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New electrical potential method for measuring crack growth in nonconductive materials

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Abstract

DC electric potential technique has been used to monitor crack growth in conductive materials. A constant DC current is passed through these materials and the crack length is measured through the changes in the electrical voltage at the crack mouth. However, this method is not applicable in crack growth measurement in nonconductive materials or adhesively bonded joints. For these materials, a new method is developed and is shown to provide a very accurate method for measuring the crack length. The surface of these materials is coated with a thin layer of carbon paint and the crack length is measured through the changes in the electrical resistance of the carbon paint, as the crack grows both in the base material and the thin layer carbon paint. In contrast to the DC electric potential technique where the position of the probes for measuring the crack length is very important for an accurate measurement of the crack length, the new technique is little sensitive to the probe location.

Crack growth is measured in adhesively bonded joints subjected to creep loadings. A modified compact tension specimen is cut in two pieces across its notch area. The pieces are then glued using an adhesive. The surface of the specimen is painted with a thin layer of carbon paint and the changes in its electrical resistance are monitored. It is shown that the carbon paint method provides a quiet sensitive method for monitoring the crack growth. The creep crack growth rate in the adhesively bonded joint is related to Mode I energy release rate, G_1. It is shown that the crack grows in the middle of the adhesive layer rather than at the interface of the joint. Micro-mechanisms of the crack growth are studied using a scanning electron microscope. The damage consists of numerous crazed regions at the crack tip. Crack grows by the linkage of the crazed region.

1. Introduction

Adhesives have had a growing role in manufacturing assembly in the last few decades. The most recent growth has been in the automotive industry, where the increasing use of plastics and the need to reduce overall vehicle weight has made adhesive an increasingly popular manufacturing solution. Adhesively bonded joints offer many advantages compared to the other methods of joining, such as, mechanical fastening, welding and brazing. The ease of manufacturing, surface appearances, stress distribution in the bonded area, cost of

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manufacturing, and capabilities of joining dissimilar materials are some of the advantages of using adhesives. Despite of these benefits, the application of adhesives in joining critical components has proceeded with caution, as mechanical behaviors of adhesively bonded joints are not fully understood. These include their failure mechanisms and crack growth behavior in adhesively bonded joints. Despite of many investigations on the crack growth behavior in monolithic materials, there is relatively little investigation on the crack growth behavior of adhesively bonded joints, [1–4]. This could be due to difficulties in monitoring crack growth in adhesively bonded joints on continuous bases. In metals and metallic joints such as welds, slow crack growth can be measured using the DC electric potential drop method (EPDM). This method relies on the spreading and oxidation of the advancing crack faces to increase the specimen's electrical resistance [5]. However, this method cannot be used in monitoring crack growth in nonconductive materials and adhesively bonded joints.

Chai [6] studied the effects of bond line thickness on the fracture toughness of adhesively bonded joints. It was found that the fracture toughness of the joint increased with the increase of the bond line thickness. However, there was no effort to measure the crack growth rate and thus obtaining the R-curve behavior of the joint. This could be due to lack of capability in monitoring the crack growth in nonconductive materials. Plausinis and Spelt [7] developed a new constant energy release rate loadjig for studying the mixed-mode creep crack growth in adhesively bonded joints. The crack growth was monitored using a microscope. It was observed that the crack growth rate decelerated, indicating that the adhesive layer was self-toughening over time. In addition, it was found that the crack propagated by the initiation and coalescence of micro-cracks, rather than by the continuous advancement of a crack tip. Natio and Fujii [8] investigated the fracture surface morphologies of adhesively bonded double cantilever beam. The fracture surface of unmodified adhesive and modified adhesive using sub-micron rubber particles were examined in a scanning electron microscope. The energy release rate for the fracture of the joints was related to the fracture surface morphologies. However, there was no systematic method to measure the crack growth rate.

Liniecki et al. [9] investigated the fatigue strength of adhesively bonded aluminum joints. The application presented for this study was the use of aluminum patches and adhesive to repair turbine blades. The bond was considered to be a doubly lapped patch across a thin-notched section. Conductive silver paint across the epoxy joints was used to detect failure in the joints. However, no consideration was given to the crack growth rate through the adhesive. Devries et al. [10] investigated the fracture of cylindrical butt joints. The test specimen was adhered to a plate with a uniformly thick layer of adhesive. The debond location and debond force were tabulated for different thicknesses of adhesive, and the fracture event recorded on a videocassette. However, crack growth and crack growth rate were not considered in this investigation.

Recent studies [11] have used optical methods to observe fracture behaviors of adhesively bonded joints. These methods are only practical when the elapsed time to failure is minimal, usually on the order of minutes. Electronic speckle pattern interferometery is also used to monitor crack growth in specimens [12]. Reflections of a split laser beam on the joint surface result in a fringe pattern. The resulting fringes from the crack surfaces are recorded on a CCD camera. The changes measured from image to image, show the advance of the crack. This method is expensive and data storage for even an hour of crack growth measurements could prove prohibitive.

Abou-Hamda et al. [13,14] developed a test method based on fracture mechanics concepts to measure Mode I fatigue crack growth rates in the bond-line of adhesively bonded double cantilever beam specimens. Fatigue crack growth rate was related to the J-integral. Here again the crack growth was monitored using an optical technique.

This paper presents a new methodology for monitoring crack growth in adhesively bonded joints and nonconductive materials. This method involves supplementing the nonconductive ligament of the joint with a uniform, thin layer of brittle, conductive material. The progress of the crack through the joint also cracks this material

and increases the system electrical resistance. A data acquisition system connected to this joint circuit provides continuous monitoring of the crack growth through the joint.

This technique has numerous advantages compared to the potential drop technique. The measured resistance across a cracked conductive specimen under EPDM can vary, depending on the placement of the leads. This necessitates the use of finite element analysis to determine the most sensitive position for the leads for potential measurements [15]. The carbon paint method has the advantage of providing a resistive element whose resistance is at least three orders of magnitude greater than the conductive path through a conductive specimen. For example, the resistance across a notched bar brass specimen is on the order of 0.002 Ω; this figure includes the contact resistance of the leads. The resistance of typical carbon paint joint is on the order of 1–15 Ω, depending on the paint thickness. Thus, the variability in calculated resistance stemming from different lead placement is negligible. This technique also uses a simple ohmmeter, and does not need the constant-current source required for the DC potential—drop method. This method has been developed and used here for the creep testing of epoxy-bonded brass butt-jointed specimens in Mode I loading.

2. Theoretical background

The typical method for the continuous measurement of crack propagation through a conductive test specimen is by using the DC potential drop technique [15]. In this method, a constant DC current is passed through the specimen. The electrical voltage is measured across the crack mouth and is related to the crack length. The electric potential across the crack mouth can be related to the unbroken crack ligament resistance, R, through the Ohm's law:

$$V = IR \tag{1}$$

For the specimen shown in the Fig. 1, the cross-sectional area of the specimen can be calculated from the measured resistance. With respect to a crack through a material of uniform thickness, the change in un-cracked length can be calculated from

$$L = L_0 \frac{R_0}{R} \tag{2}$$

where L_0 and R_0 are the initial crack length and resistance of the un-cracked ligament respectively.

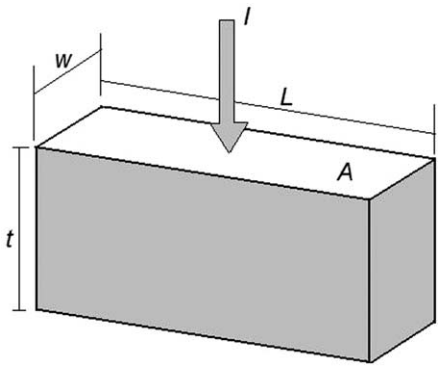

Fig. 1. Resistive element.

3. Experimental investigations and results

3.1. Coating process

To provide for the conductivity of the compact tension test (CTT) specimen, a process has developed to reliably coat the specimen with a conductive coating along the length of the bonded joint. This coating has to be comparatively weaker and more brittle than the epoxy joint, so as not to change the properties of the bonded joint system. In order to make this feasible, a thin layer of conductive material has to be evenly deposited across the surface where the crack develops. If the coating is not uniformly conductive, the resistance readings from the data acquisition system cannot be reliably related to the crack length.

Thus, the list of process requirements for the conductive coating technique becomes:

- Deposited material must be uniformly conductive across the bond surface.
- Deposited material must not change the properties of the joint.
- Conductive material must be inexpensive.

The original concept for the conductive coating process centered on the use of conductive silver paint applied across the joint with a brush. This material proved to be prohibitively expensive. Furthermore, it was difficult to maintain a uniform silver paint thickness across the bond-line. However, conductive carbon paint (typically used as a current path for nonconductive SEM specimens) proved to be much more cost-effective. To control coating thickness, a drawknife was first tried. Because the faces of the specimen are not indexed exactly when adhered, this proved to be an inaccurate method. Additionally, the drying time for carbon paint spread thickly in this manner is on the order of 3–4 days, as measured with an ohmmeter (resistance stabilization indicates drying).

The most typical way to apply a uniform coating to a surface is by spraying; the best way to apply a coating of paint is with an airbrush. Initial tests indicated that the airbrush provided an excellent regularity of coating, due to the many thin layers applied across the joint. To create the conductive path for measurement of the crack growth, the specimen face was sanded or scrubbed free of epoxy and wiped with a solvent such as acetone or isopropyl alcohol to remove residual oils or chemicals. After the specimen faces was dry and clean, a 12.7 mm wide strip was masked off across one joint face. The unmasked area was spray painted using a mixture of one part carbon paint diluted with two parts 90% isopropyl alcohol in an airbrush. The second coat was applied after insuring that the first spray was dry before applying the next coat. This procedure was repeated until the surface was uniformly coated and no gaps were visible in the joint. The paint was allowed to dry thoroughly before any crack growth experiments. It was observed that resistance of the paint was not changing once it was completely dry.

This process applies an even coat of conductive material across a nonconductive surface. An advantage of the carbon paint process over the current potential-drop method for conductive specimens is that the resistance of the specimen is easily monitored with an ohmmeter, and does not require a constant-current source to measure crack growth.

3.2. Carbon paint crack growth monitoring method

An experimental procedure was developed to evaluate the validity of Eq. (2) for the case of adhesive. In this respect, thin brass plates 63.5 mm in length were glued in sets of two onto nonconductive plastic plates with a gap of 0.127 mm, Fig. 2. This simulated glue joint was coated with a uniform layer of conductive carbon paint 47 mm in length and allowed to dry. (“Dryness” was determined by the stabilization of a resistance measurement from a multimeter).

The brass plates were soldered to the leads of a multimeter and the resistance measured and recorded. A series of cuts through the joint was made, the intact joint length measured with calipers and the corresponding resistance recorded, Fig. 3.

Tables 1–4 present the experimental and theoretical value of electrical resistance for four specimens with different carbon paint thickness. Here

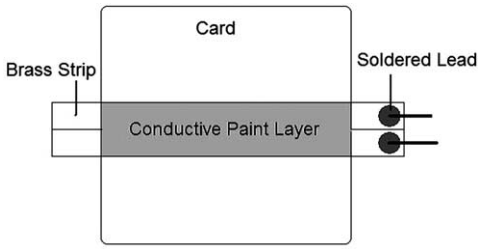

Fig. 2. Calibration sample.

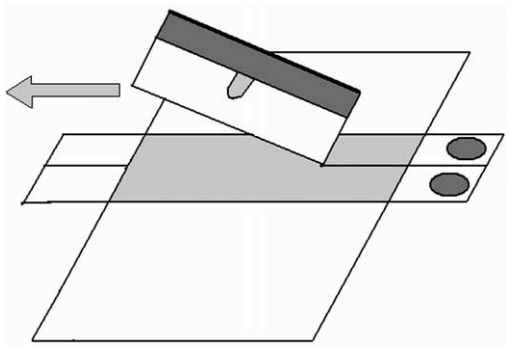

Fig. 3. Test method.

Table 1
Calibration sample 1: (conductance per m: assumed = 0.3346, optimized = 0.3346)

L (mm)	$R_{Experimental}$ (Ω)	$R_{Theoretical}$ (Ω)	L (mm)	$R_{Experimental}$ (Ω)	$R_{Theoretical}$ (Ω)
47	63.870	63.870	23.9	128.700	125.302
43.7	65.350	68.697	20.1	165.900	149.191
40.1	73.550	74.785	16.2	210.100	185.494
1.47	83.400	80.381	12.6	346.00	237.268
37.3	89.120	89.515	8.5	527.600	353.771
30.7	96.040	97.653	4.4	1512.00	686.974
27.4	109.100	109.407			

Table 2
Calibration sample 2: (conductance per m: assumed = 0.1693, optimized = 0.1693)

L (mm)	$R_{Experimental}$ (Ω)	$R_{Theoretical}$ (Ω)	L (mm)	$R_{Experimental}$ (Ω)	$R_{Theoretical}$ (Ω)
50.5	115.700	115.700	21.9	268.200	267.103
41.4	142.600	141.253	17.9	457.100	326.123
35.8	152.900	163.293	11.7	1340.00	498.361
31.0	178.200	188.724	6.9	5638.00	849.605
25.2	203.700	231.633	2.6	27600.00	2235.37

Table 3
Calibration sample 3: (conductance per m: assumed = 0.3937, optimized = 0.4409)

L (mm)	$R_{Experimental}$ (Ω)	$R_{Theoretical}$ (Ω)	L (mm)	$R_{Experimental}$ (Ω)	$R_{Theoretical}$ (Ω)
51.8	49.00	43.909	23.9	96.620	95.192
48.8	50.750	46.654	21.4	108.100	106.510
44.2	51.480	51.480	17.7	131.200	128.331
39.1	56.840	58.166	13.2	203.200	171.929
35.0	63.460	64.910	9.7	309.600	233.878
31.7	70.260	71.660	3.9	428.800	581.657
29.5	76.130	77.220	1.6	1692.00	1399.61
26.7	82.850	85.310			

Table 4
Calibration sample 4: (conductance per m: assumed = 0.3307, optimized = 0.3307)

L (mm)	$R_{Experimental}$ (Ω)	$R_{Theoretical}$ (Ω)	L (mm)	$R_{Experimental}$ (Ω)	$R_{Theoretical}$ (Ω)
51.3	59.140	59.146	24.9	173.800	121.788
44.9	63.580	67.500	21.6	218.900	140.558
44.5	66.180	68.271	19.1	280.400	158.875
41.1	70.740	73.750	17.5	346.600	173.528
38.8	73.180	78.088	15.2	385.500	199.124
37.3	77.380	81.275	12.6	476.800	239.908
34.5	85.500	87.849	9.9	630.800	307.923
32.8	94.390	92.616	7.0	1322.00	436.038
29.2	110.300	103.891	4.4	2871.00	682.710
27.2	141.400	111.658	2.0	47300.0	1493.43

the effect carbon paint thickness is reflected on the initial conductivity of each specimen. The data shows the good correlation between the experimental and theoretical values of electrical resistance

for various crack lengths. Deviations in the data from this formula represent variability in coating thickness. The estimated error from this process varies from 1% to 10%, depending on the length of the cut as compared to the remaining material.

3.3. Critical fracture load test

The carbon paint method was used to measure the crack growth in the adhesively bonded joints. Modified ASTM compact tension specimens were used to measure the crack growth in the adhesively bonded joints. The modified compact tension specimens made of brass and steel were split in two parts across their notch. The cut area was machined and sanded prior to joining them using a common two-part epoxy (Permatex Neat & Easy Epoxy, P/N 82725). Fig. 4 shows a split portion of the modified compact tension specimen used in the creep experiments. The thickness of the joint was maintained across the bond line using proper shims. Specimens with bond line thickness of 0.127–0.381 mm were manufactured for creep experiments, Fig. 5. The joints were sprayed with the carbon paint using the procedure outlined above. To perform a creep test, the critical failure load of specimens was determined by gradually loading them to failure. For specimens with bond-line thickness of 0.254 mm, the range of the critical fracture loads of the eight specimens was 756–1201 N with the average of 894 N. Despite all attempts to create a repeatable process, notable scatter in the data is apparent. This big range of failure load was due to different source of errors such as, the cure time and variability in bond properties from joint to joint. The average failure load for steel joint specimens was 311 N.

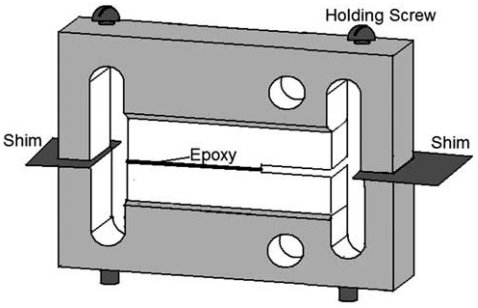

Fig. 5. Assembly of adhesive CTT specimen.

3.4. Creep test

The creep test was performed on brass–brass adhesively bonded compact tension specimens (ACTT) with bond-line thickness 0.254 mm. The specimens were incrementally loaded to 845 N, (95% of the average fracture load that was obtained experimentally), until a stable crack growth was observed. The crack growth was monitored by continuously measuring the electrical resistance of the carbon paint. Fig. 6 shows the crack length in the adhesively bonded joint as a function of time. The results show that creep crack growth in the adhesively bonded joints can be successfully measured using the carbon paint. The creep crack

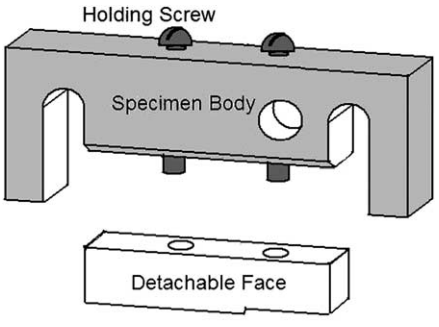

Fig. 4. Split half of the modified CTT specimen.

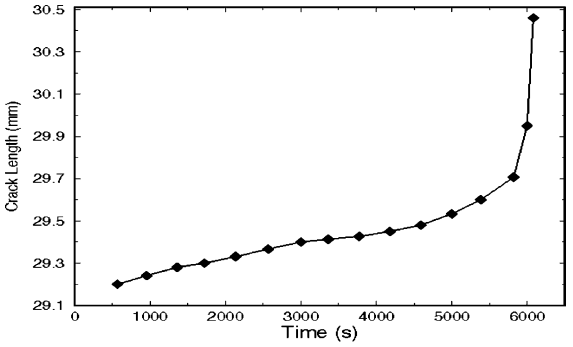

Fig. 6. Results of creep testing for brass–brass specimen.

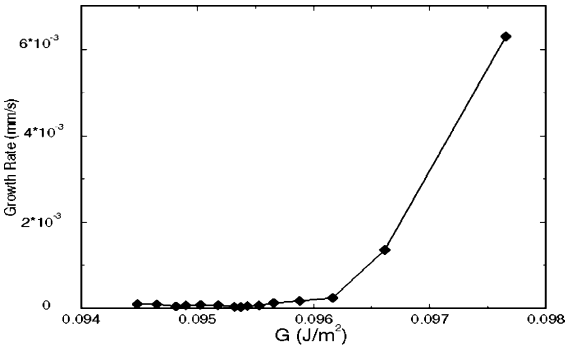

Fig. 7. Crack growth rate for brass–brass specimen.

growth rates were obtained from Fig. 6 and were related to the energy release rate G, Fig. 7. The energy release rate for crack growth in a compact tension specimens is defined as [16],

$$G = \frac{4P^2}{Eb^2}\left[\frac{3a^2}{h^3} + \frac{1}{h}\right] \tag{3}$$

where P is the applied load, a is the crack length, $2h$ is the compact tension specimen height, b is the specimen width and E is the elastic modulus of adherents. Chow et al. [17] have proposed a more accurate function for the energy release rate considering the adhesive thickness and properties. However, here we are interested in understanding the suitability of the carbon paint method for monitoring crack length rather than the crack driving force. Furthermore, Eq. (3) is recommended by the ASTM for the fracture toughness determination of the adhesively bonded joints [17].

The carbon paint method was also used to monitor creep crack growth in steel bonded joint with bond-line thickness of 0.254 mm. The joint was incrementally loaded to 245 N over five days. The period for each incrementally loading was 8 h. If a significant change in resistance was not observed, the applied load was increased and the specimen was left for another 8-h period. Once a crack growth was observed, the load was not changed any more. The creep crack growth was obtained under a constant load. It is possible that the crack was nucleating during the last incremental loading. However, here again we were interested in monitoring creep crack growth continuously and exploring the feasibility of carbon paint in monitoring the crack length. An introduction of a sharp notch to the epoxy could have expedited the joint failure. Figs. 8 and 9 shows the crack length versus time and crack growth rates versus the energy release rate.

The results provided in Figs. 6–9 show that the creep test data provided by this measurement technique is consistent and follows a recognized form of the creep crack growth law. Furthermore, the results suggest crack growth can be monitored accurately by the carbon paint method. Fractography of creep fracture surface showed that crack grow in the middle of the adhesive layer rather than at the interface of the joint. The

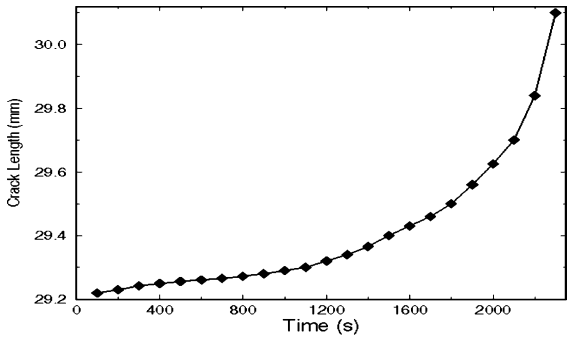

Fig. 8. Results of creep testing for steel–steel specimen.

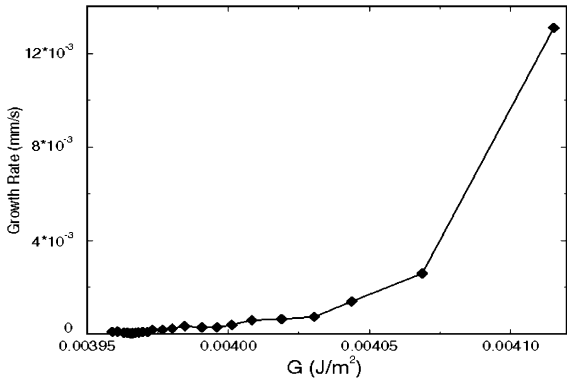

Fig. 9. Crack growth rate for steel–steel adhesively bonded specimen.

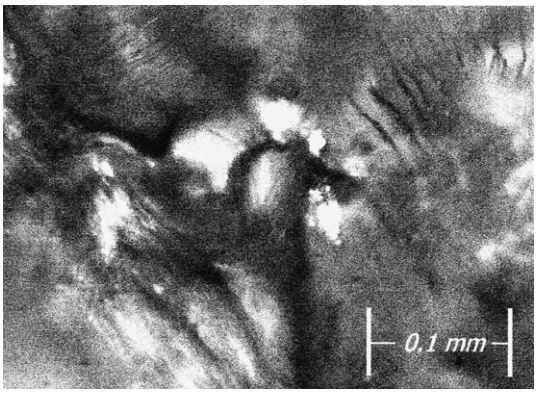

Fig. 10. SEM of the creep fracture surface of adhesively bonded joint, showing craze formation in the adhesive.

micro-mechanism of the crack growth seems to be by craze formations in the adhesive layer and linkage of the crazed regions, Fig. 10.

4. Conclusions

A carbon paint method is developed to measure crack growth in nonconductive materials and adhesively bonded joints. The crack growth could be easily measured through the changes in the electrical resistance of the carbon paint. This technique eliminates a required DC current supply used in the electrical potential drop method. The results show that carbon paint method is quite a sensitive method for crack growth measurements.

Carbon paint method is used to measure crack growth in adhesively bonded modified compact tension specimens subjected to creep loading condition. The results show that crack length could be measured continuously with the carbon paint method. The crack growth rate was related to the energy release rate. Micro-mechanisms of the crack growth were investigated using a scanning electron microscope. The results showed that crack grow in the middle of the adhesive rather than at the adhesive–adherent interface. The micro-mechanism of the crack growth was by craze formation and linkage of the crazed regions.

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