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An improved Vickers indentation fracture toughness model to assess the quality of thermally sprayed coatings

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ABSTRACT

This study presents an improved approach to the quality assessment of thermally sprayed coatings. Measurements were carried out on five different coatings. Since it is the overall extent of surface cracking during Vickers indentation that is indicative of the volumetric damage, the surface crack length was measured, including the radial cracks, edge cracks, and other cracks around the indentation. It is concluded that the proposed model provides a way forward for determining the fracture toughness (K_{1c}) of brittle materials where no radial cracks are developed. An elastic–plastic finite element simulation of the Vickers indentation test was conducted to locate the stress fields.

1. Introduction

Although indentation fracture toughness (K_{1c}) is not considered as being reliable measurement in terms of an absolute material value but comparative behaviour can be well reflected by the method. To quantify Vickers indentation cracking and fracture toughness, by far the greatest attention has been directed to the relatively well defined classical crack configurations (e.g. Palmqvist or radial-median). Further to this, the uncertainty in measuring the crack lengths in Vickers indentation fracture test makes empirical toughness models [1] particularly unsuitable for brittle coating materials (e.g. thermal sprayed cermet/ceramic coatings). Irregular networks of smaller cracks not originating at indentation corners (reported as 'no dominant cracks' [2]) have been observed by investigators [2–7] working on thermally sprayed coatings. The empirical models tend to be based on an idealised cracking pattern and do not account for other cracks around indentations. Previously, authors investigated an acoustic emission (AE) based non-destructive technique of characterising the indentation fracture pattern in thermally sprayed coatings with a view to quantitatively evaluate WC–Co coatings [8] and Al_2O_3 coatings [9,10] quality, indentation loading stages based on the AE criteria [11], and AE based analysis of fracture toughness of various cermet and ceramic coatings [12]. However, in this paper the work has been to establish a non-AE based working mathematical (empirical) model, which is based on measurable total surface crack and total surface crack length but excluding total radial cracks (i.e. edge cracks), to the quality assessment of thermally sprayed WC–Co cermet and Al_2O_3 ceramic coatings. This can provide a way forward for determining the Vickers indentation fracture toughness of brittle materials where crack other than Palmqvist or half-penny/radial-median cracks are developed.

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Nomenclature

$a_{1,2}$	Vickers indentation size for half diagonal 1, 2
a	average Vickers indentation half diagonal size
B	slope of line
c_1, c_2	radial crack along Vickers indentation diagonals, $c = l + a$
D	median crack depth
E	elastic modulus
h	Palmqvist crack depth
Hv	Vickers hardness number
k_e	fracture toughness (edge crack) empirical constant
k_L	fracture toughness (total surface crack) empirical constant
k_m	fracture toughness (half-penny/radial-median) empirical constant
k_p	fracture toughness (Palmqvist) empirical constant
k_{total}	fracture toughness (total crack) empirical constant
$K1$	stress intensity factor (type 1: opening mode)
K_{1c}	fracture stress (fracture toughness, type 1: opening mode)
l, l_a	surface radial crack length
lyn	crack path unit length
L	total surface crack length
m	edge crack depth
P	indentation load
R	linear correlation coefficient
R_a	average surface roughness
$x_{1,\,2,\,\cdots\,n}$	serrated crack path unit length
σA	uniform stress field in an infinite plane
σ_I	indentation stress (dynamic)
σ_R	residual stress (static)
σ_y	yield strength
ψ	empirical constant (stress intensity factor)
v	Poisson's ratio
AE	acoustic emission
APS	air plasma spray
FEA/FEM	finite element analysis/modelling
GE	generic equation
HVOF	high velocity oxy fuel
XRD	X-ray diffraction

The durability of thermal spray coating for wear and fatigue applications [13–16] is dependent upon a combination of coating and substrate properties including resistance to fracture within the coating (cohesive failure) or at the coating substrate interface (adhesive failure). Fracture toughness of the coating, both parallel and perpendicular to the direction of spraying due to its lamellar microstructure, ability of the substrate to support coating under indentation or contact stress, role of residual stress are some of the key design factors controlling the performance of coated components. A more reliable interpretation of crack patterns used to infer fracture toughness using Vickers test on a given coating substrate system will inevitably improve the design quality of manufactured components. Typical Vickers indentation fracture patterns for thermally sprayed cermet/ceramic coatings consist of a network of cracks around the indentation. As well as this network, radial cracks emanating from the two opposite indent corners, on a plane parallel to the coating–substrate interface, can also be seen. The indentation fracture in these coatings also tends to be asymmetric, which has been attributed to a macroscopic variation in relative density, the presence of pores or other defects around the contact and through thickness residual stresses variation [2]. It has been suggested that indentation in porous regions of the coatings results in localized densification about the contact site, resulting in little transmission of indentation stresses to the surrounding materials, and the confinement of cracking to the vicinity of the impression [2]. Interaction with large coating pores or defects near the impression diagonal would then be expected to result in longer cracks, producing a modified Boussinesq stress field. Since the degree of porosity varies between coatings (e.g. HVOF < APS [5]) as well as within a given coating, it has been suggested [2] that different loads would be required to produce cracking in different coatings of the same type and even from place to place in a single coating.

Recent investigations [3] give a typical example of the fracture pattern around Vickers indentations in functionally graded HVOF WC–NiCrBSi coating, preferring qualitative analysis to the empirical models as reviewed by Ponton and Rawlings [1] to obtain fracture toughness. They pointed out that, if micro-fissuring in the sub-surface region takes the place of surface radial cracks at lower loads, this complicates the issue of using empirical models to measure fracture toughness. Factor and Roman