**THE INFLUENCE OF BOND LINE THICKNESS AND PEEL ARM THICKNESS
ON ADHESIVE FRACTURE TOUGHNESS OF METAL POLYMER
LAMINATES**

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ABSTRACT

The adhesive fracture toughness (G_A) of metal polymer laminates is studied using two types of peel test, namely fixed arm peel and roller assisted mandrel peel. In the fixed arm tests, the peel angle is varied in the range 45° to 135° and in the mandrel peel experiments, the mandrel roller size is selected in order to ensure conformance of the peel arm to the roller during fracture.

The principal aims of the study are two fold:

- (i) To investigate the influence of adhesive bond line thickness on G_A .
- (ii) To investigate the influence of peel arm thickness on G_A .

The peel crack growth experiments were complemented with measurements of cohesive fracture toughness using tapered double cantilever beam geometry with a range of values for bond line thickness.

Throughout the work, it is important to identify the mode of peel fracture and in particular to establish whether the peel cracks are cohesive (propagating in the adhesive) or interfacial (propagating at the interface between adhesive and substrate).

To this effect, confocal laser scanning microscopy was used in order to study the peel arms after testing and to measure the thickness of adhesive coating on the peel arms.

The experimental work was conducted on a wide range of laminates where two adhesives with a common substrate were employed.

KEYWORDS

Adhesive fracture toughness, peel tests, fixed arm peel, mandrel peel, bond line thickness, peel arm thickness, substrate material, cohesive fracture, interfacial fracture, confocal microscopy, adhesive joints.

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1 INTRODUCTION

The paper is a continuation of our work related to the measurement of adhesive fracture toughness from peel tests. In early work, the focus was on converting measurements of peel strength (peel force, P , divided by specimen width, b) into values of adhesive fracture toughness (G_A) [1, 2]. This was achieved by calculation of the amount of plastic bending energy (G_P) in a peel arm (for example via *ICPeel* software [3]) and subtracting it from the external work (G) required in the peel fracture process.

$$G_A = G - G_P \quad (1)$$

Later work focused on test methods in order to examine the geometry dependence of adhesive fracture toughness [4 -7]. In particular, a roller assisted peel test, known as mandrel peel, was developed from ideas presented by earlier workers [8, 9].

The current focus relates to material aspects of the peel behaviour of metal polymer laminates. These include the thickness of the adhesive (the bond line thickness, h_a), the choice of adhesive and thickness of a common substrate (peel arm thickness, h). All of these parameters are explored in this work and their influence on the ensuing adhesive fracture toughness is investigated.

2 MATERIALS AND EXPERIMENTAL METHODS

2.1 Materials

Several combinations of epoxy adhesive and aluminium alloy substrate (AA) were used in this study. The laminates are detailed in Table 1 and include two different adhesives and a range of values for bond line and peel arm thickness. Each AA 5750-O substrate received a surface treatment, namely degreasing and then a chromic acid etch.

The bond-line thickness values are nominal and are based on the set thickness i.e. the wire diameter that was used to establish that particular thickness value. Although attempts were made to measure bond line thickness by other methods, for example by subtracting the combined substrate thickness from the laminate thickness, these approaches were found to be inaccurate. The small variations in substrate thickness thwarted such an approach.

Sample	Adhesive	Substrates	Peel arm thickness (h) (mm)	Bond line thickness (h_a) (mm)	Dimensions of peel arm (mm)
ESP 110/ 5754-0	<i>ESP110</i> (rubber-toughened epoxy paste adhesive, general purpose)	AA 5754-O	0.50, 1.0, 1.5	0.10, 0.25, 0.40	15 × 200 (15 × 180)
XD4600/ 5754-0	<i>XD4600</i> (rubber-toughened epoxy paste adhesive, automotive applications)	AA 5754-0	0.50, 1.0, 1.5	0.10, 0.25, 0.40	15 × 350 (15 × 300)

Table 1 Details of laminates.

2.2 Experimental methods

Peel measurements involved two methods; fixed arm peel [4] and mandrel peel [5]. In addition, there were some cohesive fracture toughness measurements using a tapered double cantilever beam method (TDCB) [4, 6]. All test methods are fully described elsewhere [4- 6]. Fixed-arm and mandrel peel experiments were conducted on an Instron universal testing machine. In all cases the crosshead speed was adjusted in order to give a constant 5mm/min crack growth rate, and tests were performed at standard air conditions (21°C, 55% RH). Data were collected over lengths of at least 50 mm, and at least three specimens were tested per sample.

In the peel tests, the main aim was to measure G_A although G_P was also either calculated using *ICPeel* software [3] or determined experimentally, as in the mandrel peel method. Results for adhesive fracture toughness (and cohesive fracture toughness) are in the form of plots of G_A versus D/b . D/b is an alignment force per width of peel specimen from a mandrel test [5]. The width of the mandrel specimen is 15 mm. Fixed arm peel results and cohesive fracture toughness (from TDCB) can be included on these plots as horizontal lines.

ICPeel software is based on the analysis detailed in references 1 and 2. It is used to calculate G_P from knowledge of the tensile stress-strain behaviour of the peel arm material. During these calculations, *ICPeel* also provides a value of the radius of curvature (R_0) of the peel arm at the point of peel fracture.

A simple measurement error analysis can provide a view of experimental accuracy. For the fixed arm method, G is based on two measurements, force (error 1%) and angle (error 1°) where the total error is about 2.5%. G_P is based on a calculation where input parameters from modelling the tensile stress-strain behaviour of the peel arm can lead to an error of about 2%. In the mandrel peel method, both G and G_P are experimentally determined. A bonded specimen is used for the measurement of G where the error in force is 1% with an additional 2 % error associated with conformance to the mandrel roller and alignment of the specimen leading to a 3% error in G . An unbonded specimen is used for the measurement of G_P where the only significant error is in the force measurement and is estimated at 1%, leading to a 1% error for G_P . Therefore if G were measured as 10 kJ/m² and if G_P were at 8 kJ/m² then the associated errors in a fixed arm test would be ± 0.25 kJ/m² and ± 0.16 kJ/m², respectively leading to an error in G_A of ± 0.410 kJ/m². If these data related to mandrel peel, then the associated errors would be ± 0.30 kJ/m² and ± 0.08 kJ/m²

respectively, giving an error in G_A of $\pm 0.38 \text{ kJ/m}^2$. Consequently, similar experimental errors are anticipated for G_A by either method.

The peel arm has a coated layer of adhesive after the peeling process. Several approaches have been tried in order to obtain a value of the adhesive coating thickness (t). Table 1 summarises the range of bond line thickness values where the maximum is $400 \text{ }\mu\text{m}$ although it can be as small as $100 \text{ }\mu\text{m}$. The adhesive coating will be a fraction of the total bond line thickness and values in the range $(10 \text{ to } 70) \text{ }\mu\text{m}$ can be anticipated. A simple micrometer will indent the adhesive and lead to a value of t that is too small. Scanning laser profilometry has also been attempted, but because the peel arm is severely curved after testing, it was difficult to identify a reference for the curvature and hence obtain an accurate value for t . A more accurate value of t was obtained with confocal laser scanning microscopy where a variable wavelength light source could be used to identify the depth difference between fluorescence from the metal to fluorescence from the top surface of the adhesive. Although this procedure was excellent for obtaining a scanned image of the peel arm, it was only indicative for a measurement of adhesive coating thickness since this was determined at a single and small location. The limitations of these indicative thickness measurements are discussed in Appendix I and lead to a view that each indicative measurement of t is a value from some normal distribution where the coefficient of variation is about 50%. Confocal microscopy and the attempts with laser profilometry were conducted by ICI plc Measurement Science Group (Wilton, UK).

3 RESULTS AND DISCUSSION

3.1 Preamble

Results will be presented from both fixed arm peel and mandrel peel experiments. Two principal investigations will be reported. First, an investigation of the influence of bond line thickness where two different adhesives (XD4600 and ESP110) are the subjects of the studies. Second, an investigation of peel arm thickness with adhesive XD4600.

3.2 The influence of bond line thickness for XD4600.

3.2.1 Fixed arm peel results for Imm AA 5754-0/XD4600

Three different adhesive bond lines of nominal thickness $100\mu\text{m}$, $250\mu\text{m}$ and $400\mu\text{m}$ were used in this study. Fixed arm peel measurements were conducted at three peel angles (45° , 90° and 135°). All peel fractures were cohesive since a layer of adhesive could be seen on the peel arm after testing. In Figure 1 results for the laminate of bond line thickness $250\mu\text{m}$ are shown where total external energy to peel (G), plastic bending energy (G_P) and adhesive fracture toughness (G_A) are plotted against peel angle. Adhesive fracture toughness is determined by subtracting the plastic bending energy (G_P) from the applied total external energy (G) as shown in equation 1. G is calculated from peel strength (peel force P divided by specimen width b) and the peel angle θ using equation 2:

$$G = \frac{P}{b}(1 - \cos \theta) \quad (2)$$

For the fixed arm peel tests, G_P is calculated from *ICPeel* [3] where parameters from a tensile stress-strain curve on the peel arm are required. Two possible functions are used in *ICPeel* [3] to model the stress-strain curve, namely a bilinear function or a linear elastic- power law plastic function. Although there is little difference in terms of the calculated value of G_P , we have usually employed the bilinear function, where elastic modulus is E , yield stress is σ_y , yield strain is ε_y and the slope of the linear plastic region is α . Table 2 summarises the tensile stress-strain results for the peel arms with a bilinear fit. (These data are used for analysis of all fixed arm results, including those with adhesive ESP110).

Peel arm material	E (GPa)	σ_y (MPa)	ε_y (%)	α
AA 5754-O	69	108	0.160	0.027

Table 2: Tensile stress-strain data for peel arm material.

With reference to Figure 1 it can be seen that, as expected, both G and G_P are strongly dependent on peel angle whilst G_A seems independent of peel angle. However, detailed investigation of the relationship between G_A and peel angle does show a small dependence, where G_A becomes smaller with increasing peel angle. Nevertheless, this trend lies within the expectations of experimental error for G_A . Also included in Figure 1 is a micrograph of the peel arm of the 135° fixed arm peel specimen (F135°) using confocal laser scanning microscopy where an indicative thickness of the adhesive layer is measured as 30µm.

Figure 1: Fixed arm peel results for 1mm AA 5754-0/XD4600 of bond line thickness 250 µm.

The results in Figure 1 are typical of all fixed arm data for the 1 mm AA 5754-0/XD4600 laminates. Table 3 summarises the mean values of G_A with their standard deviations and the indicative measurements of adhesive coating thickness from

confocal microscopy. The experimental error associated with these values of G_A would be $\pm 400 \text{ J/m}^2$ (as previously discussed).

Nominal bond line thickness (μm)	Adhesive fracture toughness (G_A) (kJ/m^2)	Adhesive coating thickness on peel arm (μm)
100	2.60 (0.10)	30
250	2.64 (0.02)	30
400	2.68 (0.03)	35

Table 3 Fixed arm peel results for 1mm AA 5754-0/XD4600 laminates. Standard deviations are in parenthesis.

The fixed arm peel results in Table 3 suggest no influence of bond line thickness on G_A , and all fractures would seem to be cohesive, implying that the crack runs in the adhesive.

The indicative thickness measurements of adhesive coating on the peel arm after the peel tests are quite small in comparison with the bond line thickness. Remembering that such indicative thickness measurements are part of a normal distribution where the coefficient of variation is about 50%, then it can be imagined that parts of the adhesive coating are much thinner than the indicative measurements. In any case, the peel fractures are highly asymmetric.

3.2.2 Mandrel peel results for 1mm AA 5754-0/XD4600

The laminates of 1mm AA 5754-0/XD4600 for the three different values of bond line thickness were also used in mandrel peel experiments. The choice of mandrel roller radius was varied in the experimental approach and rollers selected such that conformance of the peel arm to the mandrel roller occurred during the peel process. In general, this was achieved when the maximum value of peel arm curvature, R_o (which was calculated from *ICPeel* during the processing of the fixed arm results) was equal to or larger than the radius of the mandrel roller, R_l .

Figure 2: Mandrel peel results together with fixed arm peel for 100 μm bond line thickness for 1 mm AA 5754-O/XD4600. The TDCB data are for a 250 μm bond line thickness.

All peel fractures were observed to be cohesive in the mandrel peel experiments. Results for the three different values of bond line thickness are shown in Figures 2-4 and included in these figures are micrographs of the peel arms using confocal microscopy, where again indicative values of adhesive coating thickness on the peel arm are given.

Figure 3: Mandrel peel results together with fixed arm peel for 250 μm bond line thickness for 1 mm AA 5754-O/XD4600. The TDCB data are for a 250 μm bond line thickness.

Each of the graphs in Figures 2-4 include mandrel peel data in the form of G_A plotted against alignment load per specimen width. Also included are the mean values of G_A from fixed arm peel together with the cohesive fracture toughness from a TDCB test (with values of bond line thickness of 250 μm and 400 μm). Since all peel fractures are cohesive, it is to be expected that the G_A values from mandrel and fixed arm peel should show agreement and that these values should show agreement with the G_C value from TDCB. In fact, this is the case for the data in Figures 3 and 4. However, the mandrel test results for the 100 μm bond line thickness are well below that for G_C from TDCB and G_A from fixed arm peel.

We have no convincing explanation for the low values of G_A observed from the mandrel test for the 100 μm bond line laminates. However, such low G_A values would imply that the peel cracks are growing in a thin but variable layer of adhesive adjacent to the peel arm (despite our observation of a coating on the peel arm). The indicative thickness measurements of adhesive coating are not different for all three laminates systems, although they are small and asymmetric peel cracks are occurring. However, since the coating thickness is small and has a 50% coefficient of variation associated with the measured t , then it is possible for interfacial fractures to be included in the mandrel tests. An alternative but speculative explanation might relate to bond line thickness variations associated with the 100 μm laminates but there is no evidence for this.

Figure 4: Mandrel peel results together with fixed arm peel for 400 μm bond line thickness for 1 mm AA 5754-O/XD4600. The TDCB data are for a 400 μm bond line thickness.

3.2.3 Discussion of bond line thickness results for AA 5754-0/XD4600

Figure 5 summarises all values for G_A (from fixed arm and mandrel peel) plotted against bond-line thickness (h_a); measurement error bars are also included on this plot.

The dependence of adhesive toughness on bond line thickness is perhaps not apparent from the results in Figure 5; the fixed arm data show independence whilst the mandrel data suggest dependence. Inclusion of the error bars hints that within experimental error there might be a case for G_A being independent of bond line thickness, but the case is not entirely convincing!

Figure 5: Summary of G_A values for 1 mm AA 5754-0/XD4600 plotted against bond line thickness and including measurement error bars.

Other workers have reported some evidence of low G_A values at decreasing bond line thickness [10, 11]. Their explanation hinged around an inability for the plastic zone ahead of a crack to fully develop when h_a is too small. This would lead to low values for G_A . It would therefore be helpful to examine the dependence of G_C on bond line thickness from TDCB measurements. Unfortunately, practicality prevents a full range of bond line values to be explored. Nevertheless, some additional data are shown in Figure 6 together with the G_A results from the peel tests.

Previous work [11] suggests that a peak in toughness versus bond line thickness can be expected when twice the plane stress linear elastic fracture mechanics value of plastic zone radius (r_P) equals the bond line thickness:

$$r_P = \frac{1}{2\pi} \left(\frac{EG_C}{\sigma_Y^2} \right) \quad (3)$$

Figure 6: Toughness (G_A or G_C) from peel tests and TDCB tests as a function of bond line thickness for adhesive XD4600

Adhesive XD4600 has a modulus (E) of 3.7 GPa, yield stress (σ_Y) of 47 MPa and G_C of 3.05 kJ/m² giving a value of h_a of 1.5 mm for maximum toughness. The relationship between toughness and bond line thickness will show smaller values of toughness at $h_a < 1.5$ mm. This is consistent with the data in Figure 6 to within experimental error. However, other work [10] indicates that the shape of the plastic zone at small bond line thickness is not that described by equation 3. Therefore, although the trends of the data in Figure 6 are acceptable, the fine detail is difficult to confirm. Nevertheless, cohesive fracture from TDCB tests align with cohesive fractures from peel tests, even when the adhesive coating thickness on the peel arm is very small.

3.3 Effect of bond line thickness for ESP110

3.3.1 Fixed arm peel results for 1mm AA 5754-0/ESP110

1 mm AA5754-0/ESP110 laminates were prepared at three nominal values of bond line thickness, 100µm, 250µm and 400µm. Fixed arm measurements were conducted at a similar range of peel angles, although only the averaged results from the 90° peel tests are included. As with the previous fixed arm results, there was a small reduction in G_A with increasing peel angle, although the trend lay within experimental error. All fractures were cohesive with an indicative adhesive coating of 65µm; this amounts to a noticeable covering of adhesive on the peel arm as seen after the tests. Results are shown in Figure 7 and include micrographs from confocal microscopy and a value of G_C from a TDCB test with a bond line thickness of 400 µm. The error bands relate to measurement errors of ± 0.33 kJ/m².

It is clear that G_A is independent of bond-line thickness to within the errors of measurement and that the G_A values from fixed arm peel are in agreement with cohesive fracture toughness from TDCB tests with a bond line thickness of 400 μm .

Figure 7: Adhesive fracture toughness plotted against nominal bond line thickness for 1 mm AA 5754-0/ESP110 laminates from 90° fixed arm peel tests. Confocal microscopy images include indicative adhesive coating thickness measurements. The TDCB result relates to a bond line thickness of 400 μm .

3.3.2 Mandrel peel results for 1mm AA 5754-0/ESP110

Mandrel peel measurements were conducted on all three laminates for different values of bond line thickness. Again all three exhibited cohesive fractures. Typical results are shown in Figure 8 and indicate that G_A from the mandrel peel test agrees with G_A from fixed arm peel. Moreover, there is agreement between G_C (from TDCB) and G_A from peel. In all cases, the mandrel roller radius was selected so that conformance of the peel arm was achieved during peel.

Bond line thickness (μm)	Average G_A from mandrel peel test (kJ/m^2)
100	0.88 (0.04)
250	0.83 (0.11)
400	0.91 (0.11)

Table 4 Average G_A values from mandrel peel (with standard deviations in parenthesis) for 1mm AA 5754-0/ESP110 at three different bond line thicknesses.

The degree of scatter in the mandrel results did vary and average values were selected (with their standard deviations) in order to explore the relationship between G_A and bond line thickness. Table 4 shows these values.

Figure 8: Mandrel peel results for 1 mm AA 5754-O/ESP110 with bond line thickness 100 µm plotted in the form of G_A versus D/b together with fixed arm peel and G_C from TDCB with a bond line of 400 µm.

The scatter in the mandrel data is indicated by the magnitude of the standard deviation in Table 4. However, G_A would seem to be independent of bond line thickness.

3.3.3 Discussion of results for the effect of bond line thickness for ESP110 laminates.

The combined results from fixed arm peel and mandrel peel are plotted against bond line thickness for all laminate samples in Figure 9. In addition, results of cohesive fracture toughness measurements from TDCB tests with bond line thickness values in the range 0.25mm to 0.9 mm are also included.

A maximum value of toughness (on linear elastic fracture mechanics (LEFM) grounds and according to equation 3) should occur at h_a equal to about 0.6 mm. For ESP110, $E = 4$ GPa, $\sigma_Y = 50$ MPa and $G_C = 1.05$ kJ/m². Consequently, according to LEFM, for lower values of h_a , toughness should decrease. The data in Figure 9 could be imagined to fit this trend, although this is not completely clear. However, the general agreement between toughness from the peel tests and the TDCB tests is good.

There would seem to be little dependence on bond line thickness for the range investigated in our experiments. However, it is apparent that for cohesive fractures, it is possible to obtain agreement between toughness from TDCB and peel tests. Moreover, the thickness of adhesive coating on the peel arm can be quite small (we were recording about 60 µm), which is most certainly an asymmetric crack for laminates where the bond line thickness was up to 400 µm.

Figure 9: Toughness versus bond-line thickness for 1 mm AA 5754-0/ESP110 laminates from fixed arm and mandrel peel tests, together with results from TDCB tests.

3.4 The influence of peel arm thickness.

3.4.1 Fixed arm peel results for AA 5754-0/XD4600 laminates

Three values of peel arm thickness (0.5 mm, 1.0 mm and 1.5 mm) have been used in laminates of AA 5754-0/XD4600 at a common bond line thickness of 250 μm . Fixed arm peel tests were conducted at three peel angles (45°, 90° and 135°). Results for 0.5 mm peel arms are shown in Figure 10 and for 1.0 mm peel arms in Figure 11 (results for 1.5 mm peel arms are very similar to those for the 1.0 mm peel arms). Confocal microscopy images are included in these figures and indicative adhesive coating thickness measurements are also shown.

Figure 10: Fixed arm peel results for 0.5 mm AA 5754-0/XD4600 (250μm) with confocal microscopy image.

With reference to Figure 10, the thickness of the adhesive coating is small at 15 μm. In mind of the coefficient of variation that can be associated with this thickness measurement, it seems reasonable to believe in the possibility of regions where the coating is very thin and a contribution from interfacial fractures should not be ruled out, although the appearance of the peel arm implies cohesive fracture.

Figure 11: Fixed arm peel results for 1.0 mm AA 5754-0/XD4600 (250μm) with confocal microscopy image.

With reference to Figure 11 for the thicker peel arm, it can be seen that the adhesive coating on the peel arm is thicker and fractures are cohesive.

Figure 12 shows all the fixed arm peel results plotted against peel arm thickness. Also included is the G_C value from TDCB with a bond line thickness of 250 μm. At peel arm thickness of 1.0 mm and 1.5 mm there is agreement within experimental error between G_A and G_C . However, at the lowest peel arm thickness ($h = 0.5$ mm), the adhesive fracture toughness is lower. The one distinction for the latter result is the significantly smaller adhesive coating on the peel arm after testing; 15 μm instead of 47 μm.

Figure 12: Mean adhesive fracture toughness from fixed arm peel versus peel arm thickness for AA 5754-0/XD4600 laminates (bond line thickness 250 μm) with measurement errors. G_C from TDCB for an adhesive thickness of 250 μm is also included

3.4.2 Mandrel peel results for AA 5754-0/XD4600 (250 μm)

Mandrel peel experiments were conducted on the same set of AA 5754-0/XD4600 laminates with bond line thickness of 250 μm and where the peel arm thickness varied from 0.5 mm to 1.5 mm. Figure 13 shows results for the laminate with a peel arm of thickness 0.5 mm and Figure 14 shows results for the laminate with a peel arm of 1.0 mm thickness (Again, the laminate with a peel arm of thickness 1.5 mm showed similar behaviour to that for the 1 mm peel arm laminate). Confocal microscopy images are also included in Figures 13 and 14 together with indicative thickness measurements for the adhesive on the peel arm. (The coating thickness for the 1.5 mm laminate was 30 μm). Mandrel roller radius was selected in order to ensure conformance of the peel arm to the roller during testing.

With reference to results in Figure 13, it can be seen that for low alignment load ($D/b < 15$ N/mm) that the G_A values from the mandrel test agree with that from the fixed arm tests. However, both values are significantly smaller than the cohesive fracture toughness value from TDCB (for bond line thickness 250 μm). The indicative thickness measurement for the adhesive coating on the peel arm for the mandrel specimen is 15 μm , i.e. similar to that for the fixed arm specimen. Consequently, some contribution from interfacial fracture should not be ruled out. Moreover, agreement between these values for G_A seems acceptable since they reflect similar fracture mechanisms.

At higher alignment loads, however, there is a reduction in G_A for the mandrel data. It has been our experience that if interfacial fracture is contributing to the peel crack growth, then higher alignment loads in the mandrel peel method will drive the peel crack further to the interface. This might be occurring for the larger alignment loads in these mandrel data. Consequently, two possible values for G_A from the mandrel results are apparent and both are used for further analysis.

Figure 13: Mandrel and fixed arm peel results for 0.5 mm AA 5754-O/XD4600 (bond line thickness 250 μ m) with confocal microscopy image for mandrel specimen. TDCB data for 250 μ m bond line is also included.

Figure 14: Mandrel and fixed arm peel results for 1.0 mm AA 5754-O/XD4600 (bond line thickness 250 μ m) and confocal microscopy image for the mandrel peel arm. TDCB results are also included for bond line thickness 250 μ m.

The mandrel peel results for the thicker peel arms, 1 mm, are shown in Figure 14 and are much more straightforward (similar results are obtained for the laminate with peel arm thickness of 1.5 mm). The G_A values from mandrel peel are similar to those from fixed arm peel. In addition, both values agree with G_C from TDCB for a 250 μ m bond

line thickness. The adhesive coating thickness at 25 μm (and 30 μm for the laminate with peel arm thickness of 1.5 mm) is also higher than that for the thin peel arm laminates and despite the likely occurrence of some thinner regions for the adhesive coating, it seems to relate to cohesive fractures for the mandrel peel crack.

3.4.3 Discussion of influence of peel arm thickness for adhesive XD4600

Figure 15 shows all G_A values plotted against peel arm thickness for both mandrel and fixed arm tests. The value of G_C from TDCB tests with a bond line thickness of 250 μm is also included. Both values of G_A for mandrel peel with the thin laminates ($h = 0.5$ mm) are included. Measurement error bars are also included in this plot. There is general good agreement, to within experimental error, for G_A from fixed arm peel and G_A from mandrel peel, although the G_A value from mandrel peel at high alignment loads is an exception. It is apparent that at low values of peel arm thickness that the G_A value is smaller whilst independent of peel arm thickness at values of $h > 0.5$ mm. In addition at values of $h > 0.5$ mm there is agreement between adhesive fracture toughness (G_A) from peel tests with cohesive fracture toughness (G_C) from TDCB tests.

From previous discussion, there is an expectation that interfacial fracture during peel crack growth might be the reason why lower values of G_A are observed for thin peel arm laminates. It is difficult to provide a rational explanation for these observations. Indeed, from work reported elsewhere [10] it is suggested that the reverse trend should be expected, namely that G_A might increase as h becomes smaller. It can only be surmised that inherent difficulties might arise in the preparation of thinner peel arm laminates.

Figure 15: Summary of G_A values with error bars from fixed arm peel (continuous line for error bars) and mandrel peel (dashed line for error bars) versus peel arm thickness for AA 5754-0/XD4600 (bond line thickness 250 μm). G_C from TDCB with bond line thickness of 250 μm is also included.

4 CONCLUDING COMMENTS

This has been a study of the influence of adhesive bond line thickness, and peel arm thickness on the adhesive fracture toughness (G_A) for a number of metal polymer laminates. Two different peel geometries were used in the study, namely fixed arm peel (at different peel angles) and mandrel peel. In the mandrel peel experiments, a choice of mandrel roller radius was made such that conformance of the peel arm to the mandrel was achieved. In general, good agreement was found for G_A from both peel tests. This was the case whether cohesive fractures were observed or whether interfacial fractures were observed. In the case of cohesive fractures, the G_A values from peel tests agreed with the value of cohesive fracture toughness (G_C) from TDCB tests.

The influence of bond line thickness was studied for two types of laminate system, namely AA 5754-0/XD4600 and AA 5754-0/ESP110. It is concluded that bond line thickness can affect the value of G_A for cohesive fractures. Adopting a linear elastic fracture mechanics model to describe the relationship between toughness and bond line thickness resulted in a reasonable fit for all the experimental data. In particular, good agreement was noted between peel adhesive fracture toughness and cohesive fracture toughness for a wide range of bond line thickness. It is also noted that cohesive fracture can be observed during peel even for small coatings of adhesive on the peel arm (i.e. when the adhesive coating thickness is small compared with the bond line thickness) and even for these occasions, good agreement was observed between G_A and G_C .

One of the adhesives was used to study the influence of peel arm thickness. In general, it was observed that G_A was not affected by the value of peel arm thickness (h), although at the smallest value of h it was observed that G_A became smaller. A possibility of interfacial fracture was thought to be responsible for this observation. However, apart from this observation of a somewhat low G_A at $h=0.5$ mm, throughout this part of the study there was excellent agreement in the measurements of G_A by both peel tests and these values agreed with the cohesive fracture toughness from the TDCB tests.

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Appendix I: Confocal Laser Scanning Microscopy

A confocal laser scanning microscope was used to characterise the adhesive coating remaining on the peel arm after the peel test and also to measure its thickness. An image of the coated peel arm can be obtained from a laser scanning technique by using the microscope in a fluorescent mode. Such images may be of variable magnification; for examples, the images in Figures 1,3,4,5,7,13 and 14 are relatively low magnification since the complete width of the peel arm is included. However, in Figures 10 and 11 the magnification is higher since only part of the peel arm width is shown. These scanning images provide an indication of the presence and coverage of the adhesive on the peel arm at the end of a peel tests and hence give an indication of the nature of the peel fracture, in particular indicating whether cohesive or interfacial fractures were involved in the peel crack growth.

The confocal microscope can also be used to measure the thickness of the adhesive coating at a particular and quite small point on the peel arm. Laser beams are used to create fluoresce from the metal surface and the adhesive surface and from this a measurement of adhesive coating thickness can be made. However, such measurements are indicative since they are not scanning measurements. Naturally, a number of different thickness measurements can be made over a wide area of the peel arm and an average thickness could be determined. However, this would require considerable time with the instrument and this was not always available.

It is helpful to know what the variation in coating thickness might be and three specimens were studied in detail in order to provide such a view. Each peel arm was from a 1 mm AA 5754-0/ESP110 laminate where the bond line thickness was 400 μm and specimens from T-peel, 45° and 135° fixed arm peel were studied. The peel arms were sectioned at several positions along their length in order to view side-on the adhesive coating layer. The confocal microscope was then used to take multiple measurements of adhesive coating thickness. Figure 19 shows results for the 45° fixed arm specimen and is typical of the scatter for all three samples.

Figure 19 Adhesive coating thickness on the peel arm versus measurement number for a 45° fixed arm peel specimen from 1mm AA 5754-0/ESP110. The average thickness is 18.4 μm with a standard deviation of 10 μm .

The mean adhesive coating thickness for all three specimens is shown in Table 7. It would seem that a typical coefficient of variation for such measurements is 50%. It could therefore be assumed that each indicative measurement of adhesive coating thickness represents a value within some normal distribution where the coefficient of variation is 50%. It could further be assumed that $\pm 50\%$ is the error associated with an indicative adhesion coating thickness.

		T-peel	Fixed arm 45°	Fixed arm 135°
Mean	thickness	39	18	14
(μm)	(SD)	(19)	(10)	(6)
Coefficient	of	54	55	43
variation (%)				

Table 7 Mean thickness values for adhesive coating on peel arm with standard deviations and coefficient of variation.