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Numerical simulations of the cathodic delamination of adhesive bonded rubber/steel joints

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ABSTRACT

Cathodic delamination of mechanically loaded rubber/steel adhesive bonds occurs due to bondline degradation (weakening) followed by crack growth under mechanical (here, mostly cleavage) load. In this paper, a mechano-chemical failure criterion is proposed, which couples fracture mechanics principles with the weakening mode of debonding due to environmental effects. The latter is mainly described by electrolyte type, cathodic potential, and temperature and may be analytically described according to the recently introduced [1] analytical model based on liquid-solid reactions and is capable of simulating the weakening mode of bond degradation. This paper extends the model advanced in [1] to where we now account for externally applied mechanical loading (mostly peel mode). Such loads cause already weakened bonds to delaminate thus resulting in physical separation of the rubber from the steel substrate.

For the rubber/metal, variable-*G*, strip blister specimen (SBS) used in this work, progressive delamination proceeds as the applied strain energy release rate, *G*, decreases from an initial maximum value, G_{T0} (of about 2.24 kJ/m^2 for the most utilized specimen configuration). As the applied *G* decreases, delamination correspondingly proceeds at progressively slower rates. The fact that delamination rates decrease with increasing delaminated bond lengths has already been established experimentally and simulated using empirical [2] and semi-empirical models [3] but will be simulated numerically in this paper. The model is validated using such experimental data of bond delamination under a variety of cathodic conditions. The validated methodology provides numerical simulations of joint delamination of the SBS under the combined action of mechanical peel loads and cathodic environment.

1. Introduction

Alkaline conditions at elastomer/metal bondlines are detrimental to the durability of cathodically exposed adhesively bonded rubber-to-metal joints [4–6]. Bond degradation (weakening) propagates from the edge of the exposed bond inwards causing the bond to weaken [7,8]. If cleavage stresses act upon such a weakened bond, then complete and visible separation of the bonded constituents occurs, resulting in the form of debonding commonly referred to as delamination. Hamade and co-workers implemented empirical [2] and semiempirical [3] approaches to model the *delamination* mode of debonding in steel/rubber adhesive bonded joints under cathodic conditions.

Recently [1], an analytical model was also developed by Hamade and co-workers to model the *weakening* mode of cathodic debonding of adhesive bonded joints. Weakening progression was mathematically described via a boundary value problem (BVP), which accounts for the mass transfer and reaction kinetics that occur in the vicinity of the adhesive bond constituents under high alkaline conditions. Therefore, the analytical model for weakening describes the environment along the degraded interface as well as the accompanying chemical degradation of the interface. The resulting model is a reduced set of coupled, non linear partial differential equations, which are solved numerically.

In this work, the *weakening* model in [1] is extended in order to analytically model the *delamination* mode of debonding. Unlike the previous works by Hamade and co-workers in [2,3] where empirical or semi-empirical approaches were used, this paper offers a numerically-based approach to modeling the delamination mode of debonding. The numerical simulations of joint delamination take account of the combined action of mechanical load and the cathodic parameters. To account for the load, strain energy release rate is introduced as an explicit variable into the numerical solution scheme. It will be shown that the results of the model agree well with previously collected [2,3] experimentally collected delamination data under a variety of conditions.

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Nomenclature

a	Eq. (1): crack length in the SBS$=Z_2+12.7$ mm
ASW	artificial sea water
BVP	boundary value problem
$c1$, $c2$, $c3$	Eq. (1) coefficients
$CEHF$	cathodic environmental harshness factor
C_1 or $[\mathrm{OH}^-]$	concentration of hydroxyl ions
C_{10} or $[\mathrm{OH}^-]_0$	initial concentration of hydroxyl ions
C_1^{non}	dimensionless concentration of hydroxyl ions
C_2 or $[C.L.]$	concentration of critical linkage
C_{20} or $[C.L.]_0$	initial concentration of $C.L.$
$[C.L.]_{cr}$	critical concentration of $C.L.$
C_2^{non}	dimensionless concentration of $C.L.$
d	dowel diameter in SBS
D	diffusion coefficient of hydroxyl
D_{NaOH}	diffusion coefficient of hydroxyl in NaOH
D_{ASW}	diffusion coefficient of hydroxyl in ASW
G	strain energy release rate
$G_{applied}$	applied strain energy release rate in SBS
G_{cr}	intact bond's critical strain energy release rate
$G_{Residual}$	degraded bond's residual strain energy release rate
G_T	total applied strain energy release rate in SBS
G_{T0}	initial total applied strain energy release rate in SBS
G_{th}	degraded bond's threshold strain energy release rate
k	degradation rate coefficient
k_{ASW}	degradation rate coefficient in ASW
k_{NaOH}	degradation rate coefficient in 1 M NaOH
L	characteristic control length
NaOH	sodium hydroxide solution
SBS	strip blister specimen
SCE	standard calomel electrode
t	time
t^{non}	dimensionless time
t_R	rubber thickness in SBS
T	temperature
V	cathodic voltage (SCE)
x	distance
x^{non}	dimensionless distance
Z_1	weakened length
Z_2	delaminated length
ϕ	Thiele modulus

Therefore, the model may serve as a basis for bond life predictions under combined mechanical loading and cathodic conditions of a variable-G test configuration as the SBS.

2. The strip blister specimen

Refs. [3,4] report in detail on the materials and fabrication relevant to the experimental work needed in this paper. Here, we briefly describe the strip blister specimen used in this work along with some of its characteristics associated with bond delamination.

Fig. 1 is a schematic diagram that illustrates the geometry as well as the self-loading capability of the SBS. In constructing this sandwich specimen, the substrate is made of ANSI 1026 mild steel while the rubber strips are 5109 S neoprene (specially formulated for marine applications). The rubber is bonded to the steel using a proprietary commercially available, two-coat (a primer bottom-coat and an adhesive top-coat) vulcanizing primer/ adhesive system. The primer bottom coat was found [9] to consist primarily of a blend of phenol formaldehyde and chlorinated isoprene, and include titanium dioxide and zinc compounds as additives and carbon black as filler. The adhesive was also found to be based on allylically brominated poly-2,3-dichloro-1,4-butadiene containing 10–27% bromine. Prior to bonding, sheets of metal were vapor degreased using trichloroethane before and after grit blasting with 40-grade steel grit at 275 kPa. The primer was then brush-coated on the metal sheets and, upon drying, was followed by applying the adhesive coat also by brushing. The neoprene rubber strips were then placed in a mold in contact with the primer / adhesive-coated steel substrates. The mold was then placed in a heated platen press at a temperature of 155 ± C and under a pressure of 3.4 MPa for 50 min. This was followed by a post cure cycle at 177 ± C for 3 h. This resulted in simultaneously vulcanizing the elastomer as well as in curing the primer/ adhesive bondline.

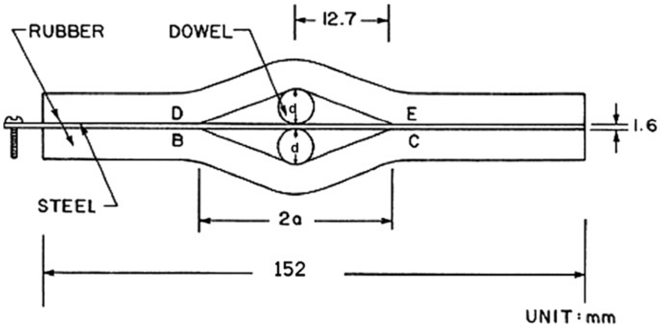

Fig. 1. Schematic diagram of the self-loading strip blister specimen (SBS).

The total applied strain energy release rate, G_T, acting at the tip of the delaminated zone is due to the self-loading capability of the SBS. This capability is accomplished by inserting plastic dowels of different diameters, d, (total of two dowels per specimen are used one on either side of the specimen), in the built-in flaw at the center of the specimen. The initial value of G_T, G_{T0}, depends on 2 parameters: dowel diameter and rubber thickness, t_R, where different configurations of the SBS can be constructed using different combinations of these parameters. The resulting applied G values in the SBS have been characterized in [10] using FEM based on the Mooney–Rivlin constitutive equations. The total (yet dominated by cleavage stresses) G_T decays (from an initial maximum value of G_{T0}) with increasing delaminated lengths.

For ease of estimating total applied G, G_T, values for the SBS, such values found in [10] were plotted in [8] as points on G vs. crack length plot. Fitted to such points were second order polynomial curves

$$G_T = c1a^2 + c2a + c3 \tag{1}$$

The coefficients $c1$–$c3$, along with the resulting G_T values, were listed in [8]. The result is that one can estimate the applied G values for varying combinations of d and t_R of the SBS with the aid of a simple equation. This will prove useful in the numerical scheme advanced below in this paper.

One feature of the experimentally collected cathodically delaminated data is that it obeys a fairly linear relation when plotted against time but as the applied strain energy release rate, G, decays so do the delamination rates.

Fig. 2 [11] is a qualitative plot of log delamination rates versus log G. The value of dry bond G_{cr} has been estimated [3] to be about 10 kJ/m^2. While the low threshold value, G_{th}, varies depending on the harshness of the environment [2] but likely values range from a very weak residual of 0.1 kJ/m^2 to just under 1 kJ/m^2 (or 1% and