Numerical Study of Stable Crack Growth

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ABSTRACT Stable crack growth under incremental theory of plasticity and plane stress conditions is investigated by the finite element (FE) method simulating experimental tests on compact tension (CT) and center cracked tension (CCT) specimens of the same material. Resistance curves of J, CTOA and CTOD from the different specimens are discussed with respect to their geometry dependencies. Continuing previous work, the possibility of utilizing the near field integrals, like that proposed by ATLURI and co-workers, for ductile fracture is analyzed further. The independence of the near field J-integral on the specimen geometries and its limitations are discussed.

INTRODUCTION

Since several years, stable crack growth has been an important, but still unsolved problem in nonlinear fracture mechanics, see HUTCHINSON [1]. Numerical simulations are often employed to study the phenomena of crack advance and to analyze the applications and limitations of commonly used fracture parameter, such as J-integral or CTOD and to introduce new ones. However, most investigations were restricted to compact specimens only, see *e. g.* [2, 3], so that any influences of the specimen geometry cannot be studied. Thus, it appears necessary to analyze different types of specimens in the same way.

In the present paper, compact specimens as well as a center cracked panel of the same material but different sizes and thicknesses are investigated by elastic-plastic finite element calculations. Experimental tests are simulated numerically to study the dependencies of various fracture parameters, such as J-integral, crack tip opening angle (CTOA) and crack tip opening displacement (CTOD), on the specimen geometry.

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Furthermore, the possibility of utilizing the incremental integral proposed by ATLURI and coworkers, see BRUST *et al.* [4], to overcome the limitations of J controlled crack growth is discussed.

INVESTIGATED PROBLEMS

Experimental tests by SCHWALBE & HELLMANN [5] on two compact tension (CT) specimens and one center cracked tension (CCT) specimen of an aluminum 2024 T351, see Table 1, have been simulated numerically. The FE program by YUAN [6] bases on the incremental theory of plasticity with VON MISES yield condition and isotropic hardening. Crack extension is modeled by the node release technique and controlled by experimental load line displacement records. The calculations assume plane stress conditions, as this yielded the best fits to the experimental load *vs.* load line displacement curves.

The FE mesh at the crack tip is the same for all three specimens. It contains no singular elements. The details of the mesh refinement are shown in Figure 1. The element length equals 0.25 *mm* in the whole region of the propagating crack, as numerical studies have shown that a further refinement does not much influence the calculated parameters, see BROCKS & YUAN [3].

In order to study the incremental integral proposed by ATLURI *et al.*, several integration contours have been defined, see Figure 2. The contour Γ_{tip} is directly located in the crack tip field and moves with the tip. It has a size of two element lengths, *i.e.* 0.5 x 0.8 *mm*. The contour Γ_{ff} lies in the far field where the J integral has become numerically path-independent even during large crack extensions. The contours Γ_1 to Γ_4 are called the "near field" paths.

NUMERICAL RESULTS AND DISCUSSION

As any material parameter must, by definition, be independent on the specimen geometry of a structure, one has to search for a mechanical quantity which, for a given amount of crack growth Δa, will not vary between the specimens. Two basic concepts of ductile crack growth relate to either crack tip displacements (CTOA, CTOD) or energy release (J-integral).

SCHWALBE & HELLMANN [5] have introduced the crack tip opening displacement δ_5 measured on the specimen surface over a gage length of 5 *mm* at the initial crack tip. Figure 3 shows that the results of the numerical simulations agree quite well with their experimental data. The CTOD does apparently not depend on the specimen shape but rather strongly on the specimen thickness. It is obvious from the viewpoint of continuum mechanics that δ_5 should be larger for a thin specimen than for thick one under the same load line displacement.

Though the crack profiles of the three specimens, see Figure 4, vary due to different sizes and different loading configurations, *i.e.* bending or tension, the angle at the current crack tip, CTOA, is less affected. Thus, it appears not to depend on the specimen geometry so much, see Figure 5.

Many investigators have shown that J control of ductile crack growth is restricted to a rather small interval, see SHIH *et al.* [2] and SCHWALBE & HELLMANN [5]. The reason is that J loses its two constitutive properties of being path-independent and of being the intensity factor of the tip stress and strain field. Figure 6 shows that it becomes strongly path dependent as soon as crack growth initiates and may take any value between 0 and J_{ff}. The numerically calculated far field integral J_{ff} corresponds to the experimental J-integral which is determined from the load vs. load line displacement curve. Thus, it represents the external work applied to the specimen some part of which is dissipated into plastic deformations and the other into surface energy necessary to propagate the crack. Now the specimen geometry determines the possible amount of plastic deformation, which is called its "plastic constraint". It is obvious that the resistance curves of J_{ff} become dependent on the shape and loading configurations of the specimens as Figure 7 shows. Moreover, GRIFFITH's energy considerations fail in the case of ductile crack growth since no finite amount of J_{tip} is left in the limit of a vanishing radius of the integration contour, see Figure 6.

ATLURI and his coworkers tried to overcome this well known restriction of J-integral by introducing some new incremental integral, see [4]. MORAN & SHIH [7] have already pointed out that this integral is actually nothing else than ΔJ_{nf}. Figure 7 does indeed show that the near field integral is less influenced by the specimen geometry, supporting the idea that it might be suited as a controlling parameter beyond the limitations of J. However, J_{nf} is a rather arbitrary and artificial value which depends on the height h of any tube shaped integration contour and does not approach a finite limit, see Figure 8. Thus, necessarily, the dependence on the geometry must diminish with a vanishing value.

CONCLUSIONS

Stable crack growth of three different specimen shapes and sizes has been analyzed by elastic-plastic FE calculations. The numerical results agreed quite well with experimental data.

The CTOD resistance curves do not depend on the specimen shape very much but on the thickness of the specimen.

The CTOA curves are less dependent on the geometry but rather sensitive to the procedure of calculation. Difficulties will also arise in measuring CTOA experimentally.

The numerical studies revealed that J loses its path-independence after very little crack extension. Calculated in the near field, J_{nf} approaches to zero for decreasing distance of the integration contour to the crack tip. No evidences have been found to utilize any near field integral as a parameter controlling ductile crack growth.

References

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Table 1- Geometries of the investigated specimens (Material: Aluminum, 2024 T 351)

No	Specimen	W(mm)	B(mm)	a_o(mm)	Δa_{Max}(mm)
1	CT	50	5.	25.1	14.44
2	CT	100	20.	71.	17.15
3	CCT	50	5.	25.3	8.58

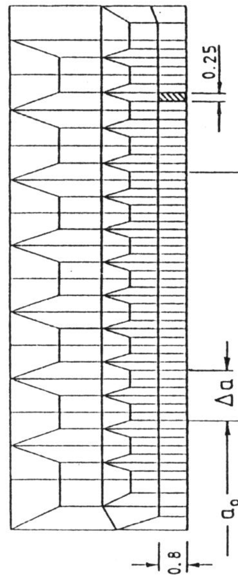

Figure 1 FE mesh at the crack tip

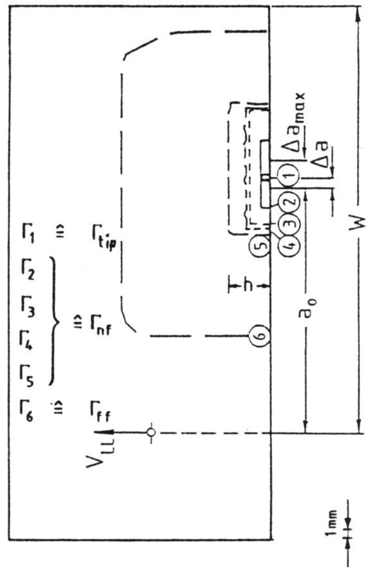

Figure 2 Integration contours for J-evaluation

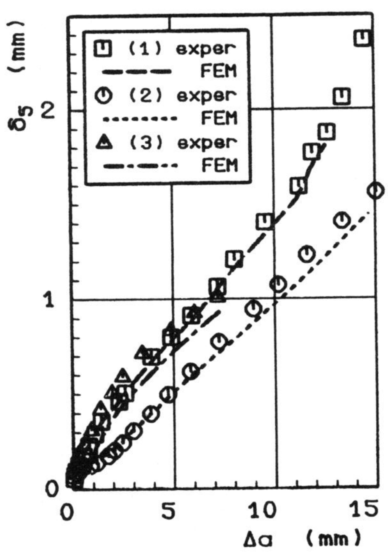

Figure 3 CTOD resistance curves

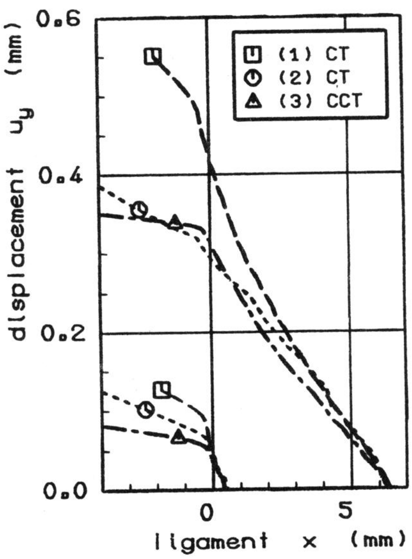

Figure 4 crack opening profiles for Δa = 0.4, 6.3 mm

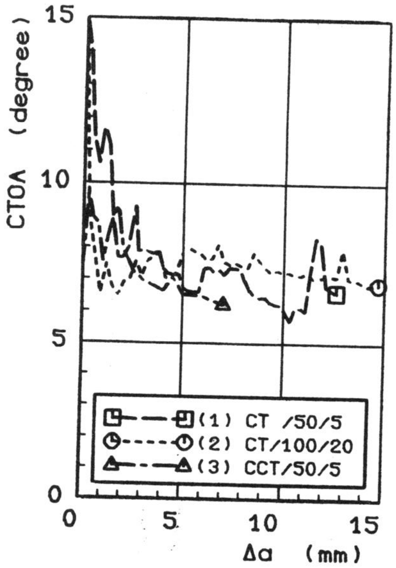

Figure 5 CTOA resistance curves

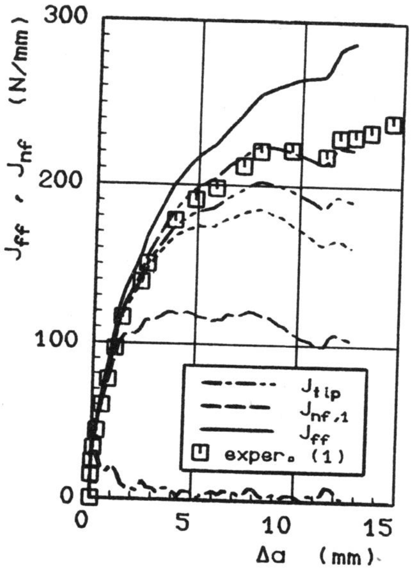

Figure 6 J-integral in near and far field, spec. (1)

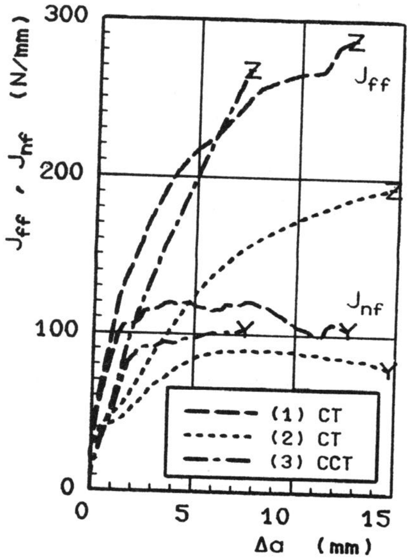

Figure 7 J resistance curves, near and far field

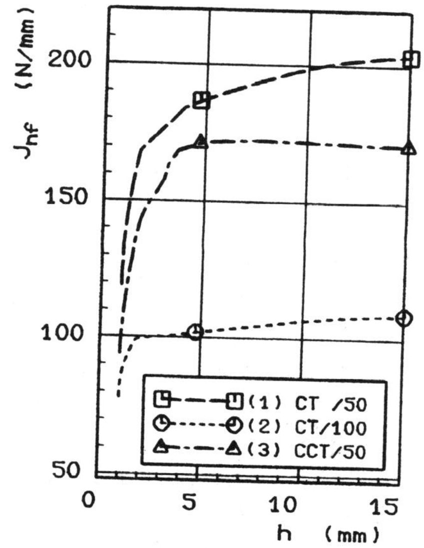

Figure 8 Path dependency of J