OBSERVATIONS ON TEARING INSTABILITY IN AN ALUMINIUM ALLOY

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Fracture toughness in thick aluminium is usually measured by K_{1c} testing. However, as shown in this paper, K_{1c} may be very over conservative for structural design. Firstly, elevated toughness is obtained at lower values of constraint (shallow notches or tension loading). Secondly, the energy dissipation rate for tearing is increased significantly when a component with structural dimensions (width much greater than thickness) is tested. The results are used to evaluate relevant constraint and tearing instability theories.

INTRODUCTION

Fracture toughness in thick section high strength aluminium alloys is usually low enough to be measured by K_{1c}; but unlike cleavage fracture in steel, crack extension is by a rate insensitive tearing mechanism, which can be stable or unstable, depending on the test configuration.

This report describes fracture toughness tests on a 7020 aluminium alloy (2% Mg, 4% Zn) with yield strength of 400 MPa and an ultimate strength of 450 MPa. The material was supplied in the form of an extruded T bar (part of a bridge section). All specimens were extracted from the web which was 25mm thick by 300mm deep (including the flange).

The data are interesting in contributing to various aspects of current research into fracture mechanics theory, particularly: the effect of constraint on fracture toughness; the meaning of the J resistance curve; and the prediction of tearing instability in a structure.

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SPECIMEN DESIGN

Most specimens were made as TPB (three point bend) with W = 50mm, B = 25mm, a/W = 0.5, and S/W = 4. After fatigue pre-cracking at K = 15 MPa√m, W was reduced on selected specimens (keeping the ligament b constant at 25mm) to give a range of a/W between 0.05 and 0.5.

A small number of centre cracked tension (CCT) specimens were also made with 2W = 75mm, 2a = 25mm (a/W = 0.3); and one very large bend specimen with W = 200mm, a/W = 0.2, and S/W = 4. These specimens were all 25mm thick. All specimens were notched in the LT direction, L is the extrusion direction.

ANALYSIS OF DATA

The fracture toughness data were used to investigate the effect of constraint on J_c using T stress as a constraint indexing parameter. J_c was defined at maximum load, which corresponded with instability in the shallow notch TPB specimens (a/W < 0.35) and the CCT specimens. Maximum load in the deeply notched TPB specimens gave a valid K_{1c}, but crack growth was subsequently stable. This enabled crack growth resistance to be determined in terms of dJ/da and the energy dissipation rate, D.

The load versus deflection curves for the shallow notched TPB and CCT specimens showed a sudden unstable crack jump at maximum load. In the CCT specimen this resulted in total separation of the specimen. In the shallow notched TPB the crack arrested within the specimen ligament. The result of the large TPB test will be discussed later.

RESULTS

Effect of Constraint

Figure 1 shows J_c (calculated at maximum load) as a function of specimen geometry. Figure 2 shows the same data rearranged as a function of T stress (for details, see Sumpter (2)). This is successful in bringing the J_c values for the CCT specimens into line with those for the shallow notch TPB with equivalent T stress. A similar result could have been obtained by the use of Q. T is used here as the test traces are nearly linear to failure.

Tearing Resistance

The tearing resistance was obtained using a/W = 0.5 TPB specimens with a multi-specimen technique. The value of $J_{0.2}$ was 0.018 MN/m, and dJ/da was

5 MN/m^2 over the first 4mm of crack growth. (Tearing modulus equal to 2.2). All the validity criteria in reference (1) were satisfied. The $J_{0.2}$ value of 0.018 MN/m (18 kJ/m^2) corresponds closely to the average G_{1c} value of all the a/W = 0.5 tests in Figure 1. An alternative measure of tearing resistance is provided by the energy dissipation rate, D. This is obtained by plotting total absorbed energy against crack extension area and determining the slope. In a perfectly elastic 'Griffith failure' it would be expected that D would correspond with J_c. Because of the occurrence of plastic energy dissipation during the propagation phase, D for the aluminium alloy is estimated to be twice J_c, at around 40 kJ/m^2.

After the first 100mm^2 of crack growth both D and dJ/da begin to increase. For instance, at 250mm^2 of crack growth (average extension 10mm) D was estimated to be around 150 kJ/m^2 and dJ/da around 15 MN/m^2. This effect can be attributed to crack tunnelling.

Tearing Instability Prediction

A burst of unstable fracture occurred in all the small (b = 25mm) TPB specimens in which a/W was 0.3 or less. In the CCT specimen, unstable propagation occurred across the whole ligament. No unstable propagation was seen in the large (b = 160mm) bend specimen.

Table 1 summarises some key parameters for these tests in order to assess the validity of various instability criteria that have been proposed in the literature. It is assumed at this stage that all the driving force terms are purely elastic, based on G and dG/da calculated at constant machine displacement for a measured test fixture stiffness of 200 kN/mm. Instability should occur if:

J_R curve approach; $$\frac{dG}{da} \rangle \frac{dJ}{da} \qquad \text{(1)}$$

or, energy dissipation rate approach; $$G \rangle D \qquad \text{(2)}$$

DISCUSSION

It can be seen from Table 1 that neither the J_R curve or energy dissipation rate theories would predict instability from the shallow notch TPB tests, except perhaps in the case of the smallest notch size, where dG/da does exceed dJ_R/da. In other cases G and dG/da are less than the measured resistance curve values of D (40 kJ/m^2) and dJ_R/da (5 MN/m^2). If any prediction could be said to be validated by the small 3PB data it would be that instability will occur whenever the elastically calculated dG/da is positive. Further more detailed analyses incorporating plasticity in the driving force term will be undertaken in the future, but meanwhile it can be noted that, from a practical point of view, all tests with a square ligament (B = b = 25mm) give a very misleading impression of the tearing resistance of a large structure.

TABLE 1 - Instability Predictions

Specimen Type	a/W	J_c kJ/m^2	G_c kJ/m^2	dG/da (kJ/m^2)/mm	Max Load/ Limit Load	Stability
Small TPB b = 25mm	0.1	44	31	7	0.79	Unstable
	0.2	24	24	1.9	0.55	Unstable
	0.3	23	22	0.7	0.47	Unstable
	0.5	22	20	-0.7	0.61	Stable
Large TPB b = 160mm	0.2	330	190	1.9	0.80	Stable
CCT b = 25mm	0.3	57	34	1.6	0.80	Unstable

Notes (i) Material resistance parameters from b = 25mm deeply notched TPB specimens dJ/da = 5 (kJ/m^2)/mm, D = 40 kJ/m^2.

(ii) Machine displacement control plus text fixture stiffness of 200 kN/mm included in dG/da calculation.

The load deflection curve of the large TPB specimen (B = 25, b = 160mm) showed initial non-linearity when J of .018 MN/m was reached at a load of 85 kN; but unlike the small TPB specimens, where crack initiation resulted in a falling load, the load in the large TPB test continued to increase. The test was eventually stopped at a load of 247 kN. At this stage G was 190 kJ/m^2, J was 0.33 MN/m, and dG/da was 1.8 MN/m^2.

Viewed from the surface, the crack appeared to be deviating at an angle from the original. Breaking open of the specimen revealed this to be the edge of a large shear lip which would eventually form part of a fully slant fracture over the full thickness of the specimen. There was an area of flat fracture in the centre of the specimen, but this tapered down much more rapidly than the flat fracture in the small TPB specimens.

It is very surprising that changing the ligament shape from square to rectangular in a given thickness should make such a large difference to the fracture mode. Crack initiation in the large TPB specimen took place at only 25% of the plane stress limit load for this design of specimen under conditions which satisfy plane strain K_{Ic} validity criteria. In spite of this, the move to a plane stress ligament (b »B) of the type that would be seen in a structure, has effectively increased the energy dissipation rate from around 40 kJ/m^2, which is low enough to induce instability in realistic test configuration, to a figure nearer 1000 kJ/m^2, which would guarantee structural safety under all possible loading scenarios short of plastic limit load.

CONCLUSION

Constraint indexing methods (T and Q) have previously been applied to explain the effect of test piece geometry on J_c for cleavage fracture of steel. This report has applied the same methods to J_c at maximum load for a 25mm thick high strength aluminium alloy, which fails by tearing. It is shown that the geometry effects can be rationalised in terms of T stress.

Although the aluminium alloy gave a valid K_{1c} (34 MPa$\sqrt{m}$) in the thickness tested, the same test could also be used to derive a J_R curve with a slope, dJ/da = 5 MN/m^2, and an energy dissipation rate, D = 40 kJ/m^2. Instabilities occurred in shallow notched bend and centre cracked tension specimens.

Various theories are explored to explain the delineation between stable and unstable tearing, but the results are inconclusive at this stage.

More significant is that when a structurally realistic specimen was tested, still 25mm thick, but with a 160mm deep uncracked ligament, the tearing mode changed completely to fully slant fracture with an energy dissipation rate nearer to 1000 kJ/m^2. This would provide fracture safety in all possible loading scenarios short of plastic limit load, and calls into question the relevance of characterising the fracture toughness of thick aluminium by K_{1c} testing.

REFERENCES

(1) ISO/TC164/SC4 - N128. Draft Unified Method of Test for the Determination of Quasistatic Fracture Toughness, March 1994.

(2) Sumpter, J.D.G. "An Experimental Investigation of the T Stress Approach", ASTM STP 1171, 1993, pp. 492-502.

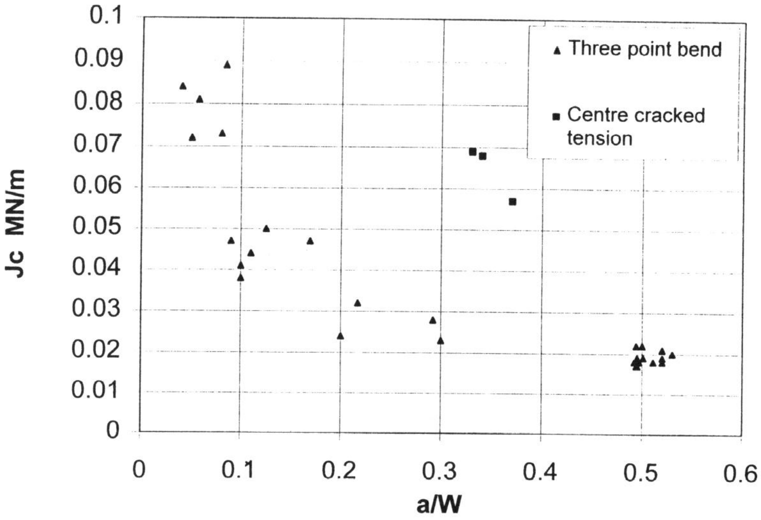

Figure 1 J_c as a function of test piece geometry for 7020 aluminium alloy

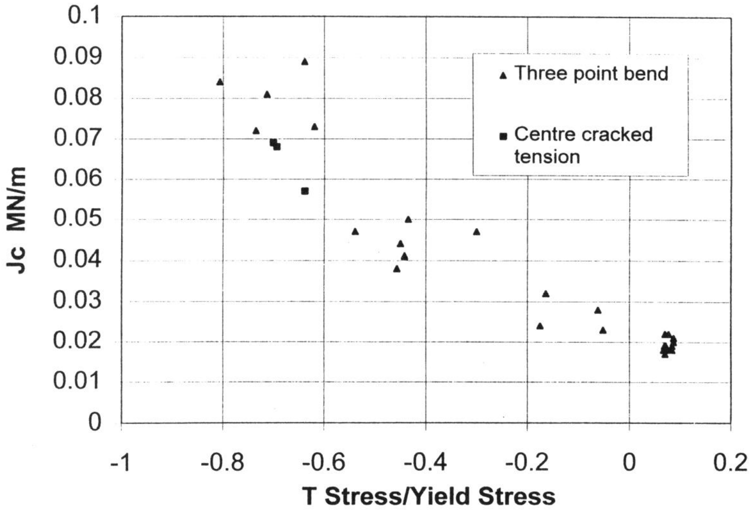

Figure 2 J_c data in figure 1 reorganised in terms of T stress