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FRACTURE ANALYSES OF THIN-DUCTILE MATERIALS USING CRITICAL CTOA AND TWO-PARAMETER FRACTURE CRITERION

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Abstract

The critical crack-tip-opening angle or displacement (CTOA/CTOD) fracture criterion is one of the oldest fracture criteria applied to metallic materials. Improved computer-aided photographic methods have been developed to measure CTOA during the fracture process; and elastic-plastic, finite-element analyses (ZIP2D) with a constant CTOA and a plane-strain core have been used to simulate fracture of laboratory specimens. The fracture criterion has been able to link the fracture of laboratory specimens to structural applications. This paper analyzes fracture of cracked thin-sheet 2219 aluminum alloy over an extremely wide range in width, crack-length-to-width ratio, and applied loading. The results from the critical CTOA fracture analyses on the thin-sheet material showed that the stress-intensity factor at failure (K_{Ie}) was linearly related to the net-section stress (S_n), as predicted by the Two-Parameter Fracture Criterion (TPFC).

1. Introduction

The paper reviews the Two-Parameter Fracture Criterion (TPFC) and analyses to predict failure loads of through-cracked aluminum alloy sheets and surface cracks in titanium alloy specimens. In addition, the critical crack-tip-opening angle (CTOA) concept using elastic-plastic finite-element analyses were applied to through cracks in 2219-T87 aluminum alloy sheets over a wide range in width, crack length and loading. Comparisons are made between the TPFC and the predict results using the critical CTOA concept.

2. Results

Linear-elastic fracture mechanics (LEFM) has served well for brittle materials under plane-strain conditions, but the fracture behavior of thin-sheet materials has required elastic-plastic fracture mechanics concepts under plane-stress and plane-strain conditions. Herein, a comparison is made between two fracture criteria: (1) Two-Parameter Fracture Criterion and (2) Critical Crack-Tip-Opening Angle.

In 1973, Newman using Ingles and Neuber equations for elastic and plastic stress-concentration factors derived an equation containing two groups of material constants. One constant was defined as K_F (elastic-plastic fracture toughness) and the other as m (fracture-toughness parameter). The equation is

$$K_F = K_{Ie} / [1 - m\,(S_n/\sigma_u)] \quad \text{for } S_n < \sigma_{ys} \qquad (1)$$

where K_{Ie} is elastic stress-intensity factor at failure, S_n is net-section stress at failure, σ_{ys} is yield stress, and σ_u is ultimate tensile strength. If m = 0 (Irwin's approach), $K_F = K_{Ie} = K_{Ic}$, the plane-strain fracture toughness. If m = 1 (Kuhn's approach) and K_F is very large, then the failure criterion is $S_n = \sigma_u$ (a failure stress criterion). Figure 1 shows a TPFC analysis of surface-crack fracture tests on a titanium alloy. The stress-intensity factor at failure (K_{Ie}) was calculated at a parametric angle (φ) of 30 degrees. A least-squares method was used to find the values of K_F and m. K_F is plotted against c_iF^2 in Figure 1(a) and K_{Ie} against c_iF^2 in Figure 1(b). F is the surface-crack boundary-correction factor. For $S_n < \sigma_u$, K_F was constant at 224 MPa-m$^{1/2}$ (m = 0.79) and the calculated K_{Ie} values (directly related to load) agreed extremely well with test data. Recently, the yield stress in Eqn. (1) has been replaced with σ_{pl}, the material proportional limit.

Mahtabi et.al used a 2D elastic-plastic finite-element code (ZIP2D) and the critical CTOA fracture criterion to predict failure loads on various cracked sheets under tension, M(T), tension plus bending, SEC(T), or pure bending, SEC(B). The widths (w) ranged from 76 to 2,440 mm and crack-length-to-width ratios ranged from 0.05 to 0.95. The critical CTOA (ψ_c) was 4.7 degrees with a plane-strain core (h_c) of 1.9 mm.

Predicted K_{Ie} at failure is plotted against S_n for pure bend specimens (Fig. 2a) and three crack configurations (Fig. 2b). For $S_n < \sigma_{pl}$, the material proportional limit, the relationship between K_{Ie} and S_n was linear and fit the TPFC results (K_F = 200 MPa-m$^{1/2}$ and m = 0.92) from the 2219-T87 cracked panel tests by Boeing. Further study is needed to improve the TPFC equations for $S_n > \sigma_{pl}$, especially for bending loads.

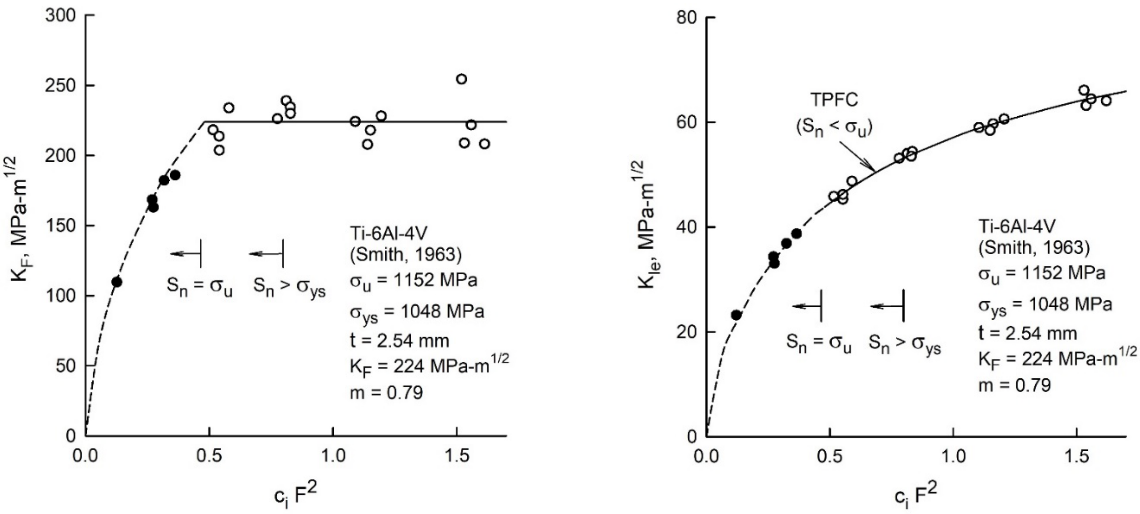

Fig. 1 – TPFC analyses on surface cracks in a titanium alloy plate.

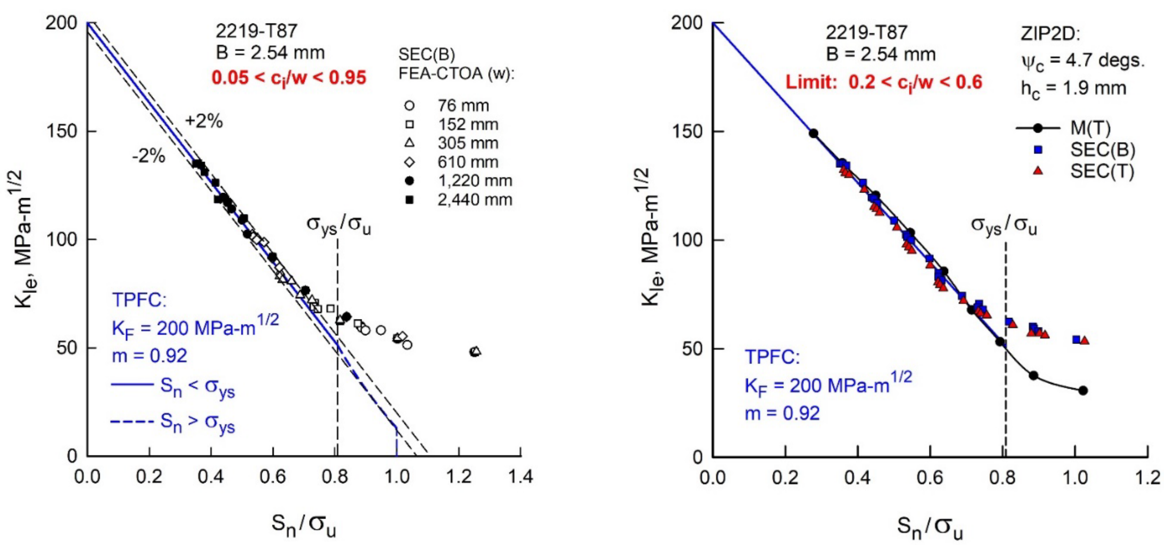

Fig. 2 – Calculated linear-elastic stress-intensity factors at failure (K_{Ie}) on 2219-T87 alloy.

3. Concluding Remarks

The paper reviewed some advanced concepts on characterizing fracture of aluminum and titanium alloys. The Two-Parameter Fracture Criterion (TPFC) was able to correlate fracture behavior of surface cracks in a titanium alloy and through cracks in an aluminum alloy extremely well. An advanced fracture analysis method, the critical crack-tip-opening angle (CTOA) concept and the elastic-plastic finite-element method, were applied to a very large range in specimen width, crack-length-to-width ratio, and applied loading on a thin-sheet 2219-T87 alloy. Elastic-plastic finite-element fracture simulations using the critical CTOA on an aluminum alloy agreed well with the TPFC analyses.