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THICKNESS DEPENDENCE OF DUCTILE TEARING IN THIN ALUMINIUM PLATES – EXPERIMENTS AND MODELLING

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ABSTRACT

The tearing resistance of 6082O aluminum panels has been investigated using DENT (Double Edge Notched Tension) specimens of various thicknesses, *t*. The J_R curves were determined using a multiple-specimens method. Several geometrical parameters were measured on polished section of the unloaded specimens such as crack tip opening displacements and reduction of thickness at the crack tip. In agreement with a previous study, the *J*-integral at cracking initiation, J_c, and the critical crack tip opening displacement, δ_{CTODc}, were found to increase with thickness (Pardoen *et al.*, *J. Mech. Phy.s Solids* 1999). The tearing resistance also increases with thickness. The potential of a 3D-interface cohesive zone model to predict the crack propagation rates and the thickness effect has been analyzed. An original method is proposed to experimentally determine the work per unit area spent for material separation in the pure plane stress regime. The limit of cohesive zone type of models for covering the full range of thicknesses from plane stress to plane strain is discussed based on considerations related to the void growth micromechanism.

INTRODUCTION

The demand for lighter structures relies on the use of thinner plates, which, in turn, implies the development of both more resistant and damage tolerant alloys and more robust methods for structural integrity assessment. One important open issue about the structural integrity assessment of thin plates concerns the thickness dependence of cracking resistance in the plane stress or approximately plane stress regime. The difficulty with thin ductile plates lies in the 3-D character of the crack tip stress and strain fields. Pure plane stress analysis is only acceptable for thin sheets. Diffuse and localized plastic yielding coexist under the form of a neck at the crack tip surrounded by a large plastic zone. The macroscopic fracture toughness of thin plates, as given by the value of the J-integral at cracking initiation J_c, results from energy spent in the fracture process zone in front of the crack tip. Two contributions can be distinguished:

- the work per unit area for necking which depends on thickness (indeed, the height of the necking zone increases proportionally to the plate thickness);
- the work per unit area for damage until final material separation in a localized band (noted Γ_0). The height of that band is dictated by the fracture mechanism and is thus, in principle, geometry independent.

The fact that J_c includes the work of necking, which can be sometimes much larger than Γ_0, induces the well-known thickness effect [1,2,3]. As long as the stress state is purely plane stress, fracture toughness linearly increases with thickness. As thickness increases, the crack tip stress field evolves towards plane strain and the increase of the fracture toughness slows down, reaches a maximum and decreases finally to the plane strain value. Strictly speaking, J_c is thus not a material property because of the thickness dependence.

Cracking in 6082O aluminum plates has been investigated using DENT specimens of various thicknesses, *t*, (from 1 to 6 mm) with constant ligament length $l_0/W = 1/3$ (see Fig. 1). In Ref. [4], only the fracture toughness at cracking initiation has been discussed in terms of J_c and of the critical crack tip opening displacement δ_{CTODc}. A method was proposed for separating the fracture work spent for localized necking and the work for material separation. 3D finite element simulations have been performed in order to investigate the effect of the thickness on the stress triaxiality inside the fracture process zone.

In this report, we present the second part of the study devoted to the characterization and modeling of the effect of the thickness on the tearing resistance. The pertinence of 3D cohesive zone elements for modeling the fracture process is investigated. The fact that the basic cohesive zone formulation does not incorporate any effect of the stress triaxiality will turn out to be a major limitation for its use in thin plate fracture.

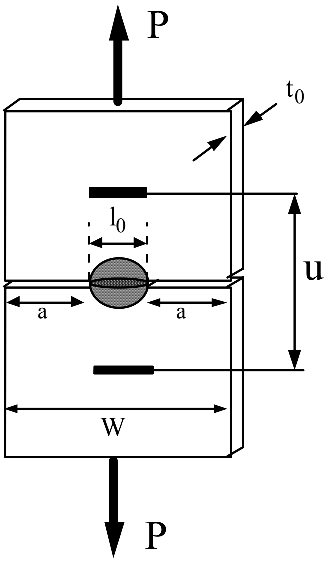

Figure 1. Testing of a DENT specimen

MATERIAL AND EXPERIMENTAL PROCEDURES

The material consists of 6 mm-thick plates of aluminum alloy 6082 in O temper. Low values of hardness (35HBN) and yield stress (σ_0 = 50MPa) are well suited for the purpose of this study. Indeed, high ductility results in a large range of thicknesses for which 3D effects (out-of-plane constraint effects) significantly affect fracture toughness. The flow rule is well represented by a power law curve

$$\sigma = 202.1\ \varepsilon^{0.247}\ . \tag{1}$$

The Young's modulus is equal to 70 GPa, and the Poisson ratio is equal to 0.34. In order to obtain a wide range of thicknesses without change of the microstructure, the 6mm-thick plates were thinned by mechanical milling. Microstructure was found homogeneous along thickness. In this report, results for 4 different plate thicknesses will be discussed: 0.6, 1, 2 and 4 mm. The other dimensions of the DENT specimens, length and width, were 150 mm x 60 mm. Notches were made by cutting the plate first with a saw and subsequently with a fresh razor blade in such a way as to obtain sharp initial notch tips. The validity of this precracking method is justified by the large values of δ_c. The specimens were strained along the rolling direction for various degree of crack extension Δa. J has been computed from the load-displacement curve using the simple relation derived by Rice *et al.* [5] to evaluate a mean value for the J integral ("mean" because J varies along the crack front)

$$J_{DENT} = \frac{K_I^2}{E} + \frac{1}{l_0 t_0}\left[2\left(\int_0^{u_p} P du_p\right) - Pu_p\right] \tag{2}$$

where K_I is the stress intensity factor, E the Young's modulus, P the applied load, and u_p is the plastic displacement. After unloading, the specimens are machined, embedded in an edge-retention resin, ground and polished. Each specimen is ground and polished several times in order to measure Δa through the thickness, which allows quantifying the magnitude of the tunneling effect. Crack tip opening quantities were also measured in order to estimate the CTOD at crack initiation, δ_{CTODc}, following the method of ref. [6].

EXPERIMENTAL RESULTS

The fracture profile of broken DENT specimens of alloy A6082O presents shear lips restricted only to the surface of the plates. The fracture profile is, for the different plate thicknesses, predominantly flat along the whole ligament length (on a macroscopic point of view). A classical profile with dimples is observed at the microscale. The phenomenon responsible for cracking initiation is mechanism of void growth and coalescence. Shear localization is definitely not the dominant phenomenon (no slant fracture). After a transient of crack extension, the crack tip necking becomes steady-state with a reduction equal to about 60% of the initial thickness [4], independently of the value of the initial thickness.

The J_R curves for thicknesses 0.6, 1, 2 and 4 mm are given on Figure 2. A change of thickness significantly affects both the initiation of cracking and the tearing resistance.

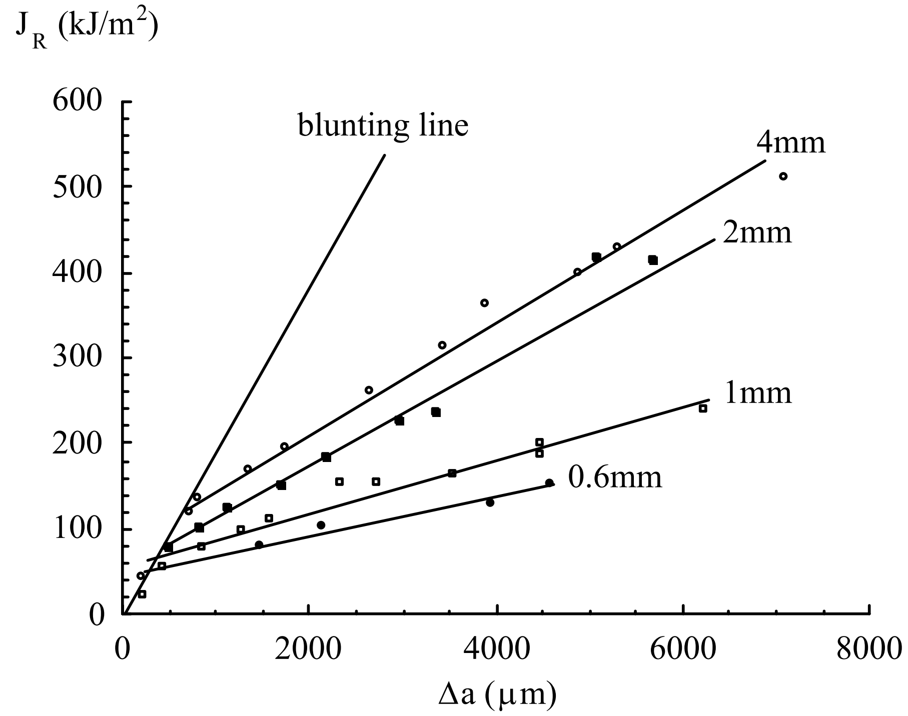

Figure 2: J_R curve for DENT plates with 0.6, 1, 2 and 4 mm thickness

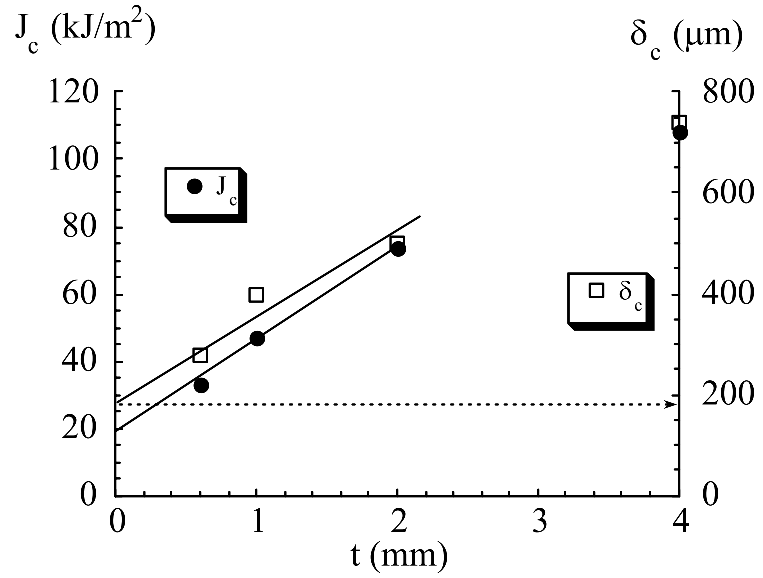

Figure 3: Variation of J_c and δ_{CTODc} as a function of the plate thickness

Figure 3 shows the variation of J_c at cracking initiation (defined in a physical sense as the first cracking event) as a function of thickness. These values of J_c are more accurate than the one obtained in ref. [4] where cracking initiation was detected by means of a camera equipped with a zoom focusing on the midsection of the specimen (the new results naturally give smaller J_c's). Linear regression of the variation of J_c as a function of t (the regression is performed only on data corresponding to small specimen thicknesses which giving rise to near plane stress regime) yields a constant terms equal to about 20 kJ/m^2, which agrees with the results of ref. [4]. Figure 3 also shows the variation of the CTOD at cracking initiation as a function of the thickness. Linear regression of the variation of δ_{CTODc} as a function of t yields a constant terms equal to 0.18 mm.

In ref. [4,7], it was proposed that this regression allows separation of the fracture work per unit area spent for material separation Γ_0 and the work for necking at the crack tip. The new parameter Γ_0 would correspond to the constant work required for nucleation, growth and coalescence of voids, until final separation in one localized band inside the fracture process zone (FPZ). This fracture work more intrinsically characterizes fracture resistance of thin plates because it does not depend on thickness and it is more directly related to the mechanisms occurring in the FPZ. It can be seen as a "purely plane stress fracture toughness". The pertinence of this idea will be assessed in the next section using the cohesive zone approach. We must stress the fact that this more "intrinsic" work of fracture does not correspond to the work of fracture of very thin plates or sheets, for which the fracture mechanisms are different. In other words, the linear regression cannot be assimilated to an extrapolation of the fracture toughness values at $t = 0$. The same interpretation holds for introducing the concept of a "plane stress crack tip opening displacement" δ_c.

Crack tunneling was found negligible for the 0.6 and 1 mm plates. In the 2 mm and 4 mm plates, the difference in crack extension between the center and the surface in the steady state regime amounts to 0.9 mm and 2 mm, respectively. The important crack tunneling effect in the 4 mm plate demonstrates significant differences of stress states between the center and surface, in agreement with the finite element results obtained in ref. [4] for a static crack.

MODELLING OF DUCTILE TEARING USING 3D SURFACE COHESIVE ELEMENTS

The tensile tests were simulated in 3-D using the general-purpose finite element program ABAQUS (Hibbit, Karlsson & Sorensen, Inc.). The bulk material is modeled by the J_2 flow theory with isotropic hardening. 3D cohesive zone elements were introduced on the plane of symmetry of the plates. The cohesive zone elements were implemented using a User defined Element (UEL). Details about the formulations of 3D cohesive zone elements can be found in [8]. The cohesive zone form (see Figure 4) used in this work can be characterized, in the case of purely mode I loading, by 5 parameters: Γ_0, δ_c, σ^{max}, λ_1, and λ_2 (but only four of these parameters are independent) as proposed by Tvergaard and Hutchinson [9].

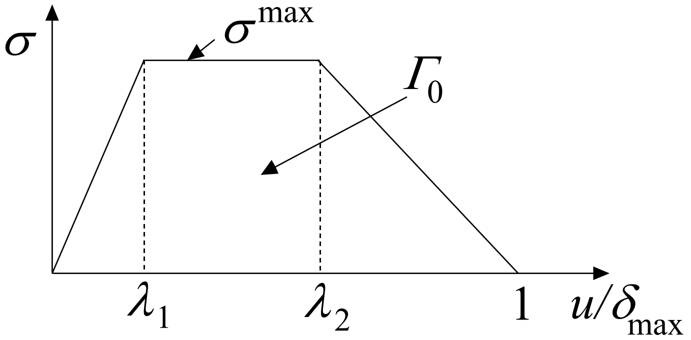

Figure 4: Cohesive zone representation with tensile stress σ as a function of normal displacement u

The parameters of the cohesive zone model were calibrated in the following way. A first set of parameters Γ_0 and δ_c is obtained from the experimental data as explained in the previous section. Then, the results obtianed for the smallest thickness (i.e. the closest to a pure plane stress state), 0.6 mm in this case, are used to calibrate the maximum stress σ^{max} (by tuning the values of λ_1 and λ_2). Figure 5 show conspicuous agreement between the results of the 3D FE simulation and the experimental J_R curve for the 0.6 mm plate using a peak stress of 200 MPa. The degree of crack tip necking is also correctly reproduced by the numerics.

However, keeping the same set of parameters (δ_c, σ^{max}) to model the cracking of the specimens with larger thickness leads to significant underestimation of the initiation toughness and, to a smaller extent, of the tearing resistance. The best choice of parameters for the other thickness are: for 1 mm, δ_c = 0.2 mm and σ^{max} = 200 MPa, for 2 mm, δ_c = 0.25 mm and σ^{max} = 220 MPa. For the 4 mm thickness, a peak stress larger than 220 MPa would be required for matching against the experimental tearing resistance. However, the low constraint close to the specimen surface prevents the tensile stress to reach peak stress larger than 220 MPa. The cohesive elements close to the surface thus never fail for such large peak stresses leading to unphysical results. Consequently, for the 4 mm plate δ_c and σ^{max} have to be tuned along the thickness too.

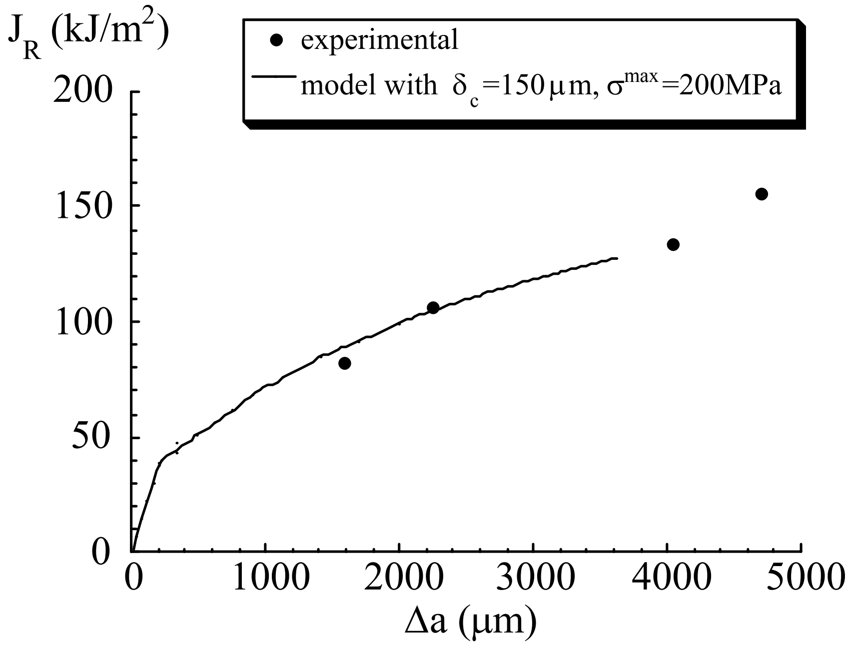

Figure 5: Comparison of the simulated and experimental J_R curve for a 0.6mm thickness DENT plate

DISCUSSION AND CONCLUSIONS

The results presented in Figure 5 suggest that the "intrinsic" critical displacement and fracture work obtained by the linear regression on the experimental fracture toughness data can be used as the maximum opening and the area under the stress / opening curve in a cohesive zone model when modeling plane stress or close plane stress fracture (same for the maximum opening equal to the constant term in the regression on δ_c data).

However, the simple formulation of a stress state independent cohesive zone model is too limited for addressing situations intermediate between plane stress and plane strain. In other words, dependence of the peak stress and of the maximum opening on the stress state is necessary, meaning that the cohesive zone parameters will depend on the thickness and on the location through the plate thickness. This fact has already been recognized by several authors [10,11]. It comes from that the mechanism of ductile fracture is very dependent on the stress triaxiality. The cohesive zone formulation can be enhanced by introducing a link with the local stress triaxiality. However, it is exactly the purpose of full constitutive models such as the various versions of the Gurson model [12,13,14], to take these effects into account based on rigorous micromechanical approach. Furthermore, full constitutive models, in principle, allow dealing with slant fracture, which is also not easy to model with cohesive zone elements.

Cohesive zone approaches remains probably very useful for addressing the two extreme plane stress or nearly plane strain situations, as well many other fracture problems. For theplane strain case, it is important to note that as long as the stress triaxiality is large enough, typically above 2.5, the parameters of the fracture process are almost independent of the stress triaxiality.

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