Engineering Fracture Mechanics 159 (2016) 1–15

Contents lists available at ScienceDirect

Engineering Fracture Mechanics

journal homepage: www.elsevier.com/locate/engfracmech

Fracture of epoxy-based marine coatings as free films and substrated coatings under static tension

T. Wu [a], P.E. Irving [a,*], D. Ayre [a], G. Dell'Anno [b], P. Jackson [c], F. Zhao [c]

[a] School of Aerospace, Transport, and Manufacturing, Cranfield University, Cranfield, Beds MK43 0AL, United Kingdom
[b] National Composite Centre, Bristol, United Kingdom
[c] AkzoNobel Performance Coatings, Felling, Gateshead, United Kingdom

ARTICLE INFO

Article history:
Received 30 September 2015
Received in revised form 26 February 2016
Accepted 27 February 2016
Available online 4 March 2016

Keywords:
Fracture
Epoxy coatings
J integrals
Residual stress
Prediction of failure strain

ABSTRACT

Factors controlling crack development in two formulations of heavily filled epoxy anti-corrosion coatings have been studied as free films and on steel substrates. Both coatings were nominally 300 μm thick. Tensile strength, Young's modulus, strain to failure and fracture toughness of coating free films were measured at 23 °C. Tensile tests of both coatings on steel substrates were performed at 23 °C and strains to development of first coating crack and crack development with increasing strain were measured using extensometry and Digital Image Correlation (DIC). Finite element models of free film and substrated samples, incorporating non-linear stress–strain curves, were used to calculate residual stresses in substrated samples and *J* values of coating cracks. It was found that strain to first crack in coatings on substrates could be predicted using fracture mechanics models of coating cracks together with data on defect size, residual stress and toughness. Channelling crack development and factors influencing the relative ductility of free film and substrated coatings are discussed.

1. Introduction

Brittle organic coatings are widely used for anti-corrosion purposes for metallic engineering structures in corrosive environments [1]. The epoxy-based coatings used for marine applications, such as water ballast tanks (WBT) of oil tankers [2], are a typical example. WBT coatings are normally prequalified using the IMO MSC215 (82) standard [3]. However, premature cracking of some prequalified WBT coatings can occur on welded panels in service. Upon failure of the coatings, the structures beneath will be rapidly corroded. This causes potential danger to tanker structural integrity [1]. Thus there is a need to investigate factors controlling cracking of WBT coatings.

Fracture mechanics treatments of coatings on substrates have been developed by a number of investigators. A comprehensive summary has been produced by Hutchinson and Suo [4]. Cracks in coatings with thicknesses much smaller than the substrate under tensile stress have two configurations as shown in Fig. 1: penetration, in which a surface crack penetrates towards the coating/substrate interface (Fig. 1a); and channelling, in which a crack propagates in the coating plane with constant depth (Fig. 1b). In Fig. 1, $\boldsymbol{a}$ is crack depth, $\boldsymbol{h}$ coating thickness, $\boldsymbol{\sigma}$ tensile stress in the coating, and $\boldsymbol{l}$ is the surface crack length. Note that "penetration", in this work, refers to crack extension perpendicularly towards the substrate, within the coating layer only.

* Corresponding author.

http://dx.doi.org/10.1016/j.engfracmech.2016.02.048
0013-7944/

Nomenclature

a	defect size/depth
b	free film width
c	local gauge length
d	crack opening displacement
E	Young's modulus
E_c	coating modulus
G	strain energy release rate (SERR)
G_C	fracture toughness
G_p	SERR for crack penetration
G_{ch}	SERR for crack channelling
H	critical inter-crack distance
h	coating thickness
J_p	J-integral for crack penetration
J_{ch}	J-integral for crack channelling
K	critical stress intensity factor
l	surface crack length
n	hardening exponent
T_g	glass transition temperature
W	half free film width
α	Dundur's parameter
β	Dundur's parameter
σ	stress
σ_f	fracture stress
σ_Y	"yield" stress
ε	strain
ε_f	fracture strain
ε_{EXT}	strain to first crack by extensometer
ε_{DIC}	strain to first crack by DIC
θ	yield offset
μ_c	coating shear modulus
μ_s	substrate shear modulus
ν_c	coating Poisson's ratio
ν_s	substrate Poisson's ratio

For linear-elastic coating/substrate systems, Beuth [5] developed closed-form solutions to calculate strain energy release rates for crack penetration ($\boldsymbol{G_p}$) and channelling ($\boldsymbol{G_{ch}}$), Eqs. (1) and (2). Here, $\overline{\boldsymbol{E}}_c$ is the coating modulus in plane strain. The full expressions of the geometric correction factors $\boldsymbol{f}$ and $\boldsymbol{g}$ are reported by Beuth [5]. These are functions of the modulus mismatch between the coating and substrate, described by the Dundur's parameters $\boldsymbol{\alpha}$ and $\boldsymbol{\beta}$ (Eqs. (3) and (4)) as well as the ratio of crack depth to coating thickness, a/h. The subscripts $\boldsymbol{c}$ and $\boldsymbol{s}$ represent coating and substrate respectively, $\boldsymbol{\upsilon}$ is Poisson's ratio, and $\boldsymbol{\mu}$ is shear modulus. Eqs. (1) and (2) show that G_p and G_{ch} for coating crack penetration and channelling at a constant stress are influenced by coating thickness, coating/substrate modulus mismatch, and ratio of crack depth to coating thickness.

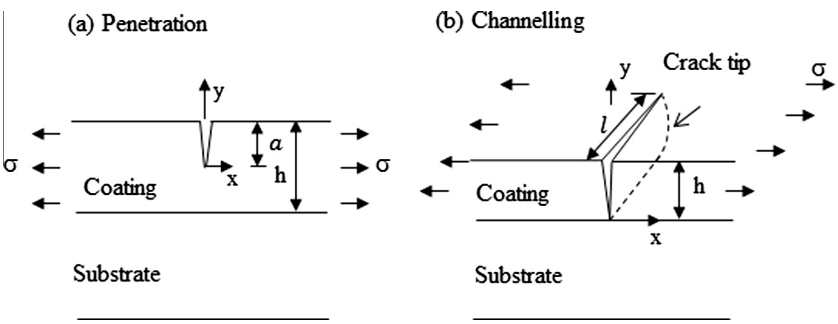

Fig. 1. Illustration of crack penetration and channelling in coating on substrate.