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The Effect of Material Property Gradient on the Fracture Toughness of a PMMA/PC Bimaterial with a Crack Normal to the Interface

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Abstract: Fracture toughness tests on CT specimens were carried out to study the fracture behavior for a crack lying perpendicular to the interface in a PMMA/PC bimaterial. Polymethylmethacrylate Acrylic (PMMA) and Polycarbonate (PC) cylindrical rods were joined together using the friction welding process. CT specimens were machined out of the bimaterial cylindrical rods. A sharp crack was introduced into the specimen perpendicular to and terminating at the bimaterial interface. Specimens including monolithic and bimaterial were loaded to fracture and experimental values of K_{IC} were obtained. Finite element analysis was used to find out the stresses in the specimens. Subsequently the stress values were used to find out the fracture toughness of each specimen. It was found that the K_{IC} values for bimaterial specimen could not be achieved by utilizing the inverse square root singularity in stress but it was dependent upon Dundurs parameters for bimaterials.

Key words: Bimaterials, interface, fracture toughness, friction welding, PMMA, PC, FGM, Dundurs parameters

INTRODUCTION

Numerous applications of bimaterials and functionally graded materials can be found in industry. One such example is the cladding used as an inner lining of nuclear pressure vessel walls where two materials are fused together using the explosion welding process. In the thickness of the wall a material properties gradient is generated, which is a topic pursued by many researchers regarding the possible failure due to the re-initiation of existing microcracks in the structures. Material property degradation due to environmental effects on the structures in service can also generate an unwanted material property gradient in the thickness direction of plate like structures. For a successful design and development of such structures it is important to have a detailed understanding of their failure process.

To study the behavior of bimaterials regarding their ability to avoid fracture failure, it is required to make proper specimens that can be tested in the laboratory. Friction welding is one of the joining processes in which two similar or dissimilar materials can be bonded together. Compared to other welding processes, friction welding is a comparatively cleaner process with a minimum heat affected zone generated at the joint. Moreover, the material property gradient that results because of friction welding can be used to study the behavior of functionally graded materials regarding their failure. Towards this end, friction welding was adopted in this study to join two polymeric materials to obtain a bimaterial joint.

The crack initiation predictions for homogeneous materials can easily be made by using the standard test methods available. However when a crack is lying in an inhomogeneous material whether it be a combination of only two materials (bimaterial) or when the material properties vary within the thickness, width, or length of the material, no standard procedure is yet available to predict the stress intensity factor reliably. The purpose of this study is to address this issue by establishing a failure criteria for bimaterials or functionally graded materials. To achieve this objective, a large number of specimens were tested. The technique developed during this research would be very helpful for further studies on the failure of bimaterials and functionally graded materials.

Similar studies have been conducted by other researchers where a crack is lying in a bimaterial and is perpendicular to the interface. Kolednik[1] performed studies that were more closely related to the present

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research but those studies could not predict the local fracture properties near a bimaterial interface. Kim *et al.*[2] compared the J-Integral variation at the crack tip of a homogeneous and inhomogeneous material using a global approach with a conclusion that if the ratio of J-Integral obtained for bimaterial and a homogeneous material was larger than 1.0 then it signaled that the crack driving force was higher than for the homogeneous material. Effect of constraint ahead of the crack tip due to the presence of a second material was also studied. The plane stress case was addressed more closely, while in the present research the specimens used essentially depicted a plane strain condition. The finite element studies on FGM made by Marur *et al.*[3] showed that as the material gradient in an FGM increased, it behaved more like a bimaterial. This also supports the approach adopted in the present research where the location of the crack tip in a material gradient region does not have any profound effect on the SIF but it is the severity of the gradient itself which is responsible for the resulting SIF values. Chang *et al.*[4] have also studied this problem, but the contour integrals developed show that the results are focused on mode II dominance while the experimental work done in the present research is essentially for mode I.

The work by Simha *et al.*[5] and the references quoted by them show that a large group of researchers have found that SIF increases significantly in cases where elastic modulus E ahead of the crack tip reduces gradually in an FGM. The elastic modulus of PMMA and PC studied in the present research has very little variation, therefore the results may not be comparable[8]. Simha *et al.*[5], Jiang *et al.*[6] have addressed a similar problem but their focus was on fatigue crack propagation, however, encouraging similarities can be found thereby verifying the present research. Effects of temperature gradient on the K_{IC} values of the materials under study have been reported by Shah *et al.*[7].

Similar work has been done by Lahiri *et al.*[9] where they proposed a solution for fracture toughness using finite element-boundary element alternating method for known values but the method is very complicated. Kang Yilan *et al.*[10] reported results for mixed mode loading regarding the near-tip displacement fields. Chen *et al.*[11] presented the analytical results for a crack perpendicular to the bimaterial interface in finite solid. They found that when the crack is within a weaker material, the stress intensity factor is smaller than that in a homogeneous material and vice versa. Their results support the present investigation strongly. Chang *et al.*[12] have reported the results of calculations for mixed mode stress intensity using contour integrals. Alberto Romeo *et al.*[13] have proposed a cohesive zone model for cracks terminating at a bimaterial interface for small scale yielding and large scale yielding using Dundurs parameters[15].

MATERIALS AND METHODS

Tensile specimens of PMMA and PC were made according to ASTM E8M to conduct the tension tests. CT specimens were made according to ASTM standard E 1820-01. Thickness for all the CT specimens was maintained at 20 mm to ensure the plane strain condition. Figure 1 shows the CT specimen sketch.

Tensile tests were carried out on PMMA and PC specimens to establish yield strength, elastic modulus, Poisson's ratio and % elongation. The fracture toughness tests on monolithic-material CT specimens were carried out. The results for both materials are shown in Table 1. It is observed that the yield strength differs by 40% in the two materials. From percentage elongation results PMMA can be considered as a brittle material.

Brinell hardness variation in the bimaterial CT specimen is shown in Fig. 2.

Fracture tests on the bimaterial CT Specimens: Fracture tests on PMMA and PC specimens were performed to establish the stress intensity factors for crack initiation in these materials using K_{IC} formula given in the ASTM standard E 1820-01. Averaged values of K_{IC} are given in Table 1. Further tests were carried out on the bimaterial specimens to find out the fracture toughness values for a crack lying normal to the interface. The K_{IC} values for bimaterial specimens were recorded according to ASTM standard formula given in ASTM E 1820-01.

RESULTS AND DISCUSSION

In Table 2 the fracture toughness results from tests on CT specimens for two monolithic materials namely PMMA and PC and two bimaterials PMMA-PC and PC-PMMA are shown. It was found that the average fracture toughness value of PMMA falls in the range of 1.23 MPam, while the fracture toughness value of PC is about 2.86 MPam. Moreover when the crack travels from PMMA to PC the fracture toughness is always above 3.0 Mpa √m, while for a crack direction of PC to PMMA its value is only 50% of the former. Some higher values in this category are the result of data scatter.

Finite element analysis of the CT specimens: Finite Element Analysis on the CT specimens were performed to find out the stresses in the specimen. The FEM model of the one half of CT specimen is shown in Fig. 3.

Table 1. Material Properties of PMMA and PC

Material	Poisson's ratio	Elastic modulus (GPa)	Yield strength (MPa)	Elongation at break (%)	Hardness (HRB)	Fracture toughness (MPa√m)
PMMA	0.35	3.3	87	4	24.58	1.35
PC	0.37	2.4	52	100~150	12.45	2.96

Table 2: Fracture toughness results for two monolithic materials PMMA and PC. Fracture toughness results for two bimaterials PMMA-PC and PC-PMMA

SPEC#	a (m)	W (cm)	Load P (N)	a (cm)	b (cm)	P (kN)	a/W	f (a/W)	K (Mpa $m^{0.5}$)
			PMMA/PC						
1	0.0198	4	1430.8	1.98	2.02	1.43	0.495	9.512	3.36
2	0.0189	4	1791.44	1.89	2.02	1.79	0.4725	8.894	3.94
3	0.0191	4	1362.2	1.91	2.02	1.36	0.4775	9.026	3.04
4	0.0198	4	1561.924	1.98	2.02	1.56	0.495	9.512	3.67
5	0.0189	4	1423.94	1.89	2.02	1.42	0.4725	8.894	3.13
6	0.0194	4	1822.8	1.94	2.02	1.82	0.485	9.229	4.16
7	0.0198	4	1470	1.98	2.02	1.47	0.495	9.512	3.46
9	0.0195	4	1561.14	1.95	2.02	1.56	0.4875	9.298	3.59
21	0.0194	4	1446.48	1.94	2.02	1.44	0.485	9.229	3.30
25	0.0186	4	1484.7	1.86	2.02	1.48	0.465	8.703	3.19
27	0.0194	4	1568.98	1.94	2.02	1.56	0.485	9.229	3.58
29	0.0185	4	1309.182	1.85	2.02	1.30	0.4625	8.641	2.80
32	0.0179	4	980	1.79	2.02	0.98	0.4475	8.281	2.00
33	0.0196	4	887.88	1.96	2.02	0.88	0.49	9.369	2.05
34	0.0186	4	1450.4	1.86	2.02	1.45	0.465	8.703	3.12
35	0.0195	4	1391.6	1.95	2.02	1.39	0.4875	9.298	3.20
37	0.019	4	1476.86	1.9	2.02	1.47	0.475	8.960	3.27
38	0.0179	4	1038.8	1.79	2.02	1.03	0.4475	8.281	2.12
43	0.0191	4	1323	1.91	2.02	1.32	0.4775	9.026	2.95
			PC/PMMA						
8	0.0195	4	642.88	1.95	2.02	0.64	0.4875	9.298	1.47
10	0.0194	4	566.538	1.94	2.02	0.56	0.485	9.229	1.29
11	0.0193	4	596.82	1.93	2.02	0.59	0.4825	9.161	1.35
12	0.0193	4	735	1.93	2.02	0.73	0.4825	9.161	1.66
13	0.0196	4	695.8	1.96	2.02	0.69	0.49	9.369	1.61
14	0.0197	4	642.88	1.97	2.02	0.64	0.4925	9.440	1.50
15	0.0195	4	1225	1.95	2.02	1.22	0.4875	9.298	2.81
16	0.0186	4	1576.82	1.86	2.02	1.57	0.465	8.703	3.39
22	0.0195	4	887.88	1.95	2.02	0.88	0.4875	9.298	2.04
23	0.0193	4	703.64	1.93	2.02	0.70	0.4825	9.161	1.59
24	0.0185	4	1871.8	1.85	2.02	1.87	0.4625	8.641	4.00
26	0.0185	4	1868.174	1.85	2.02	1.86	0.4625	8.641	3.99
28	0.019	4	642.88	1.9	2.02	0.64	0.475	8.960	1.42
36	0.0192	4	921.2	1.92	2.02	0.92	0.48	9.093	2.07
39	0.0193	4	519.4	1.93	2.02	0.51	0.4825	9.161	1.17
40	0.0189	4	1423.94	1.89	2.02	1.42	0.4725	8.894	3.13
41	0.0195	4	1675.8	1.95	2.02	1.67	0.4875	9.298	3.85
42	0.0181	4	2214.8	1.81	2.02	2.21	0.4525	8.398	4.60
			PMMA						
19	0.0193	4	596.82	1.93	2.02	0.59	0.4825	9.161	1.35
20	0.0191	4	497.644	1.91	2.02	0.49	0.4775	9.026	1.11
			PC						
17	0.0192	4	1316.14	1.92	2.02	1.31	0.48	9.093	2.96
18	0.0194	4	1209.32	1.94	2.02	1.20	0.485	9.229	2.76

The stress in Y-direction that is perpendicular to the crack plane at a small distance ahead of the crack tip is shown in Fig. 4. When the stress ahead of the crack tip is known, the fracture toughness can be calculated using the following formula.

$$K_{IC} = \sigma_y \times (\sqrt{2 \Pi r}) \quad (1)$$

Using this expression the fracture toughness values that closely agree with the experimental results can be obtained. But it was found that this expression can not be used to calculate the fracture toughness for bimaterial specimens.

To calculate the fracture toughness that agrees with the experimental results the expression proposed by Cook and Erdogan[14] was successfully used which is given here.

$$K_{IC} = \sigma_y \sqrt{2}\, r^{1-\lambda} \quad (2)$$

This is because the inverse square root singularity does not hold valid for bimaterial fracture process. Here

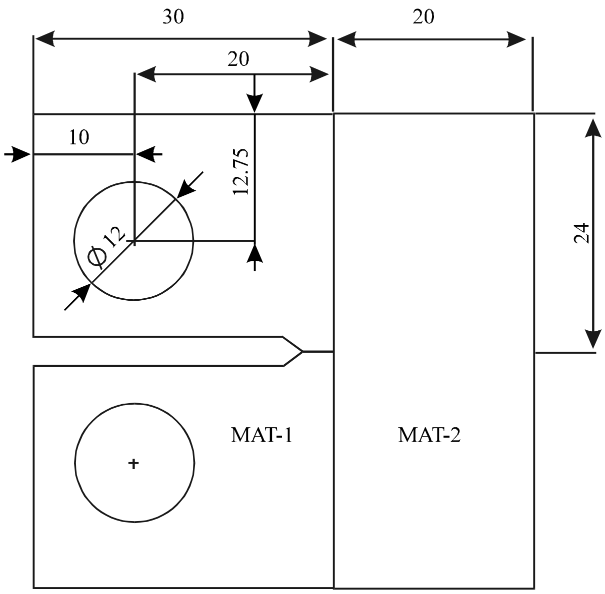

Fig. 1: The bimaterial CT specimen

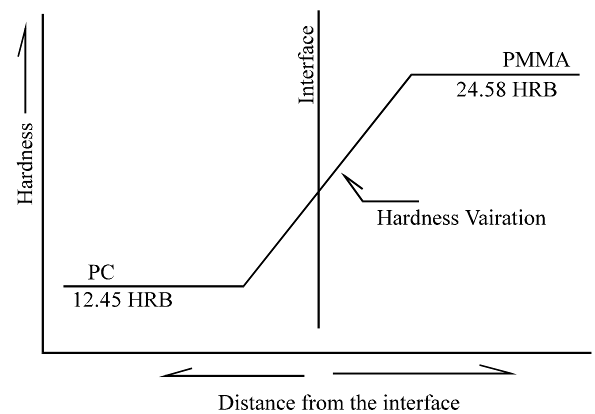

Fig. 2: Hardness variation near the interface of PMMA and PC specimens

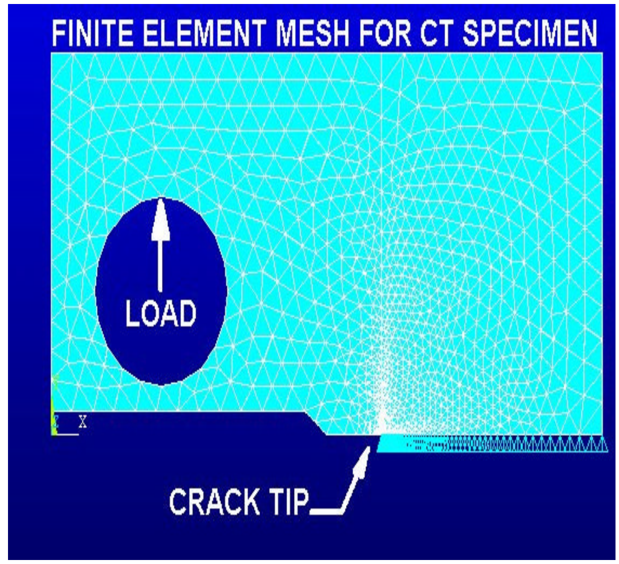

Fig. 3: Half model of CT specimen used for finite element analysis

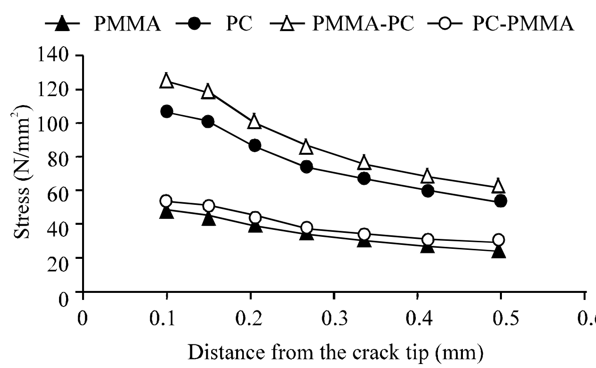

Fig. 4: The nodal stress in Y-direction ahead of the crack tip for four cases (a) PMMA, (b) PC, (c) PMMA to PC crack propagation, (d) PC to PMMA crack propagation

depends on the Dundurs parameters α and β. To find out λ the following equation[16] was solved numerically. The values of λ for which the equation becomes zero is also shown in Fig. 5.

$$\cos(\Pi\lambda) + \frac{2(\alpha-\beta)}{1+\beta}(1-\lambda^2) - \frac{\alpha+\beta^2}{1-\beta^2} = 0 \qquad (3)$$

For the combination of two materials PMMA and PC the λ was found to be 0.85. Therefore when using equation (2), the value for (1-λ) will be 0.15.

As an example the fracture toughness for a monolithic and bimaterial would be shown based upon equations (1) and (2). The fracture toughness values obtained from the stress ahead of the crack tip within a distance of (0.0~0.498) mm for monolithic and bimaterials are shown in Fig. 6.

For a crack travel direction from PMMA to PC the experimental K_{IC} value is 3.36 MPa$\sqrt{m}$ while the K_{IC} obtained from numerical and analytical work is 3.52 MPa$\sqrt{m}$. In case of PC to PMMA crack travel direction both experimental and analytical values are same (1.50 Mpa$\sqrt{m}$).

In Fig. 6 the fracture toughness values obtained from stress values based on equations (1) and (2) are plotted. For monolithic materials the fracture toughness is nearly constant but for bimaterials a variation can be seen. The

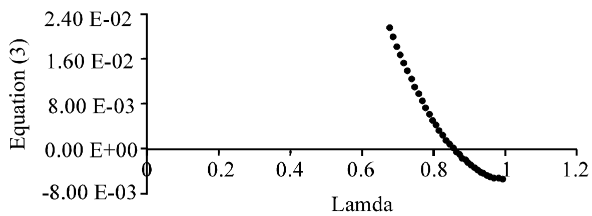

Fig. 5: Result of numerical calculation for λ (=0.85)

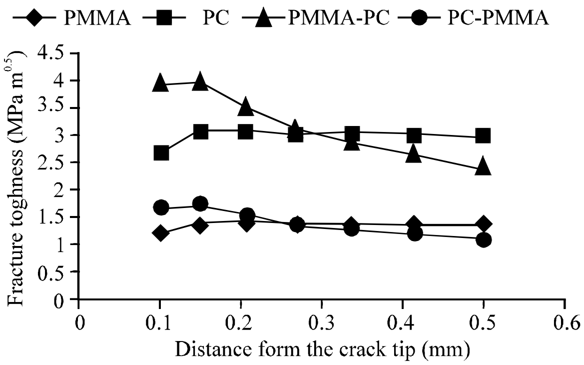

Fig. 6: The fracture toughness values obtained from stress values ahead of the crack tip. Fracture toughness of PMMA-PC (bimaterial) specimen is about 3.52 MPa√m. PC-PMMA (bimaterial) fracture toughness is about 1.50 Mpa√m

region where the monolithic and bimaterial K_{IC} lines cross each other and the bimaterial curve starts rising to the left shows the true fracture toughness for the bimaterials (at a distance of 0.206 mm from the crack tip). When observing the stress values in Fig. 4, a regular variation can be seen for all four cases but the fracture toughness results in Fig. 6 show a difference for the bimaterials specimen. The difference is not very significant due to the fact that the elastic modulii for the materials tested were close to each other. The observed change can be attributed to the fracture toughness formula used where instead of $r^{½}$,$r^{1-\lambda}$ values are used.

CONCLUSIONS

PMMA and PC materials were joined using friction welding process to manufacture the bimaterial CT specimens. Fracture toughness tests on CT specimens were made to study the crack initiation fracture toughness for monolithic and bimaterial specimens. Fracture toughness results from the experimental data were confirmed using the stress values ahead of the crack tip obtained by finite element analysis.

From the results of experimental work and numerical analysis following conclusions were made:

The fracture toughness can be calculated using equation (1) for monolithic materials while equation (2) gives the correct results for bimaterials and it is based upon the Dundurs parameters proposed by Cook and Erdogan[14]. λ was found to be 0.85 for the bimaterials tested in the present work.

The material ahead of the crack tip plays an important role to determine the fracture toughness of bimaterials.

Fracture toughness enhancement in bimaterial specimen when the material ahead of the crack tip is tougher is contributed by the higher toughness of the material ahead of the crack tip with an additional effect of the interface constraint.

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