FORMULATING THE PLASTIC DEFORMATION EXPRESSION ON COATED SUBSTRATE AS A COATING SELECTION TOOL

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"To my parents, teachers and almighty God...."

To my beloved mother and father,

Mr. Mrs. Muniandy & Nookkaretnam

For being the backbone of my life by supporting me from the very beginning

To my supervisor and mentors,

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Abstract

This study presents the investigation of elastic coating performance responses on elastic-plastic substrate of advanced alloys using Finite Element (FE) method with an explicit numerical algorithm under quasi-static condition. Cylinder-on-flat contact configuration subjected to a normal and tangential loading is examined. Two aeroengine materials, namely Ti-6Al-4V and Super CMV (Cr-Mo-V) alloys are employed. Coating mechanical properties which are applied load (500 N – 1000 N), sliding displacement amplitude (0.005 mm – 0.12 mm), friction coefficient (0.3 – 0.9), coating elastic modulus (100 GPa – 400 GPa) and coating thickness (0.01 mm – 0.1 mm) are investigated. The effect of coating parameters on stress-strain distributions along with plastic deformation of the coated substrate are evaluated. The FE model is validated by comparing with theoretical Hertzian contact solution for homogeneous substrate, meanwhile coated substrate is validated by comparing with reported literature. The evolutions of contact pressure, von Mises stress, equivalent plastic strain, tangential stress and surface profile are examined for various coating parameters. There is a clear increasing trend of development in stress-strain distributions along with plastic deformation, maximum pile-up and depth-in values with the increase in all coating parameters for both coated substrates (except for coating thickness effect on Super CMV material, where the contradict trend is noted). Friction coefficient acts as the significant coating parameter that leads to plastic deformation failure of coated substrate. The relatively higher stiffness and yield strength of the coated Super CMV alloy registered limited plastic deformation compared to the coated Ti-6Al-4V alloy. The coated substrate plastic deformation mathematical expressions are formulated according to the Lagrange multivariate interpolation which can be used as an alternative method for FE approach. The weighted scoring method is practised in coating selection approach based on plastic deformation failure of coated substrate. The verified coating selection tool can contribute to knowledge in suitable material selection for coating based on its performance.

Abstrak

Kajian ini membentangkan pengaruh pelbagai paramater lapisan (coating) elastik pada substrat elastik-plastik di bawah keadaan kuasi-statik dengan menggunakan kaedah unsur terhingga (FEM). Konfigurasi silinder atas plat rata tertakluk kepada bebanan normal dan tangen dikaji. Dua jenis bahan aeroengine, iaitu aloi-aloi Ti-6Al-4V dan Super CMV (Cr-Mo-V) dikaji dalam analisis ini. Antara sifat mekanikal lapisan yang dikaji ialah beban digunakan (500 N – 1000 N), amplitud anjakan (0.005 mm – 0.12 mm), pekali geseran (COF) (0.3 – 0.9), modulus elastik (100 GPa – 400 GPa) dan ketebalan lapisan 0.01 mm – 0.1 mm). Kesan parameter lapisan pada tegasan-terikan bersama dengan deformasi plastik substrat dinilai. Model FE tanpa lapisan disahkan dengan teori Hertzian contact manakala model FE dengan lapisan disahkan dengan penyelidikan sebelum ini. Evolusi tekanan contact, tekanan von Mises, ketegangan plastik, tegasan tangen dan profil permukaan dikaji mengikut pelbagai parameter lapisan dan bahan substrat. Didapati satu trend yang meningkat pada tegasan-terikan bersama dengan deformasi plastik, pile-up dan depth-in maksima dengan peningkatan kesemua parameter pada kedua-dua substrat (kecuali untuk paramater ketebalan lapisan pada Super CMV). Pekali geseran bertindak sebagai parameter yang jelas menyebabkan deformasi plastik. Hasil kajian juga menunjukkan bahawa kekuatan yield yang lebih tinggi pada aloi Super CMV berbanding dengan aloi Ti-6Al-4V menyebabkan deformasi plastik yang minima. Seterusnya, ungkapan matematik (mathematical expression) diperolehi dengan menggunakan interpolasi multivariat Lagrange berdasarkan deformasi plastik pada substrat melalui simulasi. Ungkapan matematik yang dihasilkan boleh digunakan sebagai pendekatan alternatif untuk menggantikan teknik analisis kaedah unsur terhingga. Selain itu, kaedah pemarkahan wajaran (weighted scoring method) digunapakai dalam pendekatan pemilihan lapisan berdasarkan deformasi plastik. Pendekatan pemilihan ini boleh menyumbang kepada pengetahuan dalam pemilihan bahan yang sesuai untuk lapisan berdasarkan prestasinya.

Contents

List of Figures

List of Tables

List of Appendices

List of Symbols

α	Dundurs parameters on elastic mismatch
β	Dundurs parameters on Poisson's ratio difference
δ	Sliding amplitude
μ	Friction coefficient
ρ	Density
σ_f	Fracture stress
σ_{pl}	Proportional limit
σ_u	Ultimate stress
σ_y	Yield stress
ε_e	Elastic strain
ε_p	Plastic strain
ε_x	Total deformation
A	Distance along the first line
a	Contact half-width length
B	Distance along the middle line
C	Distance along the last line
c	Coating
E	Elastic modulus
h	Distance betwen each line
P	Normal load
$p(x)$	Contact pressure distribution
po	Maximum contact pressure
$q(x)$	Tangential traction

R	Radius
s	Substrate
t	Time
v	Poisson ratio
2D	Two-dimensional
3D	Three-dimensional
AS	Aggregate score
COF	Coefficient of friction
CPRESS	Contact pressure
FE	Finite Element
FEM	Finite Element Method
GPa	Giga Pascal
LSMB	Lower Specimen Mounting Block
LVDT	Linear Variable Displacement Transducer
MISES	Von Mises stress
mm	Milli Meter
MPa	Mega Pascal
N	Newton
ODB	Output Data Base
PEEQ	Equivalent plastic strain
PW	Parameter weightage
S	Score
S11	Tangential stress
SCMV	Super Chromium Molybdenum Vanadium alloy
SW	Substrate weightage
Ti-6Al-4V	Titanium alloy
U	Spatial displacement at nodes
USMB	Upper Specimen Mounting Block

Chapter 1

Introduction

Contact mechanics is concerned as the study of solid deformation when two bodies (surfaces) are touching and interacting with each other at one or more points. Mechanics of contact is deliberated as an essential subject because most of the engineering applications deal with it consequently. Contact mechanics offers an interesting, yet challenging research subject as it can lead to failure effect on contacting materials such as plastic deformation, fracture, fatigue, wear and others. Obviously, the contact failure can be significant and able to develop under corrosive, erosive, high temperature and heavy contact environment.

In the recent decades, minimizing contact failure on contacting bodies is considered to be a major concern, especially in safety engineering as contact mechanics failure can result in costly flaws and fatality. So, the knowledge in protecting contacting bodies from failure is very crucial, thus advances in reducing contact mechanics failure need to be studied extensively. One of the most competent approach to protect contact engineering components is by coating application. A coating can be defined as a covering that is applied on the surface of a body which referred as the substrate. Coating widely used for decorative, functional or both purposes.

The coating purpose broadly noticeable in engineering applications such as manufacturing, automotive and aeroengine industries in order to minimize contact damage which will extend the operational life of components. Interestingly, as coating offers the first line of defence to the underlying substrate, it is vital to study the coating architecture along with coating-substrate failure mechanism to prolong the contacting components lifetime. So, the application of appropriate coatings will contribute in reducing

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(a) **Nagentrau, M.**, Siswanto, W. A., Tobi, M., & Latif, A. (2015). Investigation on the effect of linear kinematic hardening model on plasticity prediction of reciprocating sliding contact. Applied Mechanics and Materials, 773-774, 183-187.

(b) Siswanto, W. A., **Nagentrau, M.**, Tobi, M., & Latif, A. (2015). Prediction of residual stress using explicit finite element method. Journal of Mechanical Engineering and Sciences (JMES), 9(Dec), 1556-1570.

(c) Siswanto, W. A., **Nagentrau, M.**, Tobi, M., Latif, A., & Tamin, M. N. (2015). Contact pressure prediction comparison using implicit and explicit finite element methods and the validation with hertzian theory. International Journal of Mechanical & Mechatronics Engineering, 15(6), 1-8.

(d) **Nagentrau, M.**, Siswanto, W. A., Tobi, M., & Latif, A. (2016). Predicting the sliding amplitude of plastic deformation in the reciprocating sliding contact. ARPN Journal of Engineering and Applied Sciences, 11(4), 2266-2271.

(e) **Nagentrau, M.**, Siswanto, W. A., & Tobi, M., Latif, A. (2016). The influence of linear kinematic hardening and non-linear combined isotropic-kinematic hardening plasticity model on sliding contact. International Journal of Mechanical & Mechatronics Engineering, 16(4), 83-88.

ISI journal (Scopus indexed with JCR Impact factor)

(a) Siswanto, W. A., **Nagentrau, M.**, Tobi, M., Latif, A., & Tamin, M. N. (2016). Prediction of plastic deformation under contact condition by quasi-static and dynamic simulations using explicit finite element analysis. Journal of Mechanical Science and Technology, 30(11), 5093-5101.

Vitae

The author was born in March 11th, 1990, in Kulim, Kedah. He went to Sekolah Jenis Kebangsaan (SJKT) Ladang Wellesley, Lunas, Kedah and Sekolah Menengah Kebangsaan (SMK) Sultan Badlishah, Kulim, Kedah for his primary and secondary schools respectively. He first obtained his Diploma in Mechanical Engineering in 2011, at the University Tun Husseion Onn Malaysia (UTHM) located in Batu Pahat, Johor. He further pursued his degree at the same university which is University Tun Hussein Onn Malaysia (UTHM), Batu Pahat, Johor, and graduated with the B.Mech. Eng. (Hons) in Mechanical and Manufacturing Engineering in 2014. He was also a research assistant with the Department of Mechanics, Faculty of Mechanical and Manufacturing Engineering (FKMP) and worked under several grants (KTP and RACE) as well. During this time he pursue his Master Degree in Mechanical Engineering. His area of specialization is in the field of Finite Element Method and Contact Mechanics.