DUCTILE TEARING OF THIN SHEETS: A COMPARISON OF THREE PLANE STRESS TOUGHNESS CHARACTERISATION PARAMETERS

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The mode-I fracture toughness of thin sheets of Al-Mg alloy A5182 (low anisotropy) and commercial purity titanium (high anisotropy) DENT specimens under plane stress and generalised plasticity has been studied. Photographic records of the crack initiation and propagation processes have allowed for a simultaneous derivation of the "specific essential work of fracture" w_e , CTOD, and J-R curves. The effect of the initial notch tip radius on the apparent toughness has also been assesed. Aside from experimental difficulties concerned with the determination of fracture parameters of highly ductile and strongly work-hardening metal sheets, theoretical doubts remain on equating J_c to w_e, the latter requiring much simpler experimental determination tests.

INTRODUCTION

The fracture process of thin ductile metal sheets under conditions of plane stress and generalised plasticity is a common event in a wide range of engineering problems ranging from the quasi-static growth of cracks in Al-based alloy aircraft bodies to the easy-opening end tops of beverage and food cans. Nevertheless, the characterisation of the fracture toughness in such cases is far beyond the realm of LEFM, and fracture parameters specially intended for elastoplastic problems, e.g. CTOD and J, have turned out to be either difficult to determine in practice (Dawicke et al. (1)) or dependent on sample geometry and load conditions (Hodgkinson and Williams (2)).

The aim of the present work is to verify the feasibility of the "specific essential work of fracture", w_e , as a geometry-independent toughness parameter for the fracture process of thin ductile metal sheets under plane stress conditions and generalised plasticity, as stated in the literature (Atkins and Mai (3), and Mai and Cotterell (4)). A major advantage provided by this method is the need for very simple tensile tests for the determination of the "specific essential work of fracture", w_e .

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By plotting the "specific work of fracture" w_f, i.e. work of fracture divided by the initial cross section, of a series of DENT (double edge-notched tension) specimens versus the initial length of the remaining ligament between notches a linear plot is obtained, the intercept being the "specific essential work of fracture" (3,4). The obtained w_e is compared with J_c in order to verify the equivalence of both parameters.

The similitude of stress distribution in the ligament among the specimens of a series is of crucial importance when determining w_e . The effect on fracture toughness of the initial notch tip radius, NTR, which modifies the stress-strain fields around the notches, and therefore in the ligament, is analysed. Difference in fracture toughness owing to crystallographic texture is also taken into consideration.

EXPERIMENTAL PROCEDURES

Tension tests until fracture were carried out on DENT specimens obtained from thin sheets of 1.25-mm-thick Al-Mg alloy A5182 and commercial purity titanium grades T-40 and T-60, 3 and 1 mm thick respectively. All the materials had been annealed after cold-rolling. DENT specimens were 200 mm long, 72 mm wide, and with an initial gauge length of 50 mm. Due to the on-rolling-plane anisotropy of titanium sheets, tensile tests were carried out in rolling (RD) and transverse direction (TD). Straight notches with rounded tips were machined from both edges, with notch tip radii of 0.25 mm in T-40 samples, 0.25 and 0.50 mm in T-60 samples and 0.15 μm (fatigue pre-cracked from notches), 0.25 and 0.50 mm in A5182. Tests were carried out at room temperature and at a constant cross-head speed of 0.1 mm/min. Every test was photographically recorded to allow for an ulterior determination of the evolution of the crack lenght, a, and the notch tip opening displacement, COD. To make this possible, sample surfaces had been previously polished up to a mirror-like appearance.

The "specific essential work of fracture" is obtained for a series of samples with a different initial ligament lenght, l, as the intercept of the linear regression of w_f vs. l. Table 1 shows in detail the load direction, the notch tip radius and the ligament length for each one of the series analysed.

TABLE 1 - Detailed Description of the Different Series of DENT Samples.

Material	Load Direction	Notch Tip Radius (mm)	Ligament Lengths (mm)
A5182	RD	0.00015 (estimate)	9, 12, 15, 18, 21
A5182	RD	0.25	4, 6, 9, 12, 15, 18, 21, 24
A5182*	RD	0.50	4, 8, 12, 18, 20
T-40	RD	0.25	6, 9, 12, 15, 18, 21, 24
T-40	TD	0.25	6, 9, 12, 15, 18, 21, 24
T-60	RD	0.25	4, 6, 9, 12, 15, 18, 21, 24
T-60	TD	0.25	6, 9, 12, 15, 18, 21, 24
T-60	RD	0.50	4, 8, 12, 18, 20
T-60	TD	0.50	4, 8, 12, 18, 20

The method proposed by Begley and Landes (2) was applied in order to obtain the J-R curve and J_c for each sample. The value of J_c for a series of samples was determined as the average of the individual J_c values of each sample in the series. The COD was measured at 45° from the current notch tip. The COD vs. Δa curve was obtained for each sample, the CTOD being the intercept for zero Δa. The CTOD for the whole series is considered to be the average of the individual values.

RESULTS

Due to the high ductility of the sheets, the fracture process of DENT specimens takes place under quasi-static conditions, with the cracks growing slowly from both edges towards the centre of the ligament. The load is maximum near the point of crack growth initiation and decreases with crack propagation. Unstable fracture eventually occurs at very low loads.

Table 2 shows the results obtained for the different fracture parameters analysed. Note the appreciable experimental uncertainty affecting the values. Those related to w_e are partly due to the narrow range of l used in this work and partly inherent to the method as they represent, for each series, the 95%-confidence interval at the intercept for the linear regression w_f vs. l, such curve being plotted through data located far from the ordinates axis. DENT specimens with ligament lengths shorter than 3...5 times the sheet thickness would yield w_f values far below the straight line plotted through data obtained for larger values of l. Such specimens do not exhibit prevailing plane-stress conditions and present lower fracture toughness. Figure 1 shows the w_f vs. l curve for a A5182 alloy series with a notch tip radius of 0.25 mm. The 95%-confidence interval is also plotted. With respect to J_c and CTOD data, uncertainty stems from considering average values and additional errors, which cannot be estimated, are committed when measuring crack length and COD on photographs. Figure 2 shows the J-R curves obtained for the same series as in Figure 1. The J_c for each sample is the intercept for zero Δa. Blunting has already been taken into consideration on the plots. Figure 3, in turn, shows the crack opening as a function of crack length increment for the same series as in previous figures. The CTOD for each sample is the intercept for zero crack length increment minus the initial notch tip diameter.

TABLE 2 - Fracture Parameters obtained for the different Series analysed.

Material	NTR (mm)	w_e (kJ/m^2)	Jc (kJ/m^2)	CTOD (mm)
A5182, RD	0.00015	56 ± 53	33 ± 16	0.23 ± 0.12
A5182, RD	0.25	116 ± 14	144 ± 306	0.76 ± 0.21
A5182, RD	0.50	141 ± 63	170	------
T-40, RD	0.25	197 ± 112	542 ± 113	1.74 ± 0.31
T-40, TD	0.25	199 ± 181	651 ± 118	2.01 ± 0.27
T-60, RD	0.25	213 ± 91	523 ± 280	0.91 ± 0.39
T-60, TD	0.25	342 ± 146	536 ± 189	1.33 ± 0.76
T-60, RD	0.50	783 ± 388	975 ± 270	1.13 ± 0.27
T-60, TD	0.50	835 ± 141	985 ± 136	1.30 ± 0.08

DISCUSSION

The "specific essential work of fracture" seems to be a suitable parameter in the case of thin metal sheets under plane-stress and generalised plasticity conditions. A question arises when applying classical parameters in Fracture Mechanics, such as elastoplastic J_c, to situations which exhibit macroscopic unloading and appreciable stable crack growth. No restrictions are violated with the w_e-method. In addition, simple tensile test are required for the determination of w_e and specimens do not need any special treatment. The "specific essential work of fracture" is equivalent to the specific toughness R, energy consumption inside the fracture process zone during a unit fracture surface increment. The w_f vs. l data obtained from the tensile tests carried out in the present work fit reasonably well to a straight line, as shown in Figure 1. Unluckily, the method involves some disadvantages. Firstly, a large number of specimens are needed in order to reduce the uncertainty interval at the intercept, thus providing a reliable w_e value. Secondly, possible intrinsic R-effects are not detectable since w_e represents an average energy consumption during the whole fracture process, from initiation to final fracture. Indeed, w_e is very close to a propagation toughness as crack propagation accounts for an important part of the total energy consumed. Finally, a very complicate analysis is necessary in order to simulate the actual plastic processes taking place in the specimens in more complex geometries. A linear relationship between w_f and l is valid for DENT and similar geometries, not being extrapolatable to a general case.

Figure 4 is a comparison between the results for w_e and J_c obtained from the tensile tests. It is far from obvious that both parameters are equivalent. Indeed, J_c results to be clearly greater than w_e , especially in titanium specimens. This fact brings a doubt about the feasibility of the method by Begley and Landes in the presence of unloading and stable crack growth. Under such conditions, irreversible work is dissipated not only in the fracture process zone, but also in remote plastic phenomena. However, the J-integral derived from energy areas below load-displacement curves does not distinguish between both contributions to the total energy consumption, thus yielding an apparent value in excess of the actual toughness (3). Moreover, even if a valid J-integral determination method is assumed, some doubts remain as to whether w_e and J_c represent an unique physical concept and, hence, should exhibit similar values, despite the large uncertainty affecting the data. The "specific essential work of fracture" is essentially an average energy consumption inside the fracture process zone, also in the through-thickness direction, during the whole fracture process, i.e. necking, crack initiation, and propagation. The critical J_c , on the contrary, represents the energy flow to the crack tip zone at the point of crack growth initiation and, in the case of thin sheets, values are derived from crack length measurements carried out on specimen surfaces where cracks are the shortest due to a higher fracture toughness. Whether critical J-integral or w_e should exhibit a higher value is difficult to predict in advance.

By observing Figure 3, it is possible to say that crack growth initiation takes place at a constant CTOD for a series of specimens. Furthermore, the CTOD increases as cracks grow and reaches a constant value during subsequent stable crack propagation. The CTOD would hence represent a valid fracture characterisation parameter. However, the

CTOD in the present work represents the critical opening displacement of notches and an utterly different behaviour, from a maximum at crack growth initiation to a lower stable value during propagation, has been reported in literature after observing the crack tip evolution with high resolution optical devices (1).

All the parameters studied, i.e. w_e , J_c , and CTOD increase with greater NTR. This fact has been reported thoroughly in literature for J_c , but the same applies now to w_e , which is related only to the processes ocurring inside the fracture process zone. Differences in stress-strain distributions in the ligament due to different NTR are responsible for such a behaviour in the case of w_e . A very detailed analysis of this relationship could avoid the need for fatigue pre-cracking methods prior to tensile tests, simple extrapolation to near-zero NTR being sufficient. It is to be noted the apparent fracture anysotropy of both titanium sheets despite the fracture parameter used to describe their toughness. Higher values are always obtained in TD rather than in RD.

CONCLUSIONS

i) The "specific essential work of fracture" is a suitable method for the fracture toughness characterisation of thin ductile metal sheets, the w_f vs. l curve fitting well to a straight line. The experimental derivation of w_e is very simple, but some disadvantages of the method exist: unability to discern R-effects, uncertainty affecting extrapolated values and difficulty to apply to more complicate geometries. ii) Some doubts remain in the case of J-integral derivation, which does not account for irreversible work in remote areas of the specimens during unloading, and observed values could be in excess of the actual fracture toughness. Uncertainty also affects the derived J-integral. Both experimental uncertainty and theoretical aspects bring a doubt about the equivalence of w_e and J_c . iii) The CTOD seems to be a valid fracture parameter for both crack initiation and stable crack propagation, but a reliable analysis of crack tip evolution requires very complicate experimental equipment. Notch opening displacement, as measured in this work, might be a poor approach to the actual CTOD. iv) Despite the parameter used to characterise the fracture toughness of DENT specimens of thin ductile metal sheets, higher values are observed the greater the notch tip radius. v) The fracture toughness in commercial purity annealed titanium sheets is higher in TD than in RD.

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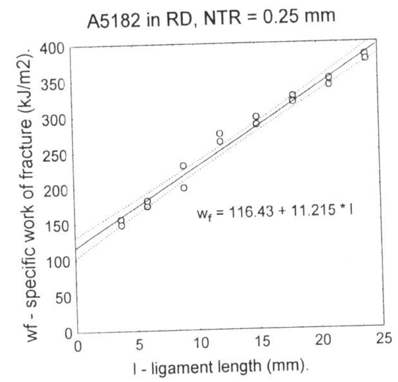

Figure 1. Linear regression w_f vs. l.

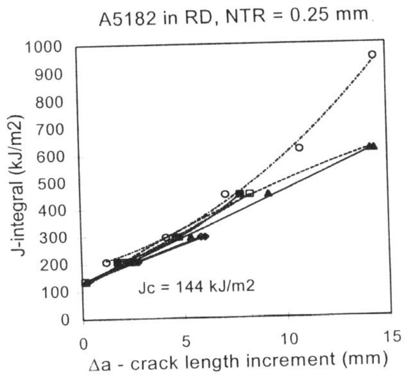

Figure 2. J-R curves and average J_c.

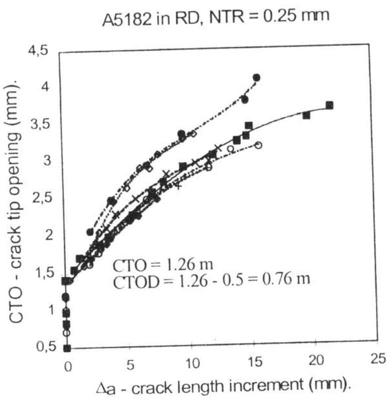

Figure 3. Crack tip opening and CTOD.

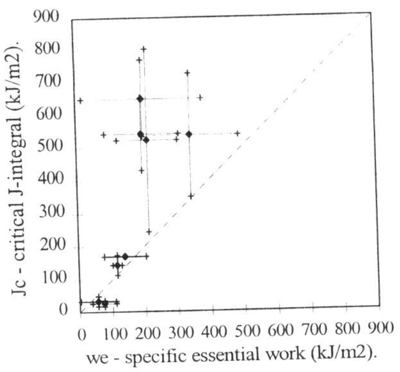

Figure 4. Comparison between J_c and w_e.