



National Physical Laboratory

**Fracture Toughness Tests for Particulate MMC
UK COSI (IACFA) Task Group**

Meeting Report October 1992

B Roebuck and J D Lord

April 1993

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ABSTRACT

This report discusses the issues related to fracture toughness tests for particulate reinforced metal matrix composites debated at the second meeting of a UK COSI Task Group, including contacts with BSI, residual stress measurements, plane strain toughness tests, Charpy impact tests, short bar chevron notch testing and crack length measurement methods. It was agreed that the main item on the agenda for the next meeting would be to reach an agreement on a recommended test method for toughness testing of particulate MMC.

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Approved on behalf of Chief Executive, NPL,
by Dr M K Hossain, Division of Materials Metrology

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1 BACKGROUND

This report summarises the issues debated at the second meeting of the UK COSI (United Kingdom Committee on Structural Integrity - formerly IACFA) Task Group for toughness testing of particulate reinforced metal matrix composites. The full background to the aims of the group are set out in a previous report [1].

The meeting was held at the conference centre of AEA Technology, Harwell on 15 October 1992. The attendance list is given in Appendix 1. A full contact list was given previously [1].

The main items discussed at the meeting were

- UK COSI Task Group remit and interaction with BSI.
- DTI MT programme report on toughness testing for particulate MMC.
- Contributions on problems with test procedures.
- Thin sheet toughness tests.
- Interlaboratory testing.

Agreement was reached to continue holding subsequent meetings at appropriate intervals when sufficient additional progress has been achieved, probably mid-1993.

2 UK COSI AND BSI

Prior to 1992 the DTI provided financial support for the UK COSI (formerly IACFA) secretariat at NPL. This support is no longer available. However, TWI and AEA Technology (Risley) have agreed to share funding of the secretariat for the time being and to each take the chair and secretary's jobs one year at a time with TWI in the lead for the first year. The chairman is John Harrison and secretary Dr S Garwood.

At the UK COSI Task Group meeting on particulate MMC toughness testing it was debated whether to continue as a UK COSI group or to change affiliation and become a group of the UK FORUM on MMC TEST METHODS. It was agreed that whichever grouping would lead to an accelerated take-up by the relevant standards body would be most appropriate. Subsequent to the Task Group meeting, B Roebuck discussed the issue with John Harrison, the UK COSI Chairman, who was keen to see the group continuing under the auspices of UK COSI. B Roebuck agreed in due course to make two presentations on the work of the Task Group, one to the main UK COSI committee and another to the Advanced Materials sub-group which is sponsoring the work of the Task Group (along with other Task Groups on composite fractography and defect characterisation).

The Task Group was expecting attendance by G Lees (B Gas), the current Chairman of the BSI Committee on fracture toughness test methods, in order to debate how best to establish links between his committee and our group. However, a last minute apology was received for non-attendance (due to illness). Subsequent to the Task Group meeting B Roebuck agreed with G Lees to present the work of the group to the BSI Committee at their first meeting in 1993.

3 DTI MT PROGRAMME ON MMC TEST METHODS

An important component of this measurement metrology programme is a study of fracture toughness tests for particulate metal matrix composites. The programme is running jointly between NPL and AEA Technology, Harwell. NPL is responsible for examining tests for plane strain fracture toughness, K_{Ic} and examining the effects of residual stresses and

problems due to crack curvature. AEA Technology are responsible for examining the chevron notch test method, toughness tests for sheet material, Charpy impact toughness and methods for crack length measurement.

3.1 NPL

NPL reported on three topics relevant to the measurement of plane strain toughness.

- Residual stress measurement.
- Toughness tests on BP 217 plate MMC.
- ASTM round robin on SiCw/Al MMC.

3.1.1 Residual stress measurement

Dr Lord is organising an intercomparison exercise to examine the hole drilling method for measuring residual stresses in a 15 mm plate (BP 217) MMC. About seven organisations have agreed to take part; material has been prepared and is being circulated in the form of rectangular blocks about 80 × 75 mm in dimensions.

Dr Roebuck described a procedure for calculating residual stresses from measurements of curvature in thin slices taken from blocks from a similar BP 217 plate (Appendix 2). The procedure assumes that a parabolic stress distribution is present in the plate in a through-thickness direction and that the net bending moment acting on a slice cut from the plate is the difference between the average forces acting on each side of the neutral plane of the slice at its midpoint. The curvature of the slice was measured using a non-contacting optical profilometer. The results gave reasonable justification for the assumption with an average value of 230 N/mm² (compressive) at the surface of the section. Further slicing experiments are to be performed and compared with the hole drilling measurements. Dr Knowles expressed the view that out-of-balance expansion after relaxation of the stresses might be an alternative explanation for the curvature and might also lead to a method for calculating the residual stresses.

NPL have conducted a number of finite element studies to examine the temperature distributions in an MMC plate during the quenching process (Fig. 1a). It was found that the temperature profile across the plate was parabolic for most of the time during the quench (Fig. 1b), except for a very short period after the start, where a square profile was present. The form of the parabolic temperature distribution was relatively insensitive to input parameters such as thermal conductivity and heat transfer at the surface. Analytical solutions for temperature profiles, which require values taken from tables of solutions to the relevant equations [2], were also examined and a plot of a typical temperature profile is shown in Fig. 2a. This also was parabolic; confirmed by taking a regression line through the data in Fig. 2b. There seems to be no doubt that the temperature profiles across quenched plates are parabolic. This is useful information which could be utilised in finite element analyses for calculating residual stress distributions in quenched sections.

3.1.2 Plane strain toughness tests

NPL are conducting a series of tests on CT fracture toughness specimens obtained from the 15 mm thick BP 217 plate. Both L-T and T-L testpieces are being tested with a range of thicknesses from 3 mm to the full plate size, 15 mm. Dr Roebuck expressed concern about the process of cutting specimens from the plate at less than the full thickness, and whether this might introduce an asymmetry to the residual stress distribution and subsequent fatigue crack front profiles. This concern arose from the observation that many of the pre-cracked testpieces at 6 and 8 mm thickness had non-symmetrical crack fronts (Fig. 3), whereas the full plate thickness (15 mm) tests were mostly symmetrical (Fig. 4). Additionally, it was noted that in use, the thickness of interest would be as-manufactured and not sectioned from a

larger piece. Further tests will be performed with 8 mm specimens cut from the midplane and either tested as - cut or re-heat treated.

Most of the tests to date have been on 6, 8 mm and 15 mm testpieces precracked either with an R ratio of 0.1 or 0.5. Very few of the tests resulted in valid K_{Ic} values, largely because of the problem of crack curvature, which was particularly excessive in the 15 mm testpieces precracked with an R ratio of 0.1 (Fig. 4a). In tests to examine the effects of pre-cracking with an R ratio of 0.5, previously recommended as a possible method for reducing crack curvature [3], the crack fronts were still invalid and had an unusual wavy shape (Fig. 4b). The results of the tests are summarised in Fig. 5. The results show that only three tests yielded valid K_{Ic} values, two on 8 mm thick testpieces and one on a 6 mm thick specimen. The testpieces precracked with an R ratio of 0.5 as apposed to that recommended in standard test methods (or R = 0.1) gave lower K_Q values by a factor of about 12%. The K_Q toughness measured in the 15 mm L-T testpieces were 5-10% less than in the T-L testpieces. However in the 8 mm specimens the opposite trend was noted with T-L testpieces less tough than L-T testpieces. The results also show the use of the effective crack length expression derived from an assumption of a parabolic crack front shape. As yet there are an insufficient number of results to draw conclusions regarding its efficacy.

3.2 AEA TECHNOLOGY

3.2.1 Charpy impact

R Boothby outlined the objectives of the programme on charpy impact toughness testing where it was planned to examine the effects of notch geometry, testpiece size and the usefulness of instrumented tests on particulate MMC. The initial tests on the BP 217 material were nearly completed and a report is due to be issued [4].

3.2.2 Short bar Chevron notch testing

Short bar chevron notch toughness testing of BP217 material has been carried out at AEA Technology, Harwell, following the recommendations of ASTM standard E 1304. Two standard geometries, with W/B of nominally 2.0 and 1.45, in both cases with B = 12.5 mm, were used. The specimens were produced by wire erosion. The notch root radius for all specimens was 0.125 mm, which is the largest value allowed by the ASTM standard for B = 12.5 mm. The specimen loading grips and mouth opening gauge were manufactured in accordance with the ASTM suggested designs.

The results of the tests are shown in Table 1, where square brackets, [], are used to denote invalidities in specimen dimensions, initial notch length (a_o) and/or plasticity (p). Note that both W and a_o were measured on completion of the test, using the knife edge marks left by the loading grips to indicate the position of the loading line. Of the twelve tests carried out, only three, with K_{Iv} values in the range 21 - 22 MN m^{-3/2}, were valid according to the ASTM criteria, though six other tests gave a similar result. Three tests, one in which cracking out of the notch plane occurred (probably due to poor alignment of the grips), and two in which the machined notch was visibly off centre, gave rise to higher K_{Qv} values of 23 - 24 MN m^{-3/2}.

All three valid results in this particular study were obtained using specimens with W/B = 2.0. It should be noted, however, that inaccurate machining, particularly with regard to the position of the tip of the chevron notch, was the primary reason that no valid data were obtained with W/B = 1.45 type specimens. Also, it must be noted that the chevron-notch angles remain to be checked and compared with the standard. This might be another source of invalidity.

In the US a recent ASTM STP (STP 1172) has been published outlining the experiences of various research groups in using the chevron notch test method in the period since the test method was published. An important conclusion of the findings in this publication is that it is not possible to predict, before a series of tests on a new material, whether the method will result in valid results which can be used to predict geometry-independent critical crack sizes. Post test analysis is essential. However, in general, materials with flat R-curves are more likely to give usefully unambiguous results than materials with extensive R-curve behaviour.

The AEA results using E 1304 indicated that for testpieces with $W/B = 2$ and notch radii of 0.125 mm only a small proportion of the tests gave valid results; with an average of $21.4 \text{ MNm}^{-3/2}$ compared with the plane strain K_{Ic} values of 20.5 (L-T) and 19.2 (L-T) $\text{MNm}^{-3/2}$ obtained in the tests at NPL on the same material. The agreement between the different test methods is good but further work is necessary to establish why a significant proportion of the CVN tests were invalid in order to recommend the correct CVN test procedure.

3.2.3 Fatigue crack growth - crack length measurements

Methods of measuring fatigue crack length in compact tension specimens are being evaluated at AEA Technology, Harwell. Results were presented from one particular test in which d.c.p.d., compliance and optical measurements were compared. This particular test was carried out at a constant ΔK of $10.5 \text{ MN m}^{-3/2}$ and an R-ratio of 0.1. These test conditions were chosen for operator convenience, to give a relatively high but steady crack growth rate. The test was interrupted periodically and the specimen was removed from the rig to enable optical measurements of the crack length to be made on both sides of the specimen.

Crack lengths were derived from p.d. measurements using a previously determined calibration curve. The p.d. calibration was carried out using a wire saw to introduce straight-fronted notches which were measured optically. Compliance was measured using a clip gauge positioned at the front face of the compact tension specimen. Compliance data were converted to crack lengths using the calibration given in ASTM standard E647. (In this particular test the specimen compliance was determined simply from the maximum and minimum loads and displacements recorded over each fatigue cycle. The procedure has since been modified so that compliance is determined from a linear regression fit to the top half of the fatigue cycle as is recommended in the ASTM standard).

On completion of the test the specimen was broken open to enable the final crack length to be determined precisely. Considerable crack curvature was evident. Because of this crack curvature, a 9-point averaging technique was considered preferable to the ASTM (E647/E399) recommended 3-point method. The final crack length, determined from a 9-point average measurement on the fracture surface, was 18.92 mm (compared to 19.74 mm for a 3-point average). The final crack lengths indicated by the various crack monitoring techniques were: p.d. 18.79 mm; compliance 18.67 mm; optical (average of two sides) 16.75 mm.

"Beach" marks on the fracture surface indicated that, once the crack had breached the specimen sides, the crack front curvature remained fairly constant. The optical measurements made during the test on the sides of the specimen were therefore corrected by the addition of a fixed length to allow for the curvature. The p.d. and compliance data were adjusted by interpolation to give agreement with the final measured (9-point) crack length. Good agreement was then obtained with the crack lengths measured by all three methods throughout the test.

In the next stage of testing the question of accuracy of crack length measurements when the precracking procedure is changed will be examined. It is likely that for routine measurements either a p.d. or a clip gauge technique will be acceptable. One notable

observation was that the shape of the crack front did not change appreciably throughout the precracking routines. In addition to constant R ratio tests a few tests were performed using a constant K_{max} procedure (decreasing K_{min} , increasing R ratio).

4 DRA FARNBOROUGH K_{Ic} TEST PROGRAMME

Dr P Powell described the results of fracture toughness tests at DRA from a DTI funded programme on landing gear struts involving suppliers and users of MMC. The testing is being carried out during an evaluation of candidate MMCs for application in aircraft undercarriages and is part of a Dowty Aerospace/DTI project. The full results of the tests are not discussed, just details of the fatigue pre-cracking procedures and of the effects of crack curvature.

Fracture toughness testing is being carried out on a range of aluminium alloys (2124, 7075 and 8090) reinforced with up to 25 vol% SiC_p . The composites have been produced by both powder metallurgy and spray casting routes. Testpieces have been machined from slabs up to 60 mm thick, in the 3 orientations L-T, T-L and ST-L.

K_{Ic} testing is carried out in accordance with BS 5447:1977, using 25 mm wide compact tension testpieces, thickness 12.5 mm. A chevron crack-starter notch is employed, having an included angle of 140° and a length at the testpiece surface of 0.15 W.

Fatigue pre-cracking was achieved by a two-stage procedure, at $R = 0.1$. In the first stage, the crack was initiated and grown to a length of $a/W = 0.2$ under a constant load amplitude of between 3.4 and 3.9 kN, depending on the material being tested. In the second stage, further growth to a final crack length of $a/W = 0.5$ was carried out under stress intensity factor control, using a decreasing K range or occasionally, a constant K range. Initial ΔK values were typically between 7 and 11 $MNm^{-3/2}$ and the final ΔK values were between 6 and 8 $MNm^{-3/2}$. The selection of ΔK levels in the second stage of pre-cracking depended on the growth rates encountered in the first stage, with the aim of achieving a final K_{max} of less than $0.7 K_Q$ as required by BS 5447.

The fracture toughness tests were carried out under displacement control at rates of between 0.3 and 0.5 mm/min; a total of 25 tests have been performed.

The fracture toughness results are given in Table 2, together with details of the fatigue pre-crack, analysed in accordance with the validity criteria in BS 5447. The majority of tests gave rise to load, P, versus COD records of Type 3, such that $P_{max}/P_Q = 1.0$ (ie valid); in one test, V4, the test record was of Type 1 and $P_{max}/P_Q = 1.05$ (valid). All of the tests also complied with the testpiece size criteria, viz average crack length a and thickness B were greater than $2.5 (K_Q/\sigma_y)^2$. In the majority of cases, the fatigue stress intensity factor K_f was successfully reduced below $0.7 K_Q$ during the final stage of fatigue pre-cracking (Table 2).

However, only one test, Y1, gave a fully valid K_{Ic} test result. The majority of tests were invalid because of excessive crack front curvature. In particular, the difference between crack length measurements at the quarter- and half-thickness positions exceeded 2.5% W in 9 tests, while the difference between maximum and minimum crack lengths exceeded 5% W in 20 of the 25 tests (Table 2, columns 4 and 5). The latter effect reflects the slower crack growth at the surfaces of the testpiece, which also led to a further 3 tests (U2, U3 and U5) being invalid because one of the surface crack lengths was less than 0.45 W (Table 2, column 2).

Crack front curvature is clearly a problem during fatigue pre-cracking and is the major cause of invalidity in K_{Ic} data. The use of a chevron notch appeared to have some success in reducing curvature but did not eliminate it when fatigue pre-cracking at a stress ratio of

$R = 0.1$. It was however observed that ten of the tests (U2, U5, U6, U8, W2, X2, Y2, Y3, Z1 and Z2) were quite close to achieving full validity.

A number of the testpieces (U7, V1, V2, W1, W3 and X3) exhibited preferential lagging of the crack at one surface, give an asymmetrical crack front. This gave rise to the largest differences between maximum and minimum crack length (Table 1, column 5). These crack fronts were not therefore of the typical parabolic shape which has been identified previously and correlated with the expected distribution of residual stress in the testpiece [3]. Further work is required to identify their cause.

The use of chevron notching appeared to reduce crack front curvature but did not eliminate it when pre-cracking at $R = 0.1$. Further tests will be carried out using higher stress ratios, R , for pre-cracking to determine if a combination of a high R and chevron notching can be employed to produce a valid crack front geometry.

5 OTHER CONTRIBUTIONS

Dr R Newley was concerned that values so far presented were still rather low for the applications with which he was concerned. It was also very important to have a test method which produced valid K_{Ic} data. He also expressed interest in knowing whether cyclic fracture toughness would be higher or lower than the static values. That is, whether the K_{max} associated with a particular fatigue ΔK at which a growing fatigue crack suddenly accelerated to gross failure was of the same value as the plane strain K_{Ic} for that material. In other words, whether the crack growth history was an important parameter to be considered in predicting the behaviour of components. Dr Newley also contributed a map (Fig. 6) of properties which specified the required toughness values for a range of material strengths and which gave some indication of the likely requirements regarding measurement uncertainties. It was agreed that $\pm 1 \text{ MNm}^{-3/2}$ was probably a reasonable figure which would be acceptable for the measurement method.

I Hughes from Alcan International expressed the view that the problem of crack curvature was not confined to MMC. Most of the strong advanced aluminium alloys for which they needed toughness data were proving troublesome in obtaining valid K_{Ic} data. In its absence K_Q values were quoted to customers.

BP Metal Composites' current requirements for toughness data were secondary to mechanical property needs on strength, ductility, stiffness and wear rates. The most important generic shapes of current interest were extruded tubes and forged plates and there was little requirement for sheet toughness tests at present.

Cambridge University were spending less time on toughness testing and were now examining short crack fatigue behaviour.

6 THIN SHEET TOUGHNESS TESTS

There are no current BS standards for metals in this area but it is likely to be an activity examined by the BS Standards Committee in the near future. However, the requirements for a suitable test method for MMC in this form are less clear. BP Metal Composites have not identified any immediate requirement but think it likely in the long term. Dr S Flitcroft (DRA, Farnborough) is starting to build up a database of thin sheet toughness tests on materials (MMC) with different thermal treatments. Sharp saw cuts are being used as the precrack in 100 mm wide testpieces. ASTM test methods are being used to generate R curves from 3 mm thick CT testpieces. C Hippsley (AEA Technology) outlined a test programme

to be performed within the DTI project where a comparison will be made of K-R and J-R tests.

7 INTERLABORATORY TESTS

Interlaboratory tests can have two main purposes

- i) To identify important problem areas
- ii) To quantify measurement uncertainties associated with a recommended procedure.

It was agreed by the meeting that sufficient work had already been carried out by the group to satisfy the requirements of i) above. It was decided that at the next meeting the most important item on the agenda would be to reach an agreement on an improved test method which could then be examined in a round robin in order to quantify uncertainties and to validate the method. This round robin will also probably include tests on a high strength Al alloy.

ACKNOWLEDGEMENTS

The NPL and AEA Technology research programme on toughness test methods for MMC is supported by the DTI "Materials Measurement Programme". Thanks are also due to detailed technical information provided by meeting participants, particularly R Boothby and C A Hipsley from AEA Technology and P Powell from DRA Farnborough.

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Table 1. Fracture toughness data (DRA Farnborough) for particulate reinforced aluminium alloys analysed in accordance with BS 5447: 1977

Test No.	Fatigue Crack Dimensions				K_I/K_Q	K_{IQ} MN m ^{-3/2}
	Minimum surface a_S/W	Average a/W	$\delta a/W$ (%)	$(a_{max} - a_{min})/W$ (%)		
BS 5477:1977	Min 0.45	0.45 to 0.55	Max 2.5%	Max 5.0%	Max 0.7	
U1	0.43*	0.49	2.3	7.3*	0.85*	11.5
U2	0.43*	0.47	0.7	4.4	0.72*	11.6
U3	0.44*	0.48	1.3	3.8	0.83*	10.5
U4	0.41*	0.51	2.5	10.8*	0.66	12.7
U5	0.44*	0.47	1.6	3.1	0.54	14.8
U6	0.46	0.50	1.5	5.4*	0.62	13.0
U7	0.43*	0.50	4.1*	7.9*	0.61	13.2
U8	0.47	0.53	1.2	5.8*	0.63	13.7
V1	0.38*	0.49	3.7*	12.7*	0.49	18.1
V2	0.36*	0.49	7.8*	16.7*	0.52	18.6
V3	0.45	0.52	1.7	8.1*	0.59	17.4
V4	0.46	0.54	3.1*	9.0*	0.65	16.3
V5	0.41*	0.49	2.9*	9.7*	0.59	16.6
V6	0.41*	0.50	2.9*	10.7*	0.52	18.4
W1	0.48	0.55	2.8*	7.5*	0.66	13.4
W2	0.46	0.51	1.7	5.5*	0.48	17.4
W3	0.42*	0.50	5.8*	10.9*	0.58	13.7
X1	0.52	0.54	0.3	2.0	0.81*	11.8
X2	0.46	0.51	1.5	6.5*	0.60	14.5
X3	0.42*	0.52	3.9*	12.3*	0.65	13.5
Y1	0.46	0.50	0.9	4.9	0.59	17.5
Y2	0.45	0.50	1.6	6.2*	0.66	13.6
Y3	0.47	0.51	1.0	5.1*	0.63	14.6
Z1	0.44*	0.49	2.5	5.2*	0.66	10.6
Z2	0.45	0.51	1.9	6.4*	0.63	11.9

* indicates that value fails to conform to BS standard

Table 2 Short Bar Chevron Notch Toughness - BP217 plate A690 (AEA Technology, Harwell)

Specimen types:

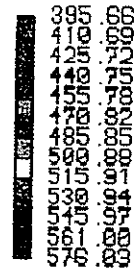
- (i) $B = 12.5 \text{ m}$, $W = 25.0$, (valid $W/B = 2.00 \pm 0.01$); valid $a_0 = 5.000 \pm 0.063$.
- (ii) $B = 12.5 \text{ mm}$, $W = 18.125 \text{ mm}$. (valid $W/B = 1.45 \pm 0.01$);
valid $a_0 = 6.013 \pm 0.063$.

Spec.	W/B	a_0 (mm)	p	$K(\text{MN m}^{-3/2})$	Comments
S11	2.010	5.008	[0.265]	[23.0]	cracking out of plane
S12	1.993	[4.776]	[0.24]	[21.6]	
S16	1.994	4.979	[-0.113]	[21.4]	
S17	2.004	4.996	0.03	21.2	valid result
S18	2.001	5.040	0.095	22.1	valid result
S19	2.004	5.022	0.056	21.0	valid result
S1	[1.463]	[5.804]	[0.119]	[23.7]	notch 0.3 mm off centre
S2	[1.475]	[5.597]	0.092	[23.7]	notch 0.5 mm off centre
S3	1.456	[6.270]	[0.14]	[21.4]	
S7	1.456	[6.343]	-0.002	[21.7]	
S8	1.458	[6.322]	[-0.0148]	[21.3]	clip gauge slipped
S9	[1.466]	[6.409]	0	[21.7]	

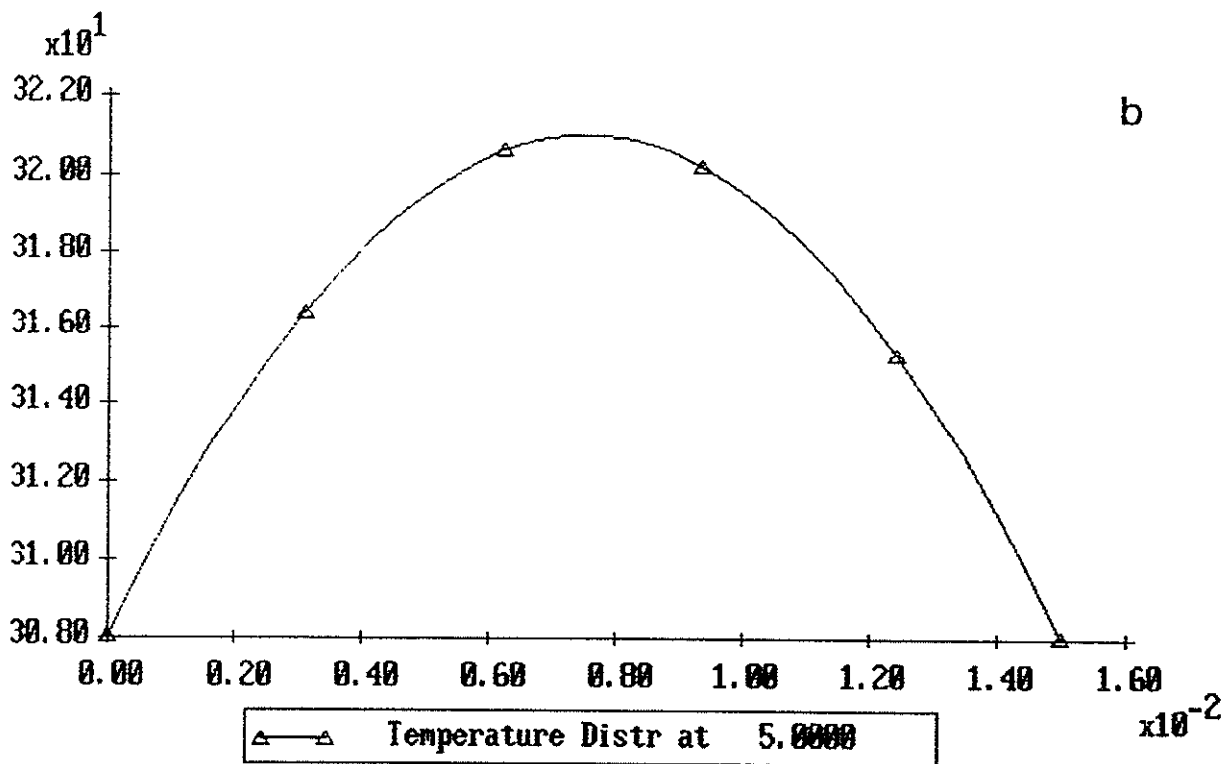
Note (i) square brackets denote invalidity:

(ii) p is a measure of plasticity, defined in ASTM E1304; the valid range is $-0.05 \leq p \leq +0.10$.

- Fig. 1 a) Contour map of temperatures in a quenched plate (showing an end effect) after 1 second.
b) Parabolic distribution across section A-A.
- Fig. 2 a) Temperature distribution across an infinite plate during a quench.
b) Parabolic fit to the temperature distribution profile.
- Fig. 3 Crack front profiles in 8 mm thick CT specimens.
a) $R = 0.1$, L-T, b) $R = 0.1$, T-L, c) $R = 0.5$, L-T, d) $R = 0.5$, T-L.
- Fig. 4 Crack front profiles in 15 mm thick CT specimens.
a) $R = 0.1$, L-T, b) $R = 0.1$, T-L, c) $R = 0.5$, L-T, d) $R = 0.5$, T-L.
- Fig. 5 Provisional values of toughness K_Q for various CT testpiece thicknesses.
- Fig. 6 Design guidelines for defect tolerance (Courtesy Dowty Aerospace).

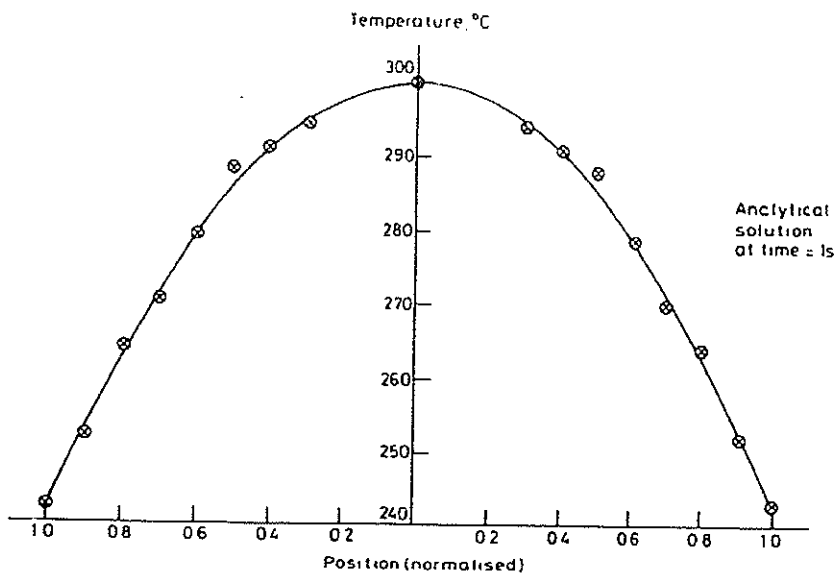


a

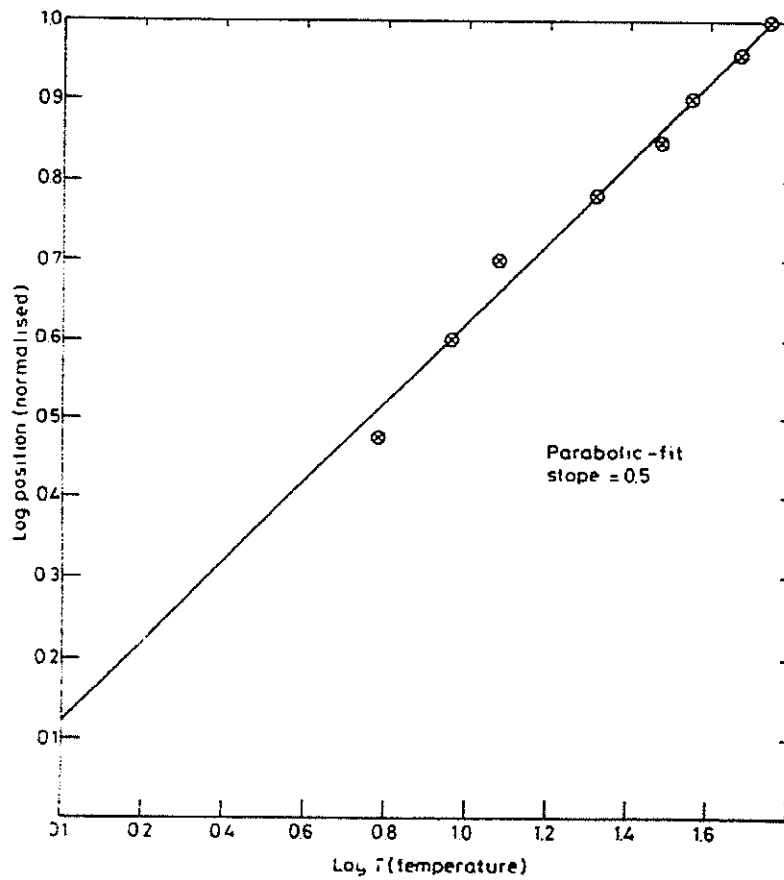


b

Fig. 1 a) Contour map of temperatures in a quenched plate (showing an end effect) after 1 second.
 b) Parabolic distribution across section A-A.



a



b

Fig. 2 a) Temperature distribution across an infinite plate during a quench.
 b) Parabolic fit to the temperature distribution profile.

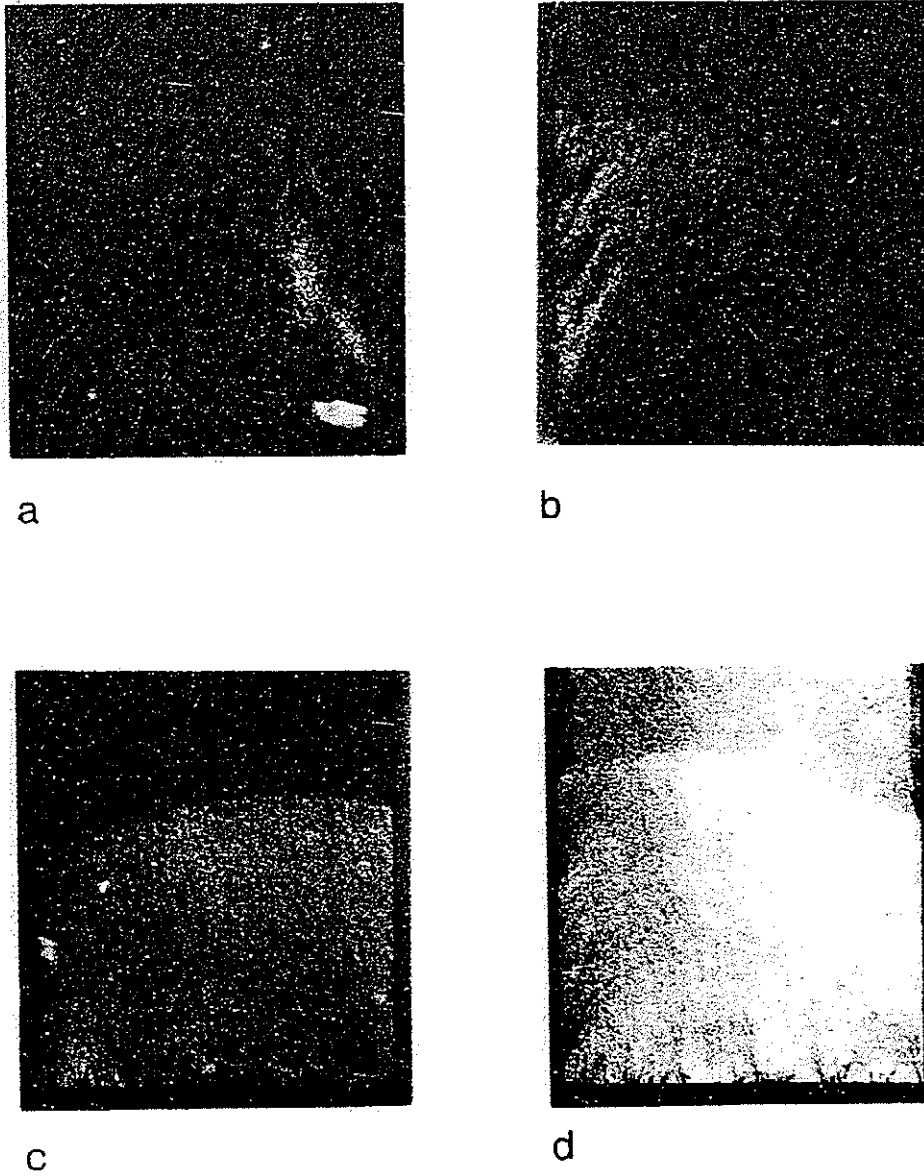


Fig. 3

Crack front profiles in 8 mm thick CT specimens.
a) $R = 0.1$, L-T, b) $R = 0.1$, T-L, c) $R = 0.5$, L-T, d) $R = 0.5$, T-L.