UNIVERSITI PUTRA MALAYSIA

SIMULATION OF FATIGUE CRACK GROWTH IN FRICTION STIR-WELDED JOINTS OF 2024-T351 ALUMINUM ALLOY

AMIRREZA FAHIM GOLESTANEH

SIMULATION OF FATIGUE CRACK GROWTH IN FRICTION STIR-WELDED JOINTS OF 2024-T351 ALUMINUM ALLOY

By

AMIRREZA FAHIM GOLESTANEH

Thesis Submitted to the School of Graduate Studies, Universiti Putra Malaysia, in Fulfillment of the Requirement for the Degree of Master of 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

SIMULATION OF FATIGUE CRACK GROWTH IN FRICTION STIR-WELDED JOINTS OF 2024-T351 ALUMINUM ALLOY

By

AMIRREZA FAHIM GOLESTANEH

November 2008

Chairman : Aidy Ali, PhD

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

AMIRREZA FAHIM GOLESTANEH

November 2008

Pengerusi : Aidy Ali, PhD

Fakulti : Kejuruteraan

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 jangkaan 88 dan 97 peratus.

ACKNOWLEDGEMENTS

I hereby convey my sincere gratitude and appreciation to my venerable supervisor Dr. Aidy Bin Ali, who supported me with invaluable and worthwhile advice on this work, and gave me a panorama of observance into the research. I also would like to appreciate the efforts of the honorable Associate Professor Dr. Wong Shaw Voon from Department of Mechanical and Manufacturing Engineering and Dr. Faizal Mustapha from Department of Aerospace Engineering, Universiti Putra Malaysia for accommodating me with helpful advice on my research. I also thank to all other faculty members who somehow helped me to implement this research.

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.

Members of the Thesis Examination Committee were as Follows:

Nor Mariah binti Adam, PhD
Associate Professor
Faculty of Engineering
Universiti Putra Malaysia
(Chairman)

Mohd Sapuan bin Salit, PhD
Professor
Faculty of Engineering
Universiti Putra Malaysia
(Internal Examiner)

Barkawi bin Sahari, PhD
Professor
Faculty of Engineering
Universiti Putra Malaysia
(Internal Examiner)

Ahmad Kamal Ariffin bin Mohd. Ihsan, PhD
Profesor
Faculty of Engineering and Built Environment
Universiti Kebangsaan Malaysia
(External Examiner)

HASANAH MOHD. GHAZALI, PhD
Professor and Dean
School of Graduate Studies
Universiti Putra Malaysia

Date: 29 January 2009

This thesis was submitted to the Senate of Universiti Putra Malaysia and has been accepted as fulfillment of the requirement for the degree of Master of Science. The members of the Supervisory Committee were as follows:

Aidy bin Ali, PhD
Senior Lecturer
Department of Mechanical and Manufacturing Engineering
Faculty of Engineering
Universiti Putra Malaysia
(Chairman)

Wong Shaw Voon, PhD
Associate professor
Department of Mechanical and Manufacturing Engineering
Faculty of Engineering
Universiti Putra Malaysia
(Member)

Faizal Mustapha, PhD
Lecturer
Department of Aerospace Engineering
Faculty of Engineering
Universiti Putra Malaysia
(Member)

HASANAH MOHD. GHAZALI, PhD
Professor and Dean
School of Graduate Studies
Universiti Putra Malaysia

Date: February 12, 2009

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.

AMIRREZA FAHIM GOLESTANEH
Date: Nov 26, 2008

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

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
BEM	Boundary Element Method
C	Paris' constant
C_0	Material constant
C', n, p, q	Constants
CT	Compact Tension
CTOD	Crack Tip Opening Displacement
$CTOD_c$	Critical Crack Tip Opening Displacement
$CTOD_c\ INIT$	Initial value of Critical Crack Tip Opening Displacement
CTS	Compact Tension Shear specimen
$E,\ E'$	Modulus of elasticity

EPFM	Elastic-Plastic Fracture Mechanics
F_1, F_2	External forces acting on specimen
FAZ	Flow Arm Zone
FNK	Forman–Newman–de Koning
FRANC2D	Fracture Analysis Code 2-D
FSW	Friction Stir Welding
G	Shear modulus
g	Energy release rate for LEFM
H	Constant strain hardening
HAZ	Heat Affected Zone
HCF	High Cycle Fatigue
I	Second moment of inertia
K	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
$Max\sigma_{rex}$	Maximum stress after relaxation
$Min\sigma_{rex}$	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, θ	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
$S_{\max}/\sigma_0$	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

α	Plane stress/strain constraint
Δa	Mesh element size or incremental crack length
ΔK	Stress intensity factor range
Δk_{eff}	Effective stress intensity factor range
ΔK_{th}	Threshold range
$\Delta \sigma_{eff}$	Effective stress range
ν	Poisson ratio
σ_{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
σ_{op}	Opening stress
σ_{res}	Residual stress
σ_0	Yield strength

2D	Two-dimension