FRACTURE BEHAVIOR OF ALUMINUM/ALUMINA AND ALUMINUM/BORON CARBIDE FUNCTIONALLY GRADED MATERIALS

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by

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Dedicated to

My beautiful wife, Sunanda and ever curious son- Sakshm & daughter Sandali

Without them my world would not be nearly as colorful

Certificate

This is to certify that the thesis entitled **"Fracture Behavior of Aluminum/Alumina and Aluminum/Boron Carbide Functionally Graded Materials"** being submitted by **Mr. Vinod Kumar Pandey** to the Indian Institute of Technology Delhi for the award of degree of **Doctor of Philosophy** in Applied Mechanics is a record of original, bonafide research work carried out by him under our supervision and guidance. The thesis work, in our opinion, has reached the requisite standard fulfilling the requirements for the degree of Doctor of Philosophy.

The results contained in this thesis have not been submitted in part or in full, to any other university or institute for the award of any degree or diploma.

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(Vinod Kumar Pandey)

Abstract

Aluminum is used in aerospace and automotive industries owing to its low density, high thermal conductivity, high specific strength, stiffness and better ductility. Aluminum alloys have limitation of low hardness and poor wear resistance leading to restricted high performance applications. Aluminum based metal matrix composites (AMMCs) with ceramic (alumina and boron carbide) as reinforcement agents are gaining popularity. Further, gradation in properties is effective method to improve fracture properties and structural integrity of aluminum based metal matrix composites.

In the available literatures, 0.2% yield stress, ultimate tensile strength and elongation of Al/Al_2O_3 are addressed up to 30% of alumina whereas elastic properties of Al/Al_2O_3 and Al/B_4C composites are covered only up to 10% weight fraction of ceramic without even comparative studies of experimental and predicted elastic properties. To the best of the author's knowledge, fracture toughness, its variation with ceramic particle size and the experimental quasi static crack growth studies of functionally graded materials using crack gauge including Al/Al_2O_3 FGM have not been reported.

This thesis deals with various characterisations (metallurgical, mechanical, fracture and quasi static crack growth) of Al/Al_2O_3 (up to 50% weight fraction of alumina) and Al/B_4C (up to 35% weight fraction of boron carbide) composites (non-FGM) and FGMs. The samples are prepared using hot isostatic sintering at optimised parameters of 600°C, 30 MPa for 90 minutes having porosity less than 2% with uniform microstructure (measured through optical microscope and SEM) except for weight fractions of Al_2O_3 greater than 40% and B_4C greater than 30% without any other phase formation (confirmed through XRD and EDS).

The experimental Young's modulus is compared with micromechanics prediction techniques and is found to lie closely between Ravichandran's/Hashin-Shtrikman lower and Ravichandran's upper bounds for Al/Al_2O_3 and Al/B_4C composites, and close to self-consistent/Miller-Lannutti methods based single value predictions for Al/Al_2O_3 and modified rule of mixture, fuzzy logic and self-consistent methods predictions for Al/B_4C. The experimental Poisson's ratio, Charpy energy measured through non-FGM samples and hardness through FGM and non-FGM samples are compared with micromechanics prediction techniques. 0.2% yield stress, ultimate tensile strength (UTS) and Young's modulus increase whereas the fracture strain/ductility reduce with increase in weight fraction of Al_2O_3 up to 40%. Ductile fracture with reducing dimple size up to 30% weight fraction of Al_2O_3 and cleavage fracture for Al_2O_3 greater than 30% are observed for Al/Al_2O_3 composites.

Fracture toughness reduces with increase in weight fraction of ceramic and lies closely between Raveendran's lower and upper bounds, and close to Raveendran effective value for Al/Al_2O_3 and Al/B_4C composites.

Quasi static crack growth study indicates that crack on stiff side undergoes stable crack growth with mixed mode failure with deviation from straight path, whereas crack on compliance side undergoes unstable crack growth with crack moving in straight line path with mode-I failure.

सारांश

कम घनत्व, उच्च ऊष्मा चालकता, उच्च विशिष्ट सामर्थ्य, उच्च विशिष्ट यंग मापांक और बेहतर लचीलेपन के कारण अंतरिक्षयांत्रिकी और मोटरयांत्रिकी उद्योगों में एल्यूमीनियम का उपयोग किया जाता है। एल्युमिनियम मिश्र धातु की कम कठोरता और कम घर्षण प्रतिरोध के कारण इसका उपयोग उच्च प्रदर्शन अनुप्रयोगों में सीमित है। सुदृढीकरण एजेंटों के रूप में सिरामिक (एल्यूमिना और बोरान कार्बाइड) के साथ एल्यूमीनियम आधारित धातु मैट्रिक्स कंपोजिट (एएमएमसी) उपयोगी सिद्ध हुये हैं। इसके अलावा, फ्रैक्चर गुणों और एल्यूमीनियम आधारित धातु मैट्रिक्स कंपोजिट की संरचनात्मक अखंडता में सुधार करने के लिए गुणों में प्रवणता प्रभावी तरीका है।

उपलब्ध साहित्य में, एल्यूमीनियम/एल्यूमिना और एल्यूमीनियम/बोरान कार्बाइड के 0.2% प्रूफ प्रतिबल, अधिकतम तनाव सामर्थ्य और तन्यता को एल्यूमिना के 30% तक अध्ययन किया गया है, जबकि एल्यूमीनियम/एल्यूमिना कंपोजिट के प्रत्यास्थता गुणों का अध्ययन सिरामिक के केवल 10% वजन अंश तक किया गया है। प्रायोगिक और अनुमानित प्रत्यास्थता गुणों का तुलनात्मक अध्ययन भी उपलब्ध साहित्य में नहीं किया गया है। लेखक की जानकारी के अनुसार, एल्यूमीनियम/एल्यूमिना सहित एफजीएम की टफनेस, सिरामिक कण आकार के साथ इसकी प्रवणता और अर्ध स्थैतिक दरार वृद्धि का विश्लेषण दरार गेज का उपयोग करते हुए अध्ययन नहीं किये गए है।

यह शोधग्रन्थ, Al/Al_2O_3 (अल्युमिना के 50% वजन अंश तक) और Al/B_4C (बोरान कार्बाइड के 35% वजन अंश तक) कंपोजिट (गैर एफजीएम और एफजीएम) के विभिन्न लक्षणों (धातु विज्ञानीय, यांत्रिक, टफनेस और अर्धस्थैतिक दरार वृद्धि) से संबंधित है। प्रत्यास्थता एवं सामर्थ्य गुणों के अध्ययन के लिए नमूने गर्म आइसोस्टैटिक सिंटरिंग (उपयुक्त सिंटरिंग तापमान = 600^oC, दाब=30 MPa, अवधि=90 मिनट) का उपयोग करके तैयार किये गए हैं। तैयार किये गए नमूने, Al_2O_3 के 40% तथा B_4C के 30% वजन अंशो तक एक सामान सूक्ष्म संरचना (प्रकाशीय सूक्ष्मदर्शी और ऐसइएम के द्वारा अध्ययन), 2% से कम सरंध्रता वाले तथा बिना अन्य फेज की उत्पत्ति (एक्सआरडी तथा इडीएस से पुस्टीकरण) वाले पाए गए हैं।

प्रयोगात्मक यंग मापांक की तुलना माइक्रोमैकेनिक्स अनुमानों से की गयी है। इस अध्ययन से, Al/Al_2O_3 तथा Al/B_4C के प्रयोगात्मक यंग मापांक रविचन्द्रन/हशीन-

स्ट्रीकमैन के न्यूनतम तथा रविचन्द्रन के अधिकतम मापो के बीच पाए गए हैं। Al/Al_2O_3 के प्रयोगात्मक यंग मापांक, सेल्फ कंसिस्टेंट/मिलर-लानुटी तथा माडीफाइड रूल ऑफ़ मिक्चर, फजी लॉजिक और सेल्फ कंसिस्टेंट अनुमानों के क्रमश: नजदीक पाये गये है। प्रयोगात्मक पोइसन अनुपात, चारपी ऊर्जा (गैर एफजीएम द्वारा मापे गये) तथा एफजीएम और गैर एफजीएम द्वारा मापी गयी कठोरता की तुलना माइक्रो मैकेनिक्स अनुमानों से की गयी हैं।

Al_2O_3 के 40% वजन अंश तक 0.2% प्रूफ सामर्थ्य, अधिकतम तनाव सामर्थ्य (यूटीएस) और यंग मापांक में वृद्धि दर्शायी गयी हैं, जबकि फ्रैक्चर विकृति/लचीलापन Al_2O_3 के वजन अंश में 40% तक की वृद्धि के साथ कम होते हैं। Al_2O_3 के 30% वजन अंश तक, डिम्पल के आकार में कमी के साथ डकटाइल फ्रैक्चर तथा Al_2O_3 के 30% से अधिक वजन अंश के लिए, क्लीवेज फ्रैक्चर का अवलोकन Al/Al_2O_3 कम्पोजिट के लिए किया गया है।

एल्यूमीनियम/एल्यूमिना और एल्यूमीनियम/बोरान कार्बाइड कंपोजिट की फ्रैक्चर टफनेस, सिरामिक के वजन अंश में वृद्धि के साथ कम होती पायी गयी है। यह रवींद्रन के निचले और ऊपरी सीमा के बीच, तथा रवींद्रन प्रभावी मूल्य के करीब पायी गयी है। अर्धस्थैतिक दरार का अध्ययन यह बताता है कि अधिक यंग मापांक की तरफ स्थित दरार की वृद्धि स्थिर और मिक्स्ड मोड फेलयोर के साथ सीधे पथ से विचलित पायी गयी है। जबकि कम यंग मापांक की तरफ स्थित दरार की वृद्धि अस्थिर और मोड-I फेलयोर के साथ सीधे पथ पर होती हुई पायी गयी हैं।

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Nomenclature

Roman Symbols

A	:	Constant parameter (IET)
A_{pl}	:	Plastic part of area under load displacement curve
a	:	Crack length
a_o	:	Initial crack length
a_p	:	Physical crack length
$\frac{a}{W}$	:	Crack length to width ratio
$u_i \ \ (i = x, y)$	:	Displacement in x and y directions
B	:	Thickness of specimen
b	:	Magnitude of Burgers vector
b_o	:	Ligament length
$\tilde{C}$	:	Constant parameter (IET)
C	:	Ravichandran's constant
c		Ravichandran's modified constant
d	:	Crystalline size
d_2	:	Particle diameter
E	:	Young's modulus
E_{30Al}	:	Young's modulus of 70Al/30Al_2O_3 composite
E_{100Al}	:	Young's modulus of 100% aluminum

$E_i \ (i=1,2)$	:	Young's modulus of phase 1 and 2/instantaneous value of Young's modulus at crack tip
E_0	:	Young's modulus at original crack tip
$E(x)$	:	Variation of Young's modulus with x coordinate
E^l	:	Lower bound of Young's modulus
E^u	:	Upper bound of Young's modulus
f_r/f_t	:	Flexural/torsional resonant frequency
G	:	Shear modulus (Modulus of rigidity)
$\tilde{G}$	:	Energy release rate
$G_i \ (i=1,2)$	:	Shear modulus of phase 1 and 2
$G(x)$	:	Variation of shear modulus with space
G^l	:	Lower bound of shear modulus
G^u	:	Upper bound of shear modulus
$g_i^{\ I}(\theta)(i=x,y)$	:	Mode-I angular distribution functions at crack tip
$g_i^{\ II}(\theta)(i=x,y)$	:	Mode-II angular distribution functions at crack tip
J	:	J-integral
J_e/J_{pl}	:	Elastic and plastic parts of J Integral
K	:	Bulk modulus
K_Q	:	Provisional Stress intensity factor
K_I, K_{II}, K_{III}	:	Stress intensity factor in Mode-I, Mode-II and Mode-III
$K_i \ (i=1,2)$	:	Bulk Modulus of phase 1 and 2
$K_1(V_2)$/ $K_2(V_2)$	:	Effective bulk modulus predicted by Kerner method

K_{IC}	:	Fracture toughness
$(K_{IC})_1$	:	Fracture toughness of phase 1
$(K_{IC})_2$	:	Fracture toughness of phase 2
$K_{IC}(x)$	:	Variation of fracture toughness with x coordinate
L	:	Length
m		Mass
m_a, m_w	:	Mass of specimen in air and water
P	:	Load
$\tilde{P}$	:	Porosity
P_{max}	:	Maximum load value
$P(V_2)$	:	Interpolation function
q	:	Stress to strain transfer coefficient
r	:	Radius of particle
$\tilde{r}$	:	Radial distance from crack tip
T	:	Temperature
$\tilde{T}$	:	T-stress
t	:	Time
S	:	Span/Distance between two roller supports
$u_i \ (i = x, y)$	:	Displacement in x and y directions
V	:	Volume fraction
$V_i \ (i = 1, 2)$	:	Volume fraction of phase 1 (matrix) and phase 2 (reinforcement)

W	:	Width
$\hat{w}$	:	Strain energy density
$w_i (i = 1, 2)$	:	Weight fraction of phase 1 and phase 2
x	:	Longitudinal coordinate
y	:	Transverse coordinate

Greek Notations

α	:	Kink angle
α_m / α_p	:	Coefficient of thermal expansion of matrix and particle
$\Delta\alpha$	:	Difference of coefficient of thermal expansion between two phases
β	:	Full width at half maximum
$\tilde{\beta}$	:	Dislocation strengthening coefficient
δ	:	Crack tip opening displacement (CTOD)
$\tilde{\delta}$	:	Interparticle spacing
ε	:	Strain
$\varepsilon_1, \varepsilon_2$	:	Principal strains
η_{pl}	:	Constant for J integral
λ	:	Wavelength of the incident X-ray
$\hat{\lambda}$	:	Microvoid spacing
θ	:	Diffraction angle corresponding to a peak
$\tilde{\theta}$	:	Location of a point w.r.t. crack axis

ρ	:	Density
ρ_s	:	Density of sintered specimen
ρ_t	:	Theoretical density
ρ_w	:	Density of water
ρ_1, ρ_2	:	Density of phase 1 and phase 2
σ_1, σ_2	:	Principal stresses
$\sigma_{.2}$	:	0.2% proof stress
σ_y	:	Yield stress
σ_u	:	Ultimate tensile strength
σ_{ij}	:	Stress tensor
$\Delta\sigma$	:	Gain in yield strength
$\Delta\sigma_{load}$	:	Yield strength enhancement due to bearing forces
$\Delta\sigma_{Hall-Petch}$	:	Change in yield strength due to change in grain size of the matrix
$\Delta\sigma_{Orowan}$	:	Orowan strengthening
$\Delta\sigma_{CTE}$	:	Strengthening due to change in temperature
υ	:	Poisson's ratio
ω_0	:	Constant used in crack tip displacement field

Abbreviations

ASTM	:	American society for testing and materials
BEM	:	Boundary element method
CEQ	:	Charpy energy equivalent
CGS	:	Coherent gradient sensing
CIT	:	Cold isostatic pressing
CMC	:	Ceramic matrix composite
CMOD	:	Crack mouth opening displacement
COD	:	Crack opening displacement
CPA	:	Coherent potential approximation
CTOD	:	Crack tip opening displacement
CVD	:	Chemical vapour deposition
DCB	:	Double cantilever beam
DIC	:	Digital image correlation
ECO	:	Ethylene carbon monoxide
EDS	:	Energy dispersive spectroscopy
EMA	:	Effective medium approximation
ERR	:	Energy release rate
FEM/FEA	:	Finite element method/analysis
FWHM	:	Full width at half maximum
FESEM	:	Field emission scanning electron microscopy

FGM	:	Functionally graded material
FLM	:	Fuzzy logic method
HCM	:	Hopkins-Chamis method
HEQ	:	Hardness equivalent
HIT	:	Hot isostatic pressing
HSLB/HSUB	:	Hashin - Shtrikman lower/upper bounds
HTM	:	Halpin–Tsai method
IET	:	Impulse excitation technique
IKM	:	Inverse Kerner method
IMTM	:	Inverse Mori-Tanaka method
IPC	:	Interpenetrating phase composite
IWTM	:	Inverse Wakashima and Tsukamoto method
JCPDS	:	Joint committee on powder diffraction standards
KM	:	Kerner method
MMC	:	Metal matrix composite
MRLB/MURB	:	Modified Ravichandran lower/upper bounds
MROM	:	Modified rule of mixture
MTM	:	Mori-Tanaka method
NDT	:	Non-destructive test
Non-FGM	:	Non functionally graded material
OP	:	Optical microscopy
PM	:	Powder metallurgy

PMC	:	Polymer matrix composite
PSZ	:	Partially stabilised Zirconia
PVD	:	Physical vapour deposition
RLB/RUB	:	Ravichandran lower/upper bounds
ROM/ RROM	:	Rule of mixture/reciprocal rule of mixture
SCM	:	Self consistent method
SEM	:	Scanning electron microscopy
SENB	:	Single edge notched beam
SFF	:	Solid free form
SG	:	Specific grid
SIF	:	Stress intensity factor
TPB	:	Three point bending
TTOM	:	Tamura-Tomoto-Ozara model
UTS	:	Ultimate tensile strength
UV	:	Ultraviolet
VDT	:	Vapour deposition technique
WTM	:	Wakashima and Tsukamoto method
XRD	:	X-ray diffraction
XRF	:	X-ray fluorescence
YS	:	Yield strength
ZLB/ZUB	:	Zimmerman lower/upper bounds