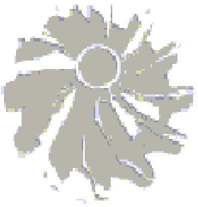

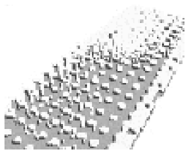

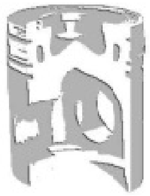

Fracture Toughness Test Methods For PRM

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J. Lord

Fracture Toughness Test Methods For PRM
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INTRODUCTION

The measurement of valid plane strain fracture toughness, (K_{IC}) values for particulate reinforced metal matrix composites (PRM) is an important step in the process of developing useful products from these materials and increasing confidence in their properties and performance. At present there are no standard fracture toughness test procedures specifically for PRM, and conventional standards for metals ASTM E399 and BS 7448 are normally used. Consideration is given in this section to the suitability of these existing standards for PRM.

The property K_{IC} characterises the resistance of a material to fracture in the presence of a sharp crack under tensile loading, where the state of stress near the crack front is triaxial plane strain, and the crack-tip plastic region is small compared with the crack size and specimen dimensions. A valid K_{IC} value is believed to represent a lower limiting value of fracture toughness, and is a key parameter in design for estimating the relationship between failure stress and defect size for a material in service under similar stress state conditions.

The plane strain K_{IC} fracture toughness test involves the loading to failure of pre-cracked notched specimens in tension or three-point bending. The test is unusual in that the calculation of a valid toughness value can only be determined after the test has been completed, via examination of the load-displacement plot and measurement of the fatigue pre-crack crack length. The provisional fracture toughness K_Q is first calculated from the following equation:

$$K_Q = (P_Q/BW^{1/2}).f(a/W)$$

where P_Q is the load corresponding to a defined increment of crack length, B is the specimen thickness, W the width, and the function f(a/W) is a geometry dependent factor that relates the compliance of the specimen to the ratio of crack length and width.

Only when specific validity criteria are satisfied, can the provisional fracture toughness KQ be quoted as a valid plane strain fracture toughness K_{IC}.

REPRESENTATIVE PRM FRACTURE TOUGHNESS DATA

Some of the published fracture toughness data for PRM [1-17] is detailed in Table 1 and shown in Figure 1, plotted against the 0.2% proof strength. It is clear from the graph that there is considerable scatter in the data and it is difficult to establish whether this results from problems with the method of test or from variations in microstructure. Also included are data for the unreinforced matrix materials for typical 2000, 6000, and 7000 series aluminium alloys. It can be seen that, in most cases, for equivalent values of yield strength, PRMs are not as tough as the unreinforced aluminium alloys.

Material Designation	**Spec type**	**B (mm)**	**K_Q (MPaÖm)**	**$Rp_{0.2}$ (MPa)**	**Refs**
6061/SiC/30p	**CT**	**11.7**	**15.5**	**390**	**1,2**
7075/SiC/30p	**CT**	**1.6**	**27**	**550**	**1,2**
7075/SiC/30p	**DENT**	**1.6**	**21**	**550**	**1,2**
7091/SiC/20p	**DCB**	**6.4**	**14**	**500**	**3**
	DCB	**6.4**	**16**	**400**	**3**
7091/SiC/20p	**Bend**	**12.7**	**24**	**380**	**4,5**
	Bend	**12.7**	**17**	**410**	**4,5**
7091/SiC/20p	**Short rod**	**?**	**25-30**	**390**	
		?	**15-17**	**405**	
		?	**15**	**510**	
2124/SiC/15p	**Bend**	**19**	**32-34**	**?**	
	Bend	**19**	**32-34**	**?**	
6061/SiC/25p	**SENT**	**2.5**	**12.5**	**415**	**7**
6061/SiC/25p	**CT**	**6.4**	**15.2**	**350**	**8**
A357/SiC/30p	**Short bar**	**22**	**18.6**	**375**	**10**
2014/SiC/15p	**CT**	**6.4**	**20-22.6**	**350**	**11**
2014/SiC/25p	**CT**	**6.4**	**11.7-13.9**	**400**	**11**
2024/SiC/15p	**CT**	**6.4**	**14.7-17.7**	**350**	**11**
6061/SiC/25p	**?**	**4.1**	**15.4**	**375**	**13**
7091/SiC/30p	**?**	**4.6**	**18.3**	**485**	
7091/SiC/30p	**?**	**8.6**	**14.7**	**485**	
A357/SiC/20p	**?**	**12.7**	**18.5**	**345**	**13**
Fe/TiB2/30p	**?**	**?**	**25**	**420**	
A356/SiC/55p	**?**	**?**	**11.3**		
A356/SiC/63p	**?**	**?**	**11.7**		
6061/Al_2O_3/15p	**?**	**?**	**14.6-18**		**17**
6061/Al_2O_3/20p	**?**	**?**	**21**		**16**
6061/Al_2O_3/10p	**?**	**?**	**24.1**	**296**	**Assess**
6061/Al_2O_3/20p	**?**	**?**	**22**	**324**	**Assess**
A359/SiC/10p	**?**	**?**	**17.4**	**303**	**Assess**
A359/SiC/20p	**?**	**?**	**15.9**	**338**	**Assess**
6000 series Al	**?**	**?**	**27-35**	**220-300**	
2000 series Al	**?**	**?**	**29-37**	**390-460**	
7000 series Al	**?**	**18**	**30-39**	**480-520**	**14**

Table 1: Representative fracture toughness data for commercial PRM

Both valid KIc and provisional KQ values are plotted on the same graph in Fig 1, and although the fracture toughness values are generally higher for the lower strength, ductile matrix materials, there does not appear to be a clear relationship between plane strain fracture toughness and proof strength. A wide variety of matrix and reinforcement combinations have been plotted in Fig 1, but for the group of PRMs with proof strengths in the range 350-500 MPa, most of the valid results fall within a relatively narrow toughness range of 13-20 MPa√m.

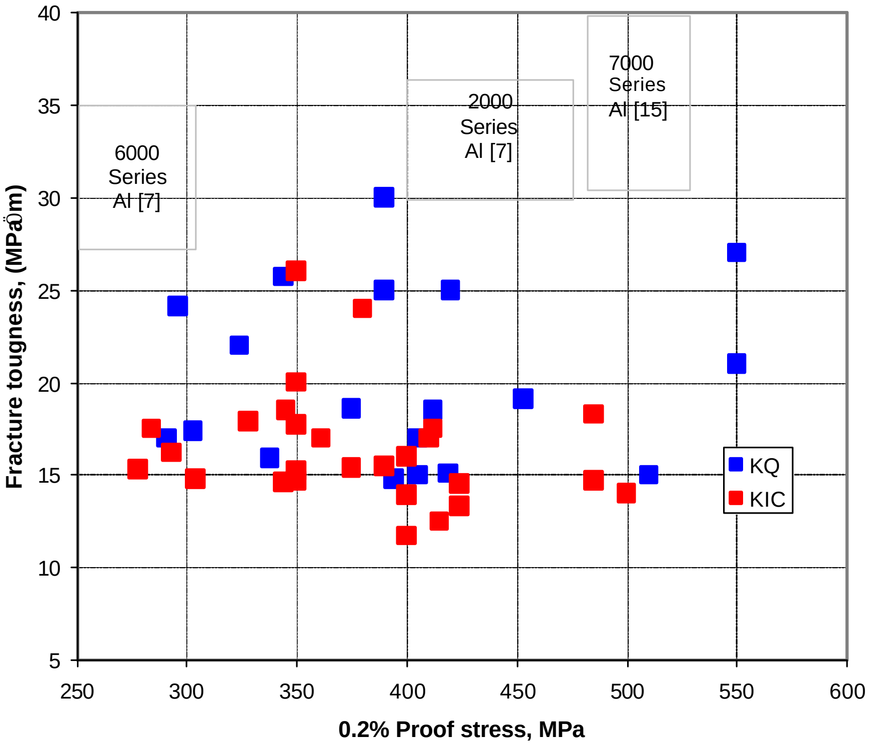

Fig 1: Representative fracture toughness data for commercial PRM [1-17]

It is difficult to analyse the results presented in Table 1 and Fig.1 in detail because of the range of materials and the fact that they were obtained using a variety of specimen geometries and pre-cracking procedures. It is difficult also to separate out the contribution of test method and material variability because there is often insufficient information reported with the results to have sufficient confidence in their validity.

Figure 2 shows the same data plotted against volume fraction of reinforcement. As might be expected the addition of increasing levels of reinforcement leads to a reduction in the fracture toughness values. For the most commonly used materials with 15-30 volume percent reinforcement there is a large degree of overlap because different combinations of matrix material, reinforcement and heat treatment conditions are included – all of which have an important effect on the fracture behaviour.

Although there have been few detailed and systematic studies of the effects of changes in reinforcement parameters on toughness, results published for SiC reinforced aluminium alloys with volume fractions of 15-30% and nominal particulate sizes of 3-10μm [15] indicate that the effects on the plane strain fracture toughness are relatively small. It appears that the heat treatment and metallurgical state of the matrix produce the greatest variation in toughness. However, the effects depend very much on the specific matrix alloy and it is not possible to make a general statement on the effect of heat treatment or chemistry on fracture toughness, which will apply to all PRM.

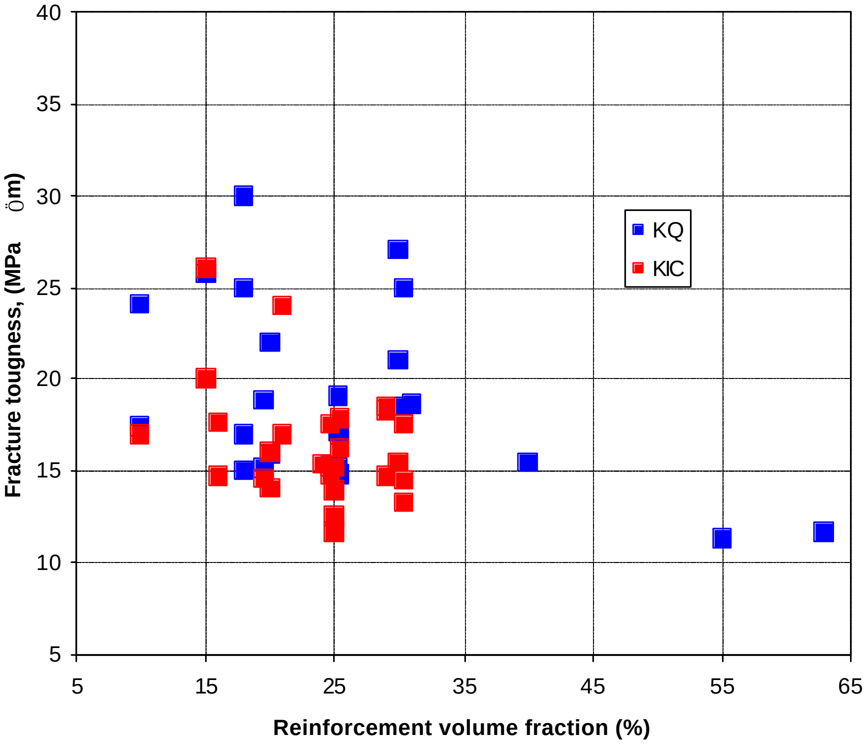

Fig 2: Fracture toughness data plotted against volume fraction of reinforcement

The issue of variability in the measurements is illustrated in Table 2, which shows a series of nominally identical repeat tests on 4 different PRM. There is some variation in thickness between the specimens, but only one batch of material yielded valid data from all four tests. Typically the repeat measurements varied by as much as 3 MPa√m (~12%) and many were reported as provisional K_Q values because they failed one or more validity criteria in the Standard.

PRM	E (GPa)	$Rp_{0.2}$ (MPa)	B (mm)	B_{min} (mm)	a/W	P_{max}/P_{min}	K_Q (MPÖ/m)	Valid ?	Reason
6061/SiC/15p	91	344	9.97	13.50	0.498	1.04	25.7	No	1,2
			9.97	15.30	0.537	1.07	27.4	No	1,2
			9.94	12.80	0.511	1.18	24.5	No	2,3
			9.91	14.00	0.52	1.20	26.1	No	2,3
6061/SiC/15p	90	361	9.95	5.50	0.561	1.07	17.0	No	4
			9.94	5.70	0.541	1.10	17.0	Yes	
			9.95	5.80	0.536	1.01	17.1	Yes	
			14.94	5.30	0.548	1.01	16.6	No	1
6061/SiC/30p	118	412	9.95	4.30	0.511	1.03	17.4	No	1
			9.9	4.90	0.554	1.02	18.5	No	1,4
			7.96	4.30	0.545	1.01	17.5	Yes	
			8.83	4.30	0.528	1.00	17.5	Yes	
6061/SiC/30p	121	424	9.96	3.00	0.534	1.00	14.6	Yes	5
			9.91	2.40	0.519	1.01	13.3	Yes	5
			9.93	2.90	0.546	1.01	14.5	Yes	5
			9.99	3.00	0.545	1.00	14.7	Yes	5

Table 2: Typical variation in properties for a batch of material.

Key 1 Excessive crack curvature

2	Thickness criteria not satisfied
3	Excessive plasticity
4	a/W out of range
5	Valid according to ASTM E399, but fails BS 7448 due to crack curvature
6	Non-symmetrical crack front

TEST METHOD CONSIDERATIONS

Standards
Validity criteria
Effect of thickness
Crack growth data
Fractography

STANDARDS

There are no standard K_{Ic} fracture toughness test procedures specifically for PRM or other types of MMCs, and conventional standards for metals ASTM E399 and BS 7448 are normally used.

- ASTM E399; "Standard Test Method for Plane-Strain Fracture Toughness of Metallic Materials"

- BS 7448: Part1:1991, “Fracture mechanics toughness tests, Part 1. Method for determination of K1C, critical CTOD and critical J values of metallic materials”.

Small differences exist between the two standards detailed above, and an important factor is how the level of crack curvature is quantified and assessed, and the effect this has on the test validity (see specific examples in Table 2, which shows data that is valid according to ASTM E399, but invalid according to the BS 7448 validity criteria). Details are not covered here, but the user is advised to study the relevant section in the standard as appropriate.

VALIDITY CRITERIA

The standards have strict validity criteria to ensure that the plane strain conditions exist in the test. These include checks on the form and shape of the load vs displacement trace, requirements on specimen size and crack geometry, and the 0.2% proof strength values at the test temperature.

More specifically the achievement of a valid K_{Ic} result depends on the following criteria being satisfied:

- The thickness of the specimen $B = (K_{IC} /Rp_{0.2})^2$ to ensure that plane strain conditions exist

- The ratio of $P_{max}/P_Q = 1.10$ to ensure that only limited plasticity is present at the crack tip

- The mean final pre-crack length must lie between the range $0.45 = a/W = 0.55$ to ensure that the compliance calibration is at its most accurate

- The difference between the crack lengths measured at specific points across the specimen thickness must not exceed a certain variation (note - there is some difference between the 2 Standards).

- The plane of the crack must always be within 10^{o} of the plane of crack extension

Essentially, these conditions are designed to ensure that the plastic zone size associated with the pre-crack is small, that plane strain conditions prevail, and that the Linear Elastic Fracture Mechanics approach is still applicable.

EFFECT OF THICKNESS

For linear elastic fracture mechanics to be of practical use, values of plane strain fracture toughness K_{IC}, must be independent of the test method, specimen geometry and thickness. The Compact Tension (CT) type specimens (Fig 3) and Single Edge Notched Bend (SENB) or Tension (SENT) are the most commonly used. For some types of PRM with low volume fractions of particulate reinforcement, soft matrices, and thin testpiece geometries, elastic-plastic or plane stress fracture toughness test methods may have to be used. These are not considered here - the emphasis being on plane strain toughness determination.

Particular attention should be paid to the effects of specimen thickness and other validity criteria such as crack curvature on the toughness, since these are probably the most common reasons for the test being invalid.

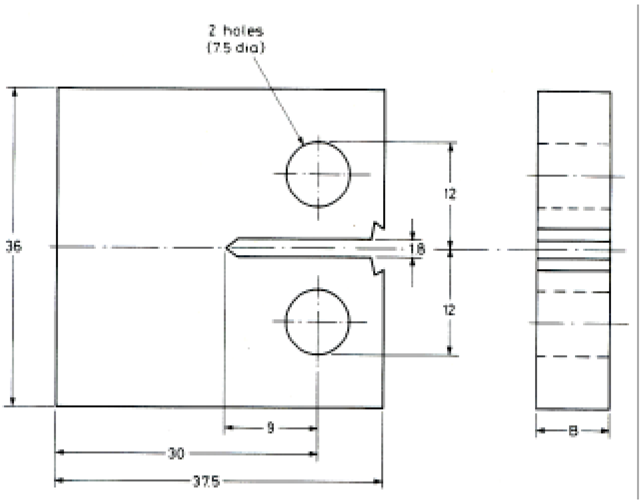

Fig 3: Typical CT specimen geometry used in fracture toughness testing

A series of tests have been carried out [15] to examine and illustrate the effect of thickness on test validity, using a series of specimens machined from heat treated blanks from 6061/SiC/25p and 2124/SiC/30p PRM with values of thickness, B ranging from 2 to 12 mm.

The fracture toughness results reported were generated from tests on CT specimens, with width W = 30 mm and height N = 36 mm, of designs given in the ASTM E399 and BS 7448 standards. Integral knife-edges were machined into each specimen, 7.5 mm from the loading line, to locate the arms of the COD gauge. Results are presented in Table 3 and plotted in Fig. 4.

PRM	B	B_{min}	a/W	P_{max}/P_{min}	K_Q	K_{IC}	Valid ?	Reason
	(mm)	(mm)			(MPa√m)	(MPa√m)		
6061/SiC/25p	11.97	3.8	0.538	1.00	15.6		No	1
	12.10	3.5	0.526	1.00	14.9		No	1
	11.95	4.5	0.586	1.00	17.1		No	1,4
	11.90	3.7	0.527	1.00	15.3		No	
	9.10	3.2	0.494	1.00		14.4	Yes	
	8.99	3.5	0.494	1.01		15.0	Yes	
	6.00	3.2	0.524	1.02		14.3	Yes	
	5.95	3.5	0.491	1.06		15.0	Yes	
	6.05	3.3	0.531	1.04		14.6	Yes	
	2.90	3.6	0.490	1.23	15.2		No	2,3
	2.80	3.2	0.569	1.21	14.2		No	4,2,3
	3.00	4.0	0.490	1.27	16.0		No	2,3
	1.50	5.3	0.487	1.27	18.4		No	2,3
	1.59	4.4	0.473	1.28	16.8		No	2,3
	1.70	4.0	0.508	1.27	16.3		No	2,3
	1.65	5.3	0.494	1.23	18.4		No	2,3
2124/SiC/30p	12.10	2.7	0.501	1.00	15.9		No	1
	12.02	3.5	0.500	1.00	18.0		No	1
	6.20	2.4	0.505	1.00		15.0	Yes	5
	5.81	3.6	0.435	1.00	18.1		No	4,6
	2.96	2.2	0.497	1.01		14.3	Yes	
	1.60	4.9	0.435	1.46	21.4		No	2,3
	1.70	5.7	0.466	1.34	22.9		No	2,3
	1.78	6.6	0.475	1.32	24.7		No	2,3

Table 3: Measurements showing the effect of thickness on KQ and test validity.

Key
1 Excessive crack curvature
2 Thickness criteria not satisfied
3 Excessive plasticity
4 a/W out of range
5 Valid according to ASTM E399, but fails BS 7448 due to crack curvature
6 Non-symmetrical crack front

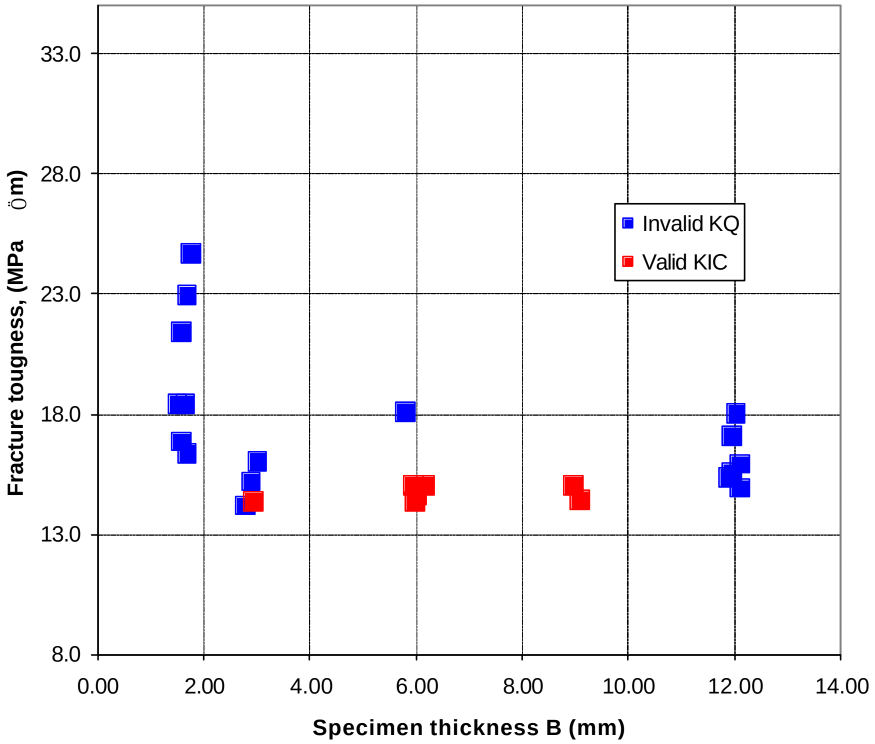

Fig 4: Effect of thickness on validity and measured toughness values

Individual data points are indicated to be valid K_{Ic} results or otherwise according to the criteria in the current standards. It can be seen that for this particular CT geometry, only results within the thickness range of about 3-10 mm were valid.

There were two reasons why specimens outside this thickness range in the reported study failed the standard validity criteria. For the thinnest specimens, the ratio of P_{max}/P_Q was generally greater than 1.10 indicating that more stable crack growth had occurred than is allowed by the standards, or the thickness of the specimen was insufficient to satisfy the minimum thickness criterion.

And as the thickness increased there was a greater propensity for excessive crack curvature (Fig 5) and most of the thickest specimens failed for this reason.

Some of the problems associated with interpreting toughness test results on both whisker and particulate reinforced aluminium alloy MMCs have been considered by Goolsby and Austin [13] and they concluded that there were very few results published that satisfied the ASTM E399 validity criteria. In a similar study on an as extruded, SiC whisker reinforced 2124 aluminium alloy, Albritton and Goree [25] could not obtain any valid KIc results from a large number of tests carried out according to standard ASTM E399 procedures. Various specimen geometries were used, including CT, centre cracked tension (CCT), and single edge notch tension (SENT) designs, and all were fatigue pre-cracked. Again they found that the main reasons for failing to obtain valid valid KIc were largely because of excessive crack curvature, non-linearity of the load-displacement trace, or out of plane crack propagation.

It has been noted in other work on the toughness of whisker and particulate reinforced MMCs [13,16] that the most frequent source of invalidity was crack curvature. For CT specimens with straight through notches, the fracture toughness standards require that the surface crack lengths should not differ from the effective crack length by more than 15%. The effective crack length æff is calculated as the mean of the crack lengths at the centre and quarter thickness positions. Also, the difference between any two of the centre and quarter thickness crack lengths should not be greater than 10% of aeff. In many of the tests on the thicker specimens (B > 10 mm) carried out at NPL, toughness values were invalid because these criteria were not satisfied, and it was observed that the shapes of the crack fronts were parabolic.

For the thicker specimens, there was excessive crack curvature and considerable non-linearity at the beginning of the load-displacement trace. For the thinnest specimens, where Pmax/PQ was greater than 1.10, the results indicated that other fracture toughness test methods are required; for example, those used for measurements of K, on sheet materials (where B < 6mm) covered by ASTM B646 and E561.

The most likely cause of the curvature is the presence of residual stresses, since the specimens had not been stress relieved. A measurement of shear lips showed that the size of the lips was fairly constant (about 0.5 mm) for each of the different testpiece thicknesses and this is small compared to the extent of curvature. Also, the shape of the crack front was similar to the distribution of residual stresses measured across the thickness of a heat treated conventional aluminium alloy.

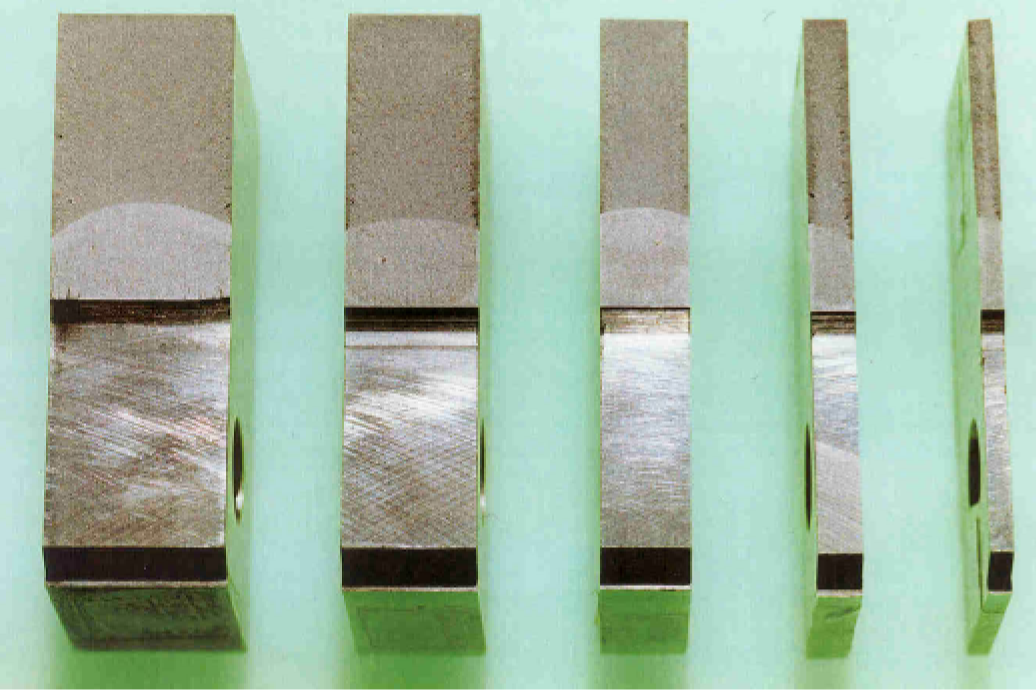

Fig 5: Variation in crack curvature with specimen thickness

The current standards also mention that some non-linearity may be present at the beginning of a test. Typically, this is small and is associated with friction between the loading pins and grips. The standards suggest that this can be ignored, but in many of the tests detailed in Table 2 and Table 3 considerable non-linearity was observed. Fig. 6 shows the issues and typical load-displacement plots for the extremes of the thick and thin specimens tested.

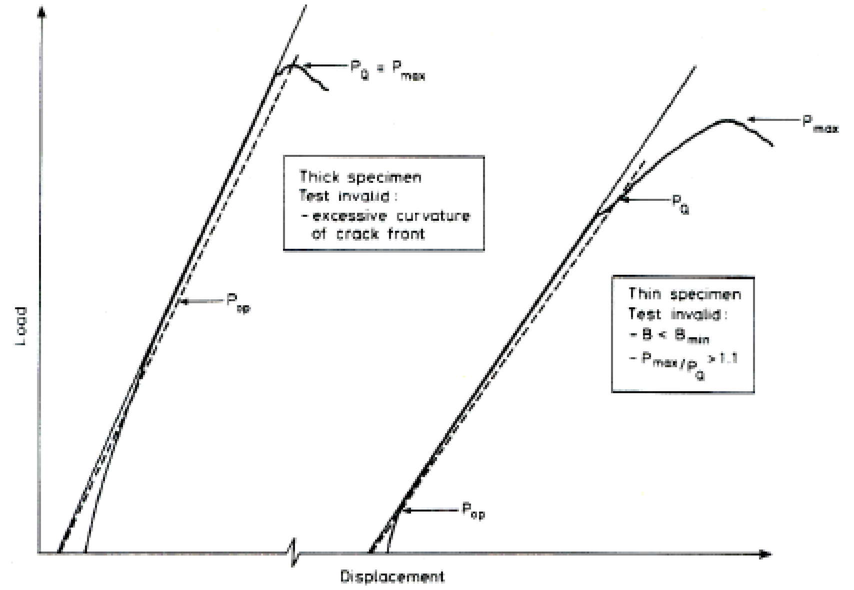

Fig 6 Typical load-displacement curves for thick and thin specimens

In this case the gross non-linear behaviour observed at the beginning of the test for both thin and thick testpieces (Fig. 6) is probably a consequence of crack closure and residual stress effects.

CRACK GROWTH DATA

Few problems have been reported in pre-cracking the specimens under computer control, provided that K_{max} is kept below about 10 MPa√m. Three different operating modes can be selected during pre-cracking,

- Constant load
- Constant ? K
- Decreasing ? K

If time is not an issue, and the user wants to develop crack growth data during precracking, the decreasing ? K mode offers the greater flexibility as it provides the opportunity to generate fatigue crack growth data over a range of stress intensities. Typical crack growth data that can be generated during fatigue pre-cracking process is presented in Fig 7, plotted against nominal ? K values, which have not been corrected for closure effects. The uncertainty in the da/dn values is about 5-10% and arises mainly from an uncertainty in measurement of crack length. The user should be aware of the effects crack curvature on the effective crack length and the potential impact this might have on the data. If appropriate, the fatigue crack growth data should be corrected accordingly.

Results indicate that at these intermediate values of crack growth rate (10^{-1} to 10^{-7} m/cycle), the PRM have properties that are at least as good as, if not better than unreinforced matrix alloys of the same composition, and this has been found also in other studies [3,7,17-20]. The trend lines show that for the 6000 series PRM shown in Fig.7 the crack growth rate decreases (for a given value of ? K) as the volume fraction of SiC reinforcement is increased.

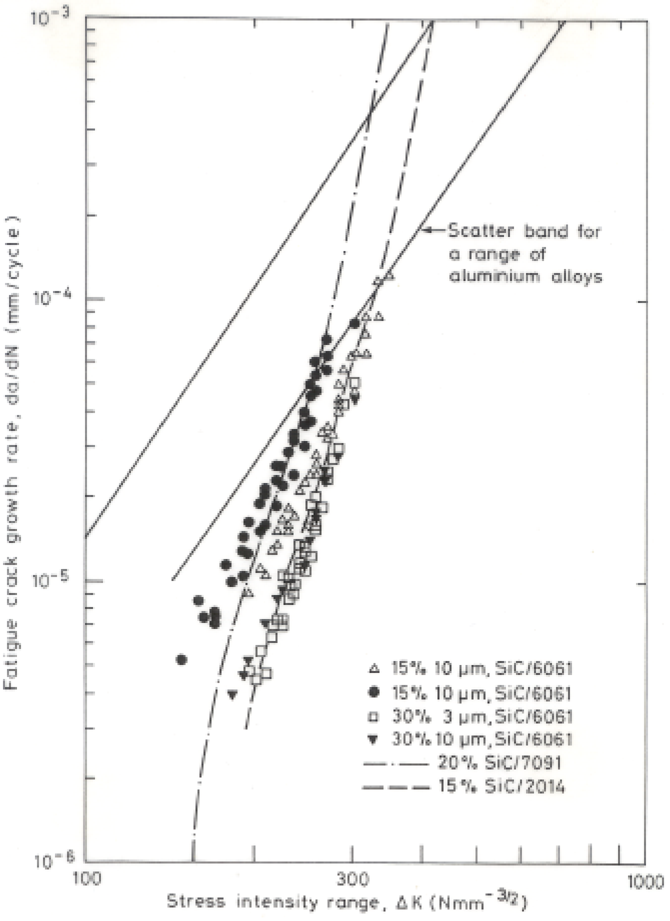

Fig 7: Typical fatigue crack growth data generated during pre-cracking

FRACTOGRAPHY

Work has shown the importance of studying both halves of the broken specimen for determining the fracture process in these materials, and it is recommended that matching micrographs be produced. Fractography of the rapid overload fracture region in specimens tested at NPL did show extensive particle fracture, but only in the PRM with relatively large (10-50 μm) SiCp reinforcement. In the samples with fine SiCp reinforcement (3 μm), the rapid fracture also occurred predominantly through the matrix and few broken SiCp particles could be found.

The fatigue fracture surface in all the materials was characterised by failure through the matrix. Isolated broken SiC particles were found, but they were few in number. These observations differ from those reported by Shang and Ritchie [26,27] for a SiCp/7000 series PRM, in which, in the intermediate crack growth range and at similar ? K values, they found evidence for crack bridging by uncracked ligaments which they considered to result from fracture events (broken SiCp) ahead of the crack tip.

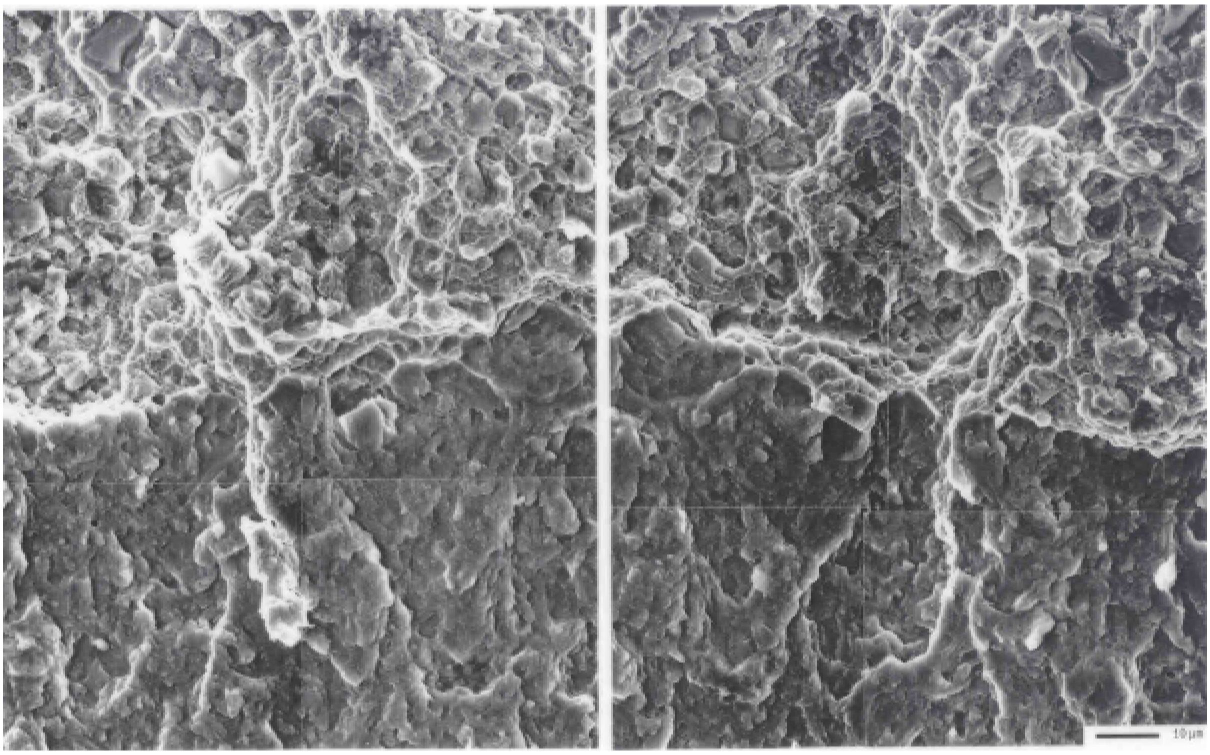

Fig 8: Matching fracture surfaces of the broken fracture toughness specimen, showing the pre-crack region and overload fracture surface

SUMMARY

- The plane strain fracture toughness data reported in the literature for PRM continue to show considerable scatter, and it is difficult to determine whether this is material variation or due to issues with the test methodology.

- Results generally indicate that the existing test procedures for the plane strain fracture toughness of metallic materials are generally suitable for PRM, but as many as 60-70% of data reported in the literature for PRM may be invalid, and should be used carefully.

- Valid K_{IC} values for PRM were significantly lower than those for the equivalent unreinforced matrix alloys.

- Crack curvature is the main cause of the test being invalid, and this becomes more prevalent as the testpiece thickness and the reinforcement volume fraction increase.

- Even in unreinforced alloys, a proportion (perhaps as high as 15% in some specimens) of plane strain toughness tests yield invalid toughness values because of excessively curved cracks. The problem in PRM however appears more severe, and a greater proportion of tests can be expected to fail the curvature criteria given in the current toughness standards.

- As with conventional metallic materials, thin specimens did not give valid K_{IC} values due to excessive plasticity and other toughness tests should be used in this case. An examination of the effect of thickness yielded valid data from only a relatively small range of specimen thickness values.

- Side grooving has been used successfully with PRM to control the shape of the crack front during precracking.

- The influence of crack curvature and closure on the fatigue crack growth data for PRM should be considered carefully.

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