MIXED-MODE CRACK INITIATION STUDIES OF ANISOTROPIC ALUMINIUM ALLOYS

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ABSTRACT

Experimental determination was made of crack initiation in two aluminium alloys, displaying elastic-plastic behaviour. Evaluation in terms of K, J, and T was carried out for various orientation of the crack plane with reference to loading direction and rolling direction. A mixed-mode crack may initiate for a smaller load than a mode-I-crack, should the fracture toughness anisotropy be suffiently large. T_c values are almost independent of orientation which may prove useful in the formulation of an initiation criterion for engineering applications.

INTRODUCTION

A frequently encountered problem in engineering applications of fracture mechanics is the mixed-mode loading of a crack in a sheet subjected to biaxial tension. For obtaining a conservative estimate of the load required for crack initiation, it is sufficient in many cases to perform calculations according to mode I type of loading. This way of underestimating the fail-safe load holds very well in isotropic media. Also, very soon after initiation the crack continues to grow in a direction corresponding to pure mode I.

Initiation criteria in mixed-mode loading.

A more accurate estimate of the load reguired for crack initiation is sometimes needed. In linearly elastic fracture mechanics, an effective stress-intensity factor K_e may be introduced (Carlsson, 1974) and initiation is assumed to occur when K_e reaches a critical value which equals the fracture toughness in mode I.

$$K_e = K_{IC} \tag{1}$$

In non-linear fracture mechanics, the J-integral concept may be used in an initiation criterion, as was shown experimentally (Ohlson, 1981),

$$J = J_{IC} \tag{2}$$

Due to its ability of predicting the direction of crack growth as well, the strain energy density function S is superior to other quantities used for determining initiation under mixed-mode conditions (Sih, 1981).

Crack initiation in anisotropic materials.

As seen from Fig. 1, the orientation of the crack in pure mode I implies that the load for crack initiation reaches its lowest value. This diagram only holds, however, for isotropic materials, whose fracture toughness does not depend on the direction. A certain degree of anisotropy is usually present in most engineering materials. Rolled metal sheets, for example, display higher fracture toughness when loaded parallel to the rolling direction than when loaded perpendicular to this direction, Fig.2. Therefore, mixed-mode loading of a crack in an anisotropic sheet should be treated by means of a theory which takes into consideration the dependence of material properties with the direction in the material.

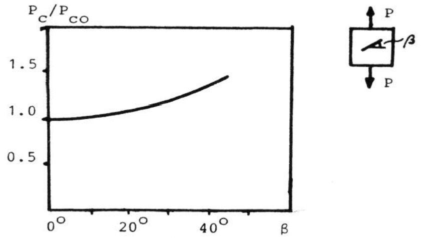

Fig. 1. Relative critical load for crack initiation at constant crack length as a function of the crack angle β.

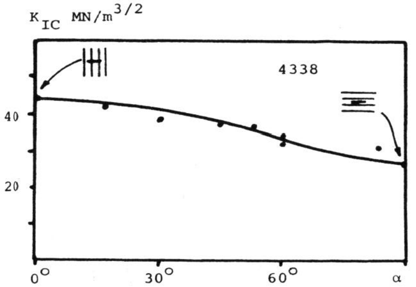

Fig. 2. Experimental values of fracture toughness of alloy 4338 in pure mode I as a function of the angle α between crack plane and rolling direction.

Experiments

Specimens of commercially available aluminium alloys were manufactured in the form of sheets of 3 mm thickness with a central notch placed at different angles with the direction of loading. The rolling direction of the sheet formed an angle with the direction of loading, Fig. 3.

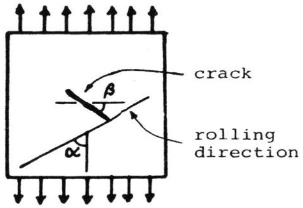

Fig. 3. Definition of angles α and β .

The sheet specimens were then subjected to uniaxial tension in an MTS hydraulic tensile testing machine. The machined notch at the center of the sheet was previously sharpened in each end through the development of fatigue cracks, obtained by subjecting the sheet to cyclic tension perpendicular to the plane of the notch. For an "angled" notch, i.e. a notch whose plane formed an angle with the rolling direction that differed from 0° or 90°, it was sometimes necessary to adjust the direction of the load, in order to let the fatigue crack grow in the direction desired. This is due to the fact that fatigue cracks also tend to grow primarily in mode I, cf. Badaliance (1981), and Ohlson (1983), with due regard to the anisotropy of the material.

Materials

Two alloys were tested, namely, Swedish code no. 4212 and no. 4338, respectively, having the approximate chemical composition and mechanical properties listed in Table 1.

Table 1. Chemical composition and mechanical properties of materials tested.

Alloy no.	Si (%)	Mn (%)	Mg (%)	Cu (%)	E (MN/m^2)	$\sigma_{0.2}$ (MN/m^2)	$K_{IC\perp}$	$K_{IC\parallel}$ (MN/m$^{3/2}$)
4212-06	0.1-1.2	0.4-1.0	0.7-1.0	-	69000 *	250	32	28
4338	0.5-1.2	0.4-1.2	0.2-0.8	3.9-4.8	71000 **	370	44	26

* $E_{\parallel} = 69000$, $E_{\perp} = 59000$
** $E_{\parallel} = 71000$, $E_{\perp} = 60000$

Load versus displacement between the two clamped boundaries of the specimens were registered during the test. For the purpose of determining when crack initiation takes place in the course of loading, the change in compliance of the specimen was observed throughout the test by frequently subjecting the specimen to small, elastic unloadings.

Evaluation

The limited thickness of the specimens does not allow for an evaluation according to LEFM, $(\frac{K_{IC}}{\sigma_{0.2}})^2$ being of the order of 0.01 m for these materials. Even although true K_{IC} values, however, cannot be obtained from these tests, an evaluation in terms of K may be used for studying the effect of anisotropy on mixed-mode loading. Also, a conservative estimate of the critical load for crack initiation may be obtained through use of a stress-intensity factor criterion.

The J integral values were calculated through use of the formula

$$J = \frac{1}{Bb}\int P dD, \tag{3}$$

4.

B being the thickness and b the ligament length of the specimen. P denotes the tensile load applied and D the displacement between loading grips.

Since extensive plastic deformation was observed in these specimens after crack initiation had started, an evaluation of the T-modulus (Paris, 1979) may be appropriate, for the purpose of obtaining a design criterion in engineering applications. T is calculated from the plot of the J integral as a function of crack length a:

$$T = \frac{E}{\sigma_o^2} \cdot \frac{dJ}{da}, \tag{4}$$

where σ_o may be taken as the yield stress of the material, for simplicity.

RESULTS

1. LEFM evaluation

Introducting the angles α and β according to Fig. 2 and

$$K_o = \sigma\sqrt{\pi a}, \tag{5}$$

σ being the normal stress at a large distance from the crack, one may express the effective stress-intensity factor K_e as

$$K_e = \sqrt{K_I^2 + K_{\parallel}^2} = K_o\sqrt{\cos^4\beta + \sin^2\beta\cos^2\beta} = K_o\cos\beta \tag{6}$$

For an isotropic material, K_{ec} values may be computed directly from this formula.

For an anisotropic material, the critical value of the stress-intensity factor in mode I may be written as

$$K_{IC} = \sqrt{K_{IC_\perp}^2 \cos^2\alpha + K_{IC_\parallel}^2 \sin \alpha} \tag{7}$$

Hence, in mixed-mode loading the critical value of the effective stressintensity factor becomes

$$K_{ec} = \sqrt{K_I^2 + \xi \cdot K_{\parallel}^2} \tag{8}$$

where

$$\xi = \sqrt{a_{\parallel}/a_{22}} = \sqrt{E_{\perp}/E_{\parallel}} \tag{9}$$

a_{ij} being the currently used elastic constants of an orthotropic material. One obtains that

$$K_{ec} = K_{IC_\perp}\cos\beta\sqrt{(\cos^2\alpha + \eta\sin^2\alpha)\ (\cos^2\beta + \xi\sin^2\beta)} \tag{10}$$

In Fig. 4, curves of $K_{ec}/K_{IC_\perp}$ were plotted versus α for various values of β. Experimental points of $P_c \cdot \sqrt{\pi a}/B \cdot W$ were plotted in the same diagram. The critical value of the load P_c for crack initiation according to the compliance technique has been used.

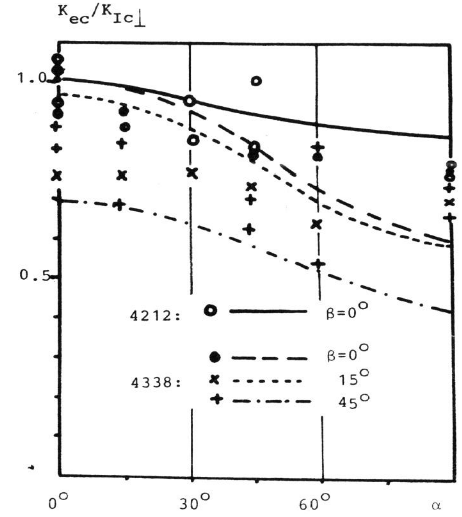

Fig. 4. Relative effective stress-intensity factor as a function of rolling direction for various crack angles. Experimental values are shown as points in the diagram, whereas the curves denote theoretically expected dependence.

2. NLFM evaluations

Fig. 5 shows the maximum values of J versus the angle α for various values of β.

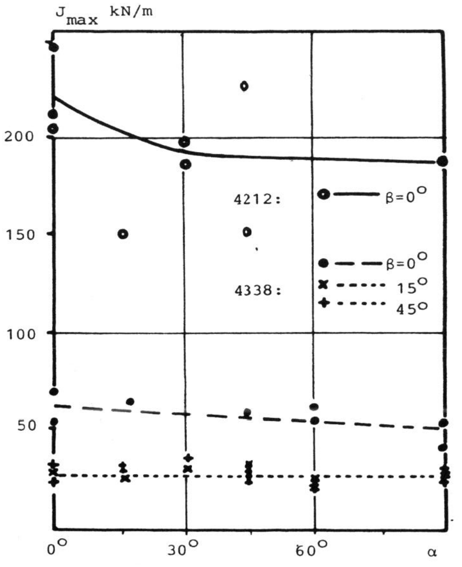

Fig. 5. Experimental values of J_{max} as a function of rolling direction for various crack angles.

Fig. 6 shows the principal appearance of a plot of J as a function of the crack extension Δa. From these plots, one for each specimen, the T-modulus may be evaluated, Fig. 7.

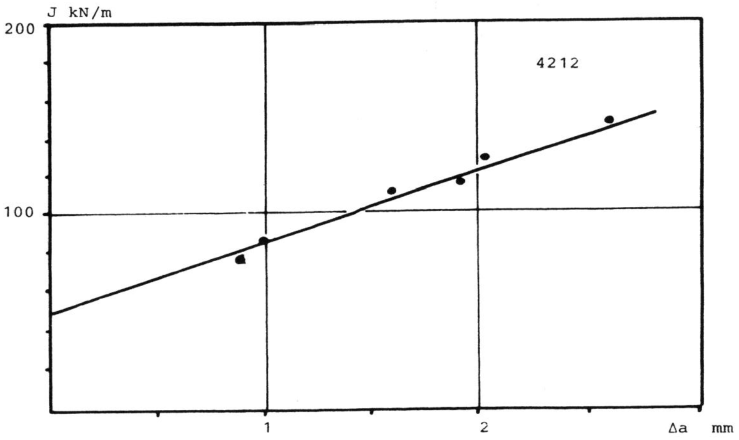

Fig. 6. Experimental values of J as a function of crack extension.

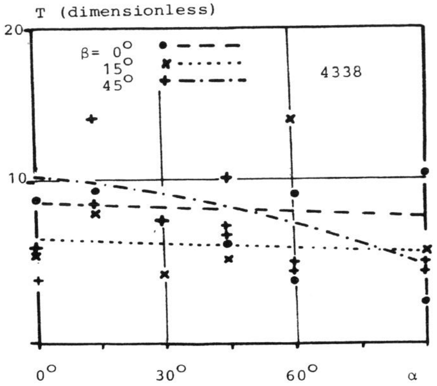

Fig. 7. Experimental values of T for alloy 4338 as a function of rolling direction for various values of crack angle.

DISCUSSION

From Fig. 4, it is realised that the experimental values make good agreement with theory. Anisotropy as well as mixed-mode effects may be simply predicted for engineering applications. As expected, mixed-mode crack initiation may take place at a load much smaller than in pure mode I for materials with anisotropic fracture properties.

A similar principal behaviour is observed for the J_c values in Fig. 5. The reduction of J_c with increasing β is due to an unexpectedly large sensitivity to a small mode II component, which may facilitate yielding at the crack tip. The use of J_c for an initiation criterion in a highly anisotropic material was successfully attempted experimentally (Ohlson, 1982).

The T values are rather insensitive to changes in α as well as in β. That T_c seems insensitive to α may be explained by the fact that the effect of elastic anisotropy was automatically eliminated in the unloadings used for determining the change in compliance of the specimen.

As T is not sensitive to changes in α and β, a simple T criterion may be utilised, stating that $T < T_c$ would imply fail-safe design, regardless of the orientation of cracks as well as of the rolling direction for these types of materials.

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