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Subcritical crack growth in Low Temperature Co-fired Ceramics under biaxial loading

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ABSTRACT

The biaxial strength of Low Temperature Co-fired Ceramics was determined using the ball-on-three-balls test in several environments (dry oil, air and water). Subcritical crack growth phenomenon was observed, activated by the prolonged presence of humidity at the specimen surface. Whereas high strength values were reached during high-rate testing in dry oil, up to a 50% lower strength was measured on specimens immersed in water tested for longer periods. Experiments in a relative dry environment have shown for the first time evidence of two different crack growth mechanisms in this material. A model has been implemented to interpret the experimental results.

1. Introduction

Low Temperature Co-fired Ceramics (LTCCs) consist of a complex three-dimensional micro-network of metal structures embedded within a ceramic substrate with a large content of glass. They are layered ceramic based components, which can be used as electronic devices (e.g. for mobile and automotive technologies) in highly loaded (temperatures, inertia forces, etc.) environments. LTCC technology was established in the 1970s as an alternative to overcome conductivity problems with tungsten metallisation in alumina substrates employed in high temperature co-fired ceramics [1]. The low sintering temperature of the ceramics in LTCC (i.e. below 900 °C) can be achieved by using a glass matrix with a low melting point, allowing a vitrification of the glass ceramic composite material [2]. This makes feasible the use of excellent electronic conductors such as silver, gold or mixtures of silver–palladium, arranged within and/or on the surfaces of the ceramic substrate, forming complex multi-layered structures. Today, they can be found in devices which have to operate under harsh conditions such as relatively high temperatures and mechanical shock under different environments.

The lifetime prediction of LTCCs is associated with their mechanical strength and crack growth resistance during service. Therefore, the understanding of cracking in LTCC components and the response to crack propagation must be assessed if a reliable design is pursued. A limiting factor for the lifetime of glasses and ceramics is associated with the subcritical crack growth (SCCG) phenomenon which may occur in glass-containing components subjected to tensile stresses, especially in environments with high moisture content [3–5]. In order to obtain crack propagation data, both direct and indirect methods may be employed [5]. With direct methods crack velocity is measured on fracture mechanics type specimens (e.g. double cantilever specimen, double torsion specimen with a crack), as function of the stress intensity factor. With indirect methods the growth of internal defects causes a degradation of strength, which is used to derive the underlying crack propagation parameters. Using this method only the average crack behaviour can be measured. However, they allow direct testing of component-like specimens, so that extrapolation of strength data to real components is more accurate.

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Nomenclature

a	crack length
a_c	critical flaw size
$a_{c,0}$	initial crack length
B	specimen thickness
D	SCCG parameter
da	crack length increment
$\mathrm{d}t$	time increment
E	Young's modulus
f	dimensionless factor
F	probability of failure
G	shear modulus
K_I	stress intensity factor
K_{Ic}	fracture toughness
K_T	transition stress intensity factor
$\widehat{K}_I$	normalised stress intensity factor
$\widehat{K}_T$	normalised transition stress intensity factor
m	Weibull modulus
$\bar{m}$	mean Weibull modulus
n	SCCG exponent
P	maximum load at failure
R	R-square fitting parameter
S_{eff}	effective surface
$S_{eff,PIA}$	effective surface calculated using PIA criterion
S_i	inner span
S_o	outer span
t	plate thickness
t_f	time to failure
v	crack growth velocity
V_{eff}	effective volume
$V_{eff,PIA}$	effective volume calculated using PIA criterion
W	specimen width
Y	geometric factor
Y^*	geometric factor for an edge crack
δ	ratio between crack length and specimen width
$\mathrm{d}\sigma$	increment of stress
ν	Poisson's ratio
ρ	density
σ	failure stress
σ_a	applied stress
σ_f	fracture strength
σ_0	characteristic strength
$\sigma_{0,\ in}$	inert characteristic strength
$\sigma(t)$	stress as a function of time
$\dot{\sigma}$	stress rate
v_0	critical crack growth velocity
BOR	ball-on-ring
B3B	ball-on-three-balls
LTCC	Low Temperature Co-fired Ceramic
MU	measurement uncertainty
PIA	Principle of Independent Action
POB	pin-on-three-balls
RH	relative humidity
ROR	ring-on-ring
SCCG	sub-critical crack growth
SEVNB	Single Edge V-Notch Beam
SPT	Strength–Probability–Time