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Mixed-mode ductile failure analysis of V-notched Al 7075-T6 thin sheets

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ABSTRACT

First, several rectangular thin sheets made of Al 7075-T6 and weakened by blunt V-notches were tested for mixed mode I/II fracture, and the load-carrying capacity and the fracture initiation angles were experimentally recorded. Then, the Equivalent Material Concept (EMC), proposed originally by the first author, was utilized in conjunction with the maximum tangential stress (MTS) and the mean-stress (MS) criteria to predict the experimental results. By approximately 9% and 6.5% discrepancies for the VMTS-EMC and VMS-EMC criteria, respectively, it was found that both criteria could predict successfully the mixed-mode ductile fracture of Al 7075-T6 thin sheets without performing elastic–plastic analyses.

1. Introduction

Aluminum alloys of the 7xxx series are extensively used in engineering structures, particularly in aerospace structures. By using special heat treatment processes like the age-hardening, high strengths, appropriate ductility, good fracture toughness and fatigue strength can be achieved for theses alloys. The most well-known alloy in the grade 7xxx is certainly Al 7075 (with different heat treatments such as T6 and T651) which is used in various parts of aerial structures, e.g. spar, stringer, etc. Due to the importance of the health of aero-structures, they must be designed so that they can sustain material and structural failure modes like yielding, buckling, crack initiation and propagation. The most important mechanical properties of aerial aluminum alloys are probably the fatigue strength, the crack growth rate and the fracture toughness which are widely associated with the maintenance and repair of aerial vehicles. Therefore, these properties have been extensively studied in the past by many researchers and engineers both experimentally and theoretically.

A large bulk of the researches in the context of structural integrity of aerial vehicles has been performed on fatigue life prediction and fatigue crack growth rate of aluminum alloys (for example, one can refer to Refs. [1–10]). Dealing with evaluation of fracture toughness of aerial aluminum alloys under various loading conditions e.g. mode I, mode II, mode III and mixed mode loading, several papers have also been published [11,12].

Unlike cracks, defects, and scratches which are all harmful for aerial vehicles, notches can be simultaneously useful and harmful. Their usefulness is mainly due to the fact that they are introduced for joining two or more components (recall a large number of riveted joints and many V- and U-threaded screws in aero-structures). Their harmfulness, however, is because they concentrate stresses at their vicinity which may lead to crack nucleation from the notch edge. The nucleated crack may propagate rapidly or slowly depending on the brittleness and ductility of material which can lead to final fracture.

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Nomenclature

d_c	critical distance of the VMS criterion measured from the notch tip
$d_{c,v}$	critical distance of the VMS criterion measured from the coordinate origin
E	elastic modulus
K	strain-hardening coefficient
$K_I^{V,\rho}$	mode I notch stress intensity factor (NSIF) for a blunt V-notch
$K_{II}^{V,\rho}$	mode II notch stress intensity factor (NSIF) for a blunt V-notch
$K_{Ic}^{V,\rho}$	mode I notch fracture toughness for a blunt V-notch
K_c	Fracture toughness of material
K_{Ic}	plane-strain fracture toughness of material
VMS	V-notch mean-stress
$VMTS$	V-notch maximum tangential stress
n	strain-hardening exponent
PS	point-stress
r_c	critical distance of the VMTS criterion measured from the notch tip
$r_{c,v}$	critical distance of the VMTS criterion measured from the coordinate origin
r_0	distance between the coordinate origin and the notch tip
SED	Strain energy density
2α	notch angle
β	notch rotation angle
ε_f^*	strain at crack initiation for the equivalent material
ε_p	true plastic strain
ε_u	engineering plastic strain at maximum load
$\varepsilon_{u,true}$	true plastic strain at maximum load
ε_p^Y	true plastic strain at yield point
ε_Y	elastic strain at yield point
λ_1	eigen value in mode I (singularity exponent)
λ_2	eigen value in mode II (singularity exponent)
μ_1	eigen value in mode I (real parameter)
μ_2	eigen value in mode II (real parameter)
ρ	notch radius
σ	true stress
σ_c	critical stress
σ_f^*	tensile strength of the equivalent material
σ_{rr}	radial stress
$\sigma_{r\theta}$	in-plane shear stress
$\sigma_{\theta\theta}$	tangential stress
$\overline{\sigma_{\theta\theta}}$	mean value of tangential stress
σ_u	ultimate tensile strength
σ_Y	yield strength

To avoid crack initiation from the notch border in aerial aluminum alloys, the notch fracture toughness (NFT) of such alloys should be studied both experimentally by performing fracture tests on test specimens and theoretically by means of appropriate fracture criteria.

Two of the most recent papers on evaluation of the NFT in aluminum alloys are those published in Refs. [13,14]. Vratnicaa et al. [13] investigated successfully the mode I NFT of a commercial aluminum alloy by conducting fracture tests on single-edge-notched-bend (SENB) specimens containing U-shaped notches of various notch radii and by using the linear-elastic stress distributions around a blunt crack-like notch. A combined experimental-theoretical study has also been performed by Madrazo et al. [14] on mode I fracture of Al 7075-T651 weakened by notches in which tensile fracture tests have been conducted on the compact-tension (CT) specimens and the experimental NFT values have been theoretically predicted by means of the Theory of Critical Distances (TCD). It has been shown in Ref. [14] that the TCD could predict the test results successfully.

The key parameter in fracture analysis of notched plates and sheets made of aluminum alloys is the thickness. For relatively large thicknesses (like those investigated in Refs. [13,14]), the component experiences nearly or exactly plain-strain fracture conditions which is recognized by small-scale yielding around the notch. In this state, K_{Ic}-based theories of the linear-elastic notch fracture mechanics (LENFM) are valid. However, for thin sheets, moderate or large-scale yielding may usually be realized at the notch neighborhood as a result of plain-stress conditions. In this case, although the fracture