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Introduction of a reverse simulation approach to identify the fatigue stress intensity factor crack arrest threshold from fretting cracking experiments

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ABSTRACT

The aim of this study was to estimate the ΔK_{th} crack arrest stress intensity factor related to the crack arrest condition of a material subjected to partial slip fretting loadings, by coupled experimental and numerical simulation. The study focuses on a plane (Al-alloy)/cylinder (TA6V) interface. Fretting tests were performed for each configuration to obtain the crack length as a function of the number of fretting cycles, in order to establish the crack length related to crack arrest condition. Using a reverse FEM analysis of crack arrest fretting experiments, the thresholds $\Delta K_{th(fr)}$ are extracted. Two 2196-T8 and 2196-UA aluminium alloys were compared, while the short crack arrest versus the crack length evolutions were formalized using a Kitagawa Takahashi formalism.

1. Introduction

Araujo et al. [1] demonstrated that fretting fatigue endurance can be formalized using a short crack arrest methodology. This approach was adopted in [2] to estimate the crack arrest boundary in the fretting fatigue map approach. Such analysis consists in computing the evolution of the stress intensity factor as a function of crack length and assessing whether this K-factor loading path intercepts the short crack arrest boundary. If the ΔK_{eff} loading path crosses the boundary, then fretting fatigue failure can be expected. Note that the short crack arrest boundary [3] is approximated using either the Kitagawa Takahashi or the El-Haddad formalism [2].

This methodology usually considers a crack located at the contact border, perpendicular to the contact surface. However, experimental results show that the crack path below the interface is more complex and usually displays in the first stages of growth an oblique angle oriented towards the inner part of the contact. A major question is whether the normal crack approximation is able to describe real crack path evolution.

A second aspect concerns the short crack methodology which is usually applied to approximate the crack arrest condition. The present study considered an original reverse approach, consisting in estimating the $\Delta K_{th(fr)}$ (threshold crack arrest intensity factor) in partial slip fretting for the studied material, by applying a reverse identification method to the experimental plain fretting cracking results. The study focused on cylinder/plane fretting models with TA6V/Al-alloys (2196-T8 and 2196-UA) under partial slip conditions.

2. Materials and experimental procedure

2.1. Materials

A 2196 aluminium alloy was investigated, with a chemical composition detailed in Table 1.

Two different heat treatments were investigated: industrial peak aged, called T8, and an experimental treatment at low temperature (120 °C for 96 h), called Under-Aged (UA). These two ageing treatments involve equivalent elastic properties with an elastic modulus E of about 79,000 MPa and a Poisson's coefficient about 0.305, but with differing monotonic and cyclic mechanical properties such as ultimate stress R_m, yield stress $R_{0.2}$, elongation rate $A\%$ and fatigue limit σ_d (Table 2). The related ΔK_0 long crack arrest thresholds are unfortunately not available. However, according to the differences in fatigue limits and R_m values, different ΔK_0 values can be expected, such that $\Delta K_{0(UA)} > \Delta K_{0(T8)}$.

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Nomenclature

Material properties

E	Young's modulus
ν	Poisson's coefficient
R_m	ultimate stress
$R_{0.2}$	yield stress
$A\%$	elongation rate
σ_d	fatigue limit
ΔK_0	nominal threshold stress intensity factor range value related to the long crack arrest condition (constant value)
$\Delta K_{0(fr)}$	range of the fretting long crack arrest stress intensity factor threshold

Contact loadings, stress and crack parameters

P	linear normal force
Q	fretting linear tangential force
Q^*	fretting linear tangential force amplitude
δ	fretting displacement
δ^*	fretting displacement amplitude
$R_{(fr)}$	fretting stress ratio (Q_{min}/Q_{max})
R	radius of the cylinder pad
W	width of the specimen
N	number of cycles
$p_{max}=p_0$	Hertzian maximum peak pressure
q_{max}	maximum interfacial shear stress at $x=-c$
μ	coefficient of friction
μ_t	coefficient of friction at the sliding transition
μ_{crack}	coefficient of friction in the crack
a	half width of the contact area
c	radius of the stick zone
b	crack length
b_p	maximum projected crack length (to the normal of the surface)
b_{p_CA}	maximum projected crack length related to the crack arrest condition
b_0	short crack/long crack transition
$b_{0(fr)}$	fretting short crack/long crack transition
σ_{11max}	maximum principle stress
σ_{11}	principle stress
J	strain energy release rate
ΔK_{th}	crack arrest stress intensity factor threshold
ΔK_{eff}	effective stress intensity factor range
K_I	mode I stress intensity factor
K_{II}	mode II stress intensity factor
K_{Imax}	mode I stress intensity factor at $+Q$
K_{Imin}	mode I stress intensity factor at $-Q$
K_{IImax}	mode II stress intensity factor at $+Q$
K_{IImin}	mode II stress intensity factor at $-Q$
ΔK_I	nominal stress intensity factor in mode I ($K_{Imax}-K_{Imin}$)
ΔK_{II}	nominal stress intensity factor in mode II ($K_{IImax}-K_{IImin}$)

Subscripts

GS	gross slip
PS	partial slip
avg	average value
_KINKED	kinked crack path
_NORMAL	normal crack path
_I	mode I
_II	mode II
_CA	crack arrest condition
(K–T)	related to the Kitagawa Takahashi approximation
(C-T)	related to C-T experiments
(fr)	value extrapolated from the reverse fretting crack arrest analysis
(UA)	related to 2196-UA
(T8)	related to 2196-T8

For each alloy, small cubic specimens were machined and polished to achieve a 0.2 µm R_a roughness. Samples were adjusted so that fretting loading was applied in the rolling direction of the alloy (Fig. 1).

2.2. Plain fretting experiment

Plain partial slip fretting tests were performed using a hydraulic set-up at the LTDS laboratory, as previously described by Heredia [5]. The normal force (P) was kept constant while tangential force (Q) and displacement (δ) amplitudes were recorded. The fretting loop could be plotted and the corresponding amplitude values (respectively Q^* and δ^*) defined (Fig. 2). The stress ratio was kept at $R_{(fr)}=-1$.

In the present fretting cracking investigation, the displacement amplitude was monitored in order to maintain partial slip conditions, keeping tangential force amplitude constant throughout the test. A cylinder/plane configuration was applied. The fretting pad consisted of a Ti–6Al–4V alloy, displaying the following elastic properties: 119,500 MPa elastic modulus and 0.287 Poisson coefficient. Two cylinder radius configurations were investigated: $R=40$ mm and $R=80$ mm. The maximum constant Hertzian pressure was fixed at $p_{max}=300$ MPa, adjusting linear normal force to $P=217$ N/mm and $P=436$ N/mm respectively. The lateral width of the cylinder pad was about 8 mm, allowing plane strain conditions to be assumed along the median axis of the fretting scar. Preliminary tests determined the friction coefficient at the sliding transition $\mu_t=0.85$ [4]. Note that no fatigue test was performed: only contact loads were applied so that,

Table 2
Mechanical properties of the 2196 aluminium, according to heat treatment.

State	$R_{0.2}$ (MPa)	R_m (MPa)	A (%)	σ_d (MPa) at 10^7 cycles
T8	559	594	5.9	150
UA	428	520	11.1	140

Table 1
Chemical composition of the 2196 aluminium.

% Cu	% Li	% Mg	% Mn	% Ag	% Zr	% Zn	% Si	% Fe
2.5–3.3	1.4–2.1	0.25–0.8	< 0.35	0.25–0.6	0.04–0.18	< 0.35	< 1.2	< 0.15