hayat kelesuan rambatan retak di dalam kimpalan secara geseran (FSW) bahan Aluminium 2024-T351 logam campuran. Kajian adalah berasaskan kaedah unsur terhingga berangka (FEM) dan didalam kod analisis patah dua dimensi (FRANC2D/L) yang dibangunkan oleh Kumpulan Kajian Patah Cornell University U.S.A. Sifat retak dikaji melalui elastik plastik mekanik patahlinear menggunakan hukum Paris. Kajian tertumpu kepada rambatan retak yang stabil keputusan hayat kelesuan adalah selari dengan jangkaan yang diperolehi daripada eksperimen dan formulasi. Kajian menggabungkan 1) bebanan ulangalik dengan nisbah daya  $R=0.1$ , 2) daya dalaman regangan, 3) konsep retak tertutup dan 4) penggunaan daya dalaman.

Faktor tegasan tumpu dikira melalui teknik anjalan korelasi, mengambilkira anjakan di depan tip retak. Perisian FRANC2D/L berupaya menjangka dengan tiga kaedah, di mana tegasan regangan maksimum lilitan dipilih. Kajian

mendapati perisian FRANC2D/L tidak berupaya menyerap pemalar Paris untuk zon yang berbeza ketika retak merambat di dalam kimpalan geseran ini. Kajian membentangkan kaedah penyelesaian masalah ini. Keseluruhan keputusan disahkan dengan keputusan eksperimen dan formulasi memberikan ketepatan jangkakan 88 dan 97 peratus.

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Finally, I would like to express my gratitude to my beloved parents, for their guidance, supports, love and encouragement.





I certify that a Thesis Examination Committee has met on 7 November 2008 to conduct the final examination of Amirreza Fahim Golestaneh on his thesis entitled “Simulation of Fatigue Crack Growth in Friction Stir-Welded Joints of 2024-T351 Aluminum Alloy” in accordance with the Universities and University Colleges Act 1971 and the constitution of the Universiti Putra Malaysia [P.U.(A) 106] 15 March 1998. The Committee recommends that the student be awarded the Master of Science.

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## **DECLARATION**

I hereby declare that the thesis is based on my original work except for quotations and citation, which have been duly acknowledged. I also declare that it has not been previously or concurrently submitted for any other degree at UPM or other institutions.

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**AMIRREZA FAHIM**  
**GOLESTANEH**  
Date: Nov 26, 2008

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## LIST OF ABBREVIATIONS

$a$	Edge crack length
$a_{eff}$	Total size of the crack
$\frac{\partial a}{\partial N}$	Crack growth rate
$b$	Empirical factor
<i>BEM</i>	Boundary Element Method
$C$	Paris' constant
$C_0$	Material constant
$C', n, p, q$	Constants
<i>CT</i>	Compact Tension
<i>CTOD</i>	Crack Tip Opening Displacement
$CTOD_c$	Critical Crack Tip Opening Displacement
$CTOD_c INIT$	Initial value of Critical Crack Tip Opening Displacement
<i>CTS</i>	Compact Tension Shear specimen
$E, E'$	Modulus of elasticity

<i>EPFM</i>	Elastic-Plastic Fracture Mechanics
$F_1, F_2$	External forces acting on specimen
<i>FAZ</i>	Flow Arm Zone
<i>FNK</i>	Forman–Newman–de Koning
<i>FRANC2D</i>	Fracture Analysis Code 2-D
<i>FSW</i>	Friction Stir Welding
<i>G</i>	Shear modulus
<i>g</i>	Energy release rate for LEFM
<i>H</i>	Constant strain hardening
<i>HAZ</i>	Heat Affected Zone
<i>HCF</i>	High Cycle Fatigue
<i>I</i>	Second moment of inertia
<i>K</i>	Stress intensity factor
$K_C$	Fracture toughness
$K_I, K_{II}, K_{III}$	Stress intensity factor of three modes
$K_{\max}$	Stress intensity factor of the maximum applied stress

$K_{op}$	Opening stress intensity factor
$L$	Crack length on the crack face
$L_{1/4}$	Distance from the quarter node to the crack tip
$LCF$	Low Cycle Fatigue
$LEFM$	Linear Fracture Mechanics
$M$	Moment
$Max\sigma_{relax}$	Maximum stress after relaxation
$Min\sigma_{relax}$	Minimum stress after relaxation
$m$	Paris' constant
$N$	Number of cycles
$n$	Strain hardening exponent
$NZ$	Nugget Zone
$OSM$	Object Solid Modeler
$P$	External applying load
$PJL$	Plane Joint Line
$PZ$	Parent plate Zone

$R$	Stress ratio
$R_1, R_2$	Support reaction forces
$r, \theta$	Polar coordinates
$r_f$	Plastic zone radius
$r_{p(6\pi)}$	Plastic zone radius for plane strain
$r_{p(combo)}$	Plastic zone radius for planar condition
$SCT$	Surface Crack Tension
$\frac{S_{max}}{\sigma_0}$	Ratio of maximum applied stress to the material yield strength
$TMAZ$	Thermomechanically Affected Zone
$TWI$	The Welding Institute
$u, V$	Nodal displacements in x and y direction
$w$	Walker exponent
$x$	Distance from origin
$y$	Distance from neutral axis of cross section
$Y$	Correction factor

$\alpha$	Plane stress/strain constraint
$\Delta a$	Mesh element size or incremental crack length
$\Delta K$	Stress intensity factor range
$\Delta k_{eff}$	Effective stress intensity factor range
$\Delta K_{th}$	Threshold range
$\Delta \sigma_{eff}$	Effective stress range
$\nu$	Poisson ratio
$\sigma_{eff}$	Effective stress
$\sigma_{max}$	Maximum applied stress
$\sigma_{max+res}$	Maximum stress after incorporating residual stress
$\sigma_{min}$	Minimum applied stress
$\sigma_{min+res}$	Minimum stress after incorporating residual stress
$\sigma_{op}$	Opening stress
$\sigma_{res}$	Residual stress
$\sigma_0$	Yield strength



2D

Two-dimension

