UNIVERSITI PUTRA MALAYSIA

CHARACYERIZATION OF FRETTING FATIGUE OF 7075-T6 ALUMINIUM ALLOY

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By

M. SURESH DEVANESAN JACOB

Thesis Submitted to the School of Graduate Studies, Universiti Putra Malaysia, in Fulfilment of the Requirement for the Degree of Doctor of Philosophy

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DEDICATION

MY SON JESHUA BENNY JACOB
AND
WIFE REENA

Abstract of thesis presented to the Senate of Universiti Putra Malaysia in fulfilment of the requirement for the degree of Doctor of Philosophy

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Chairman : Associate Professor Prithivi Raj Arora, PhD

Faculty : Engineering

The main aim of the research work is to present theoretical and experimental approaches to the problem of fretting fatigue using 7075-T6 aluminum alloy as a specimen and En24 steel as a pad. A literature review is carried out to explain the contact mechanics of complete contact configuration for the fretting fatigue loading condition. The literature review includes fretting fatigue crack initiation, crack propagation and failure mechanisms and concludes with the different fretting fatigue test facilities. A novel fretting fatigue test rig has been designed to measure and control the critical parameters: normal load, frictional force and relative displacement at the contact interface using a data acquisition facility. The crack initiation and propagation data also recorded during the experiments to ascertain the crack behavior.

The fretting fatigue tests have been carried for the three cyclic axial stresses 290 MPa, 300 MPa and 325 MPa with normal stress 45 MPa, 60 MPa, 90 MPa. During the

experiments the frictional force, Q is measured and plotted with the number of cycles. The frictional force response increases rapidly during initial stage of experiments and attains a steady state condition approximately after 100 cycles and dwells there until the specimen fails. The frictional force versus axial load hysterias loops for different cycles are drawn which shows that the contact zone experiences partial slip regime. The Coulomb law is applied to determine the coefficient of friction which shows that higher coefficient of friction is observed for the lower normal stress and decreases gradually with an increases in normal stress. The crack propagation with *dl/dN* and Δk_I growth curves shows that considerable retardation in crack growth is observed for the higher normal stress of 90 MPa with the three axial stresses which are caused by crack closure due to high compressive normal load. The experimental observation of fretting fatigue life results shows that increase in normal stress reduces the crack initiation cycles as well as the total life to failure for that constant axial stress. The fatigue life reduces by an average factor of 7.34, 12.46 and 17.48 respectively for the axial stress of 290 MPa with the normal stress of 45 MPa, 60 MPa and 90 MPa. The similar behaviour is observed for the other combinations fretting fatigue loading condition.

A theoretical model is developed using the asymptotic analysis to study the equivalence of stress state at the pad edge for the complete contact of dissimilar materials with Dundurs parameters α,β and at the root of the notch based on the order of stress singularity, (λ-1). The strain energy density criterion is applied to predict the crack initiation angle using the order of stress singularity, (λ-1). The crack initiation angle compares well with the experimental angle values, which is obtained through the

scanning electron microscope. A fretting fatigue life prediction model is developed based on the strain energy density criterion in which a critical process zone size is used to estimate crack initiation life and crack analogue model is used to determine the crack propagation life. The critical process zone size is estimated using the notch analogy for the fretting fatigue loading condition. The theoretically calculated crack initiation and propagation lives compares well with the experimental results.

Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia sebagai memenuhi keperluan untuk ijazah Doktor Falsafah

PENCIRIAN KELESUAN PENGGESELSUAIAN BAGI 7075-T6 ALUMINIUM ALOI

Oleh

M. SURESH DEVANESAN JACOB

Oktober 2006

Pengerusi : Profesor Madya Prithivi Raj Arora, PhD

Fakulti : Kejuruteraan

Tujuan penyelidikan ini adalah untuk menunjukkan pendekatan secara teori dan uji kaji bagi masalah kelesuan penggeselsuaian menggunakan aloi aluminium 7075-T6 sebagai spesimen dan besi En24 sebagai pad. Asas mekanik sentuhan bagi penyambungan kelesuan penggeselsuian telah dikaji dengan memberi kepentingan khusus kepada konfigurasi sentuhan menyeluruh (rata atas rata). Pelbagai teori untuk menerangkan permulaan retakan, perambatan retakan dan mekanisme kegagalan kelesuan penggeselsuaian turut dibincangkan. Satu penelitian jelas bagi peralatan ujian kelesuan penggeselsuain yang berbeza telah dijalankan. Satu rig ujian kelesuan penggeselsuaian cipta baru telah direka bentuk sedemekian cara di mana parameter genting iaitu beban sentuh normal, daya geseran, dan sesaran relatif diantara permukaan sentuhan spesimen/pad dikuasai secara berkesan dan diukur dengan tepat.Terdapat satu kemudahan tambahan dimana mikroskop video digunakan untuk melihat permulaan retakan kecil (diantara 60μm) pada hujung sentuhan dan dengan menggunakan

kemudahan yang sama data perambatan retakan turut direkodkan. Kemudahan peralatan digunakan untuk tujuan pengumpulan data.

Ujian kelesuan penggeselsuaian telah dijalankan menggunakan rig kelesuan pengeselsuaian bagi tiga tegasan paksi berkitar 290 MPa, 300 MPa dan 325 MPa dengan tegasan normal 45 MPa, 60 MPa, dan 90 MPa. Semasa ujian kelesuan penggeselsuaian, daya geseran, *Q* diukur dengan daya geseran sel beban dan tindakbalas daya geseran diplot dengan bilangan kitaran. Tindakbalas daya rintangan meningkat secara mendadak di peringkat permulaan kajian dan mencapai keadaan mantap lebih kurang selepas100 kitaran dan berada dalam keadaan tersebut sehingga spesimen gagal. Daya geseran dengan beban paksi gelung histeresis bagi kitaran yang berbeza turut diperolehi. yang menunjukkan bahawa "*partial slip regime*" terhasil pada permukaan sentuhan sepanjang keseluruhan ujikaji. Teori Coulomb digunakan bagi memperolehi pekali geseran yang menunjukkan bahawa pekali geseran yang lebih tinggi dapat dilihat pada tegasan normal yang rendah dan pekali geseran menurun secara perlahan dengan penambahan beban normal.

Lengkungan perambatan keleseuan keretakan dan *da/dN* melawan Δk_I kelengkungan pertumbuhan keretakan menunjukkan bahawa kadar kelambatan pertumbuhan diperhatikan untuk tegasan normal 90MPa yang lebih tinggi dengan tiga tegasan paksi disebabkan oleh penutupan keretakan oleh beban normal mampatan yang tinggi. Didapati bahawa, penambahan yang berlaku pada tegasan normal mengurangkan keretakan permulaan kitaran dan juga mengurangkan jangka hayat kegagalan bagi tegasan paksi yang malar. Hayat keretakan kelesuan bahan mengurang dengan factor purata 7.34, 12.46 dan 17.48 untuk tegasan paksi 290 MPa dengan tegasan normal 45 MPa, 60 MPa dan 90 MPa. Tegasan paksi yang lain dan kombinasi tegasan normal dengan kelakuan yang sama dapat diperhatikan.

Model teori dibangunkan berdasarkan pada analisis asimtot untuk mempelajari tegasan pada hujung pad untuk sentuhan menyeluruh di antara bahan berlainan dengan parameter Dundur's iaitu α, β dan punca berdasarkan turutan tegasan singularity $(\lambda\text{-}1)$ yang sama. Kriteria ketumpatan tenaga terikan digunakan bagi meramalkan sudut permulaan keretakan menggunakan tegasan singularity $(\lambda\text{-}1)$. Keretakan yang dikenalpasti memberi perbandingan yang sempurna dengan keretakan permulaan melalui pengimbasan electron mikrografik.

Model peramalan jangka hayat kelesuan penggeselsuaian dibangunkan berdasarkan kepada kriteria ketumpatan tenaga terikan dimana proses zon saiz genting digunakan untuk menganggarkan jangka hayat permulaan keretakan dan model analog keretakan digunakan untuk menentukan jangka hayat perambatan keretakan. Proses zon saiz genting dianggarkan menggunakan analogi notch bagi keadaan bebanan keseluan penggeselsuaian. Permulaan keretakan dan jangka hayat perambatan yang dihitung secara teori mempunyai persamaan yang baik dengan keputusan eksperimen.

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"The fear of the Lord is the beginning of knowledge,
But fools despise wisdom and discipline" (Psalm 1:7)

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NOMENCLATURE

σ_a	(MPa)	Cyclic axial stress
σ_n	(MPa)	Normal stress
σ_y	(MPa)	Yield strength
σ_u	(MPa)	Ultimate strength
$\sigma_{\theta\theta}$	(MPa)	Normal stress in polar coordinate
$\sigma_{r\theta}$	(MPa)	Shear stress in polar coordinate
F_a	(kN)	Cyclic axial load
P	(N)	Normal load
Q	(N)	Frictional force
$2a$	(mm)	Contact width
l	(mm)	Crack length
k_1	(MPa√m)	Mode I stress intensity factor
k_2	(MPa√m)	Mode II stress intensity factor
k_{eff}	(MPa√m)	Effective stress intensity factor
K_{IC}	(MPa√m)	Fracture toughness
E	(GPa)	Young's modulus (Elasticity modulus)
μ	(GPa)	Shear modulus (Rigidity modulus)
δ	(mm)	Relative displacement
θ	(deg)	Polar coordinate
r	(mm)	Polar coordinate
θ_0	(deg)	Crack initiation angle

S	(MPa m)	Strain energy density factor
$\frac{dW}{dV}$	(MPa/m)	Strain energy density function
r_c	(μm)	Critical process zone size
φ	(deg)	Wedge angle
γ	(deg)	Notch half angle
λ		Eigen value
v		Poisson's ratio
f		Coefficient of friction
α		Dunudrs' first parameter
β		Dundurs' second parameter
N_I		Crack initiation life
N_P		Crack propagation life
N_T		Total life

CHAPTER 1

INTRODUCTION

1.1 Background

Fretting damage is due to small oscillatory relative displacement between two contacting components under compression and one of them is subjected to a cyclic axial load. It involves a synergistic action of three discrete mechanisms wear, corrosion and fatigue (see Section 2.1 for more details on a definition of fretting fatigue). This fretting damage is known as fretting fatigue and is responsible for reduction in component's service life (Forsyth, 1981 and Hoeppner, 1974) and thereby increased maintenance cost of the component. Since the fretting fatigue study requires interaction of many fields e.g. fatigue, contact mechanics, material science and fracture mechanics, the understanding of fretting fatigue has become rather more challenging topic for material research community for many decades. The uncertainty in controlling and/ or measuring the large number of contributing parameters e.g. friction force, relative slip, surface damage, and environment etc further makes it difficult to understand the mechanics of fretting fatigue. Till to date not much study has been carried out to give a concrete picture of fretting fatigue process. Due to the numerous occurrences of fretting damage and fretting fatigue failures in structural members the fundamental understanding of fretting fatigue has become more important. For example the fretting fatigue failures do occur around the riveted joints, spline joints, bolted connections, rotor blade dovetail joint assemblies etc.

Moreover most aerospace structural components experience some form of clamping force either via direct compression by an applied load (e.g. roller thrust against a bearing raceway) or through transfer by fastener or series of fasteners (e.g. riveted joints in a wing or fuselage panel). In each case the conditions for fretting contact are met and the concurrent damage leads to fretting and fretting fatigue failures. Common materials suffer by fretting fatigue are the aviation aluminium alloys (2xxx or 7xxx series alloys) and titanium alloys (Iyer et al, 1996 and Szolwinski and Farris, 2000). Moreover the aluminium alloy of 7xxx series is used in most of the engineering applications due to lightweight and good mechanical properties (Hoeppner and Goss, 1971). Thus the material 7075-T6 will be the primary focus of the experiments in this study.

1.2 Recent Developments in Fretting Fatigue Study

The study of fretting fatigue can be traced back to the failure analysis of railroad tracks in the late eighteen century; however the remarkable headway has occurred in the last twenty years. During nineteen century the development in fretting fatigue research centred around the progression of wear damage and its impact in fretting fatigue life. In particular the research teams in France developed fretting maps from the large quantity of experiments showing regimes of no slip, partial slip or stick-slip, gross slip plotted in an analytical space bounded by the applied normal load and displacement (Vingsbo and Soderberg, 1988) by which the effect of wear on fretting damage and fretting fatigue life is estimated. During the same time Oxford university research team took extensive effort in developing an experimental apparatus to measure and control all fretting