

A Mixed-Mode Fracture Criterion for AHSS Cracking Prediction at Large Strain

2011-01-0007

Published
04/12/2011

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doi:[10.4271/2011-01-0007](https://doi.org/10.4271/2011-01-0007)

ABSTRACT

Predicting AHSS cracking during crash events and forming processes is an enabling technology for AHSS application. Several fracture criteria including MatFEM and Modified Mohr-Coulomb Criterion were developed recently. However, none of them are designed to cover more fracture modes such as bending fracture and tearing fracture with initial damage. A mixed-mode fracture criterion (MMFC) is proposed and developed to capture multiple fracture modes including in-plane shearing fracture, cross-thickness shearing fracture with bending effect and tearing fracture with initial damage. The associated calibration procedure for this criterion is developed. The criterion is implemented in a commercial FEA code and several lab validations are conducted. The results show its promising potential to predict AHSS cracking at large strain conditions.

INTRODUCTION

Facing the pressure of increasing requirements for environmental protection and safety as well as fuel economy, vehicle manufacturers are struggling to balance vehicle weight, collision performance and cost. Advanced high strength steel (AHSS), such as Dual Phase (DP) steel and TRansformation-Induced Plasticity (TRIP) steel, offers a great opportunity to make vehicles lighter and stronger due to its excellent combination of strength and ductility ([Zuidema and Adam, 2002](#)). With continuously increasing strength, AHSS cracking phenomena at large strain are more often observed in both crash tests (e.g., folding-caused base metal fracture and joint failure on column crash, B-pillar cracking from cut-out on side impact, bumper fracture on front impact)

and manufacturing processes (e.g., bending fracture on tooling radii, sheared edge cracking on stamping). However, lacking proper crack prediction technology, FEA simulation may over-predict AHSS crash performances ([Yan, Kantner, Zhu, Nadkarni and Horvath, 2005](#)). Thus, developing a realistic prediction technique for AHSS cracking at large strain has become necessary to enable the use of AHSS to ensure proper crash energy management and robust stamping processes.

Although much progress has been made in the past decade in simultaneously modeling a system's structure behavior in the fracture process, realistic predictions of these fracture-associated structure behaviors pose great challenges in materials science, solid mechanics and computational sciences. In the following sections, brief reviews will be given of these fields focusing on AHSS fracture mechanisms under large strain, material modeling for large strain metal fracture behaviors, and the state of the art of crash and stamping simulations in the automotive industry.

AHSS FRACTURE MECHANISMS UNDER LARGE STRAIN

In general, metal ductile fractures at large strain go through several stages including micro-void nucleation and growth, strain localization between voids and the associated void coalescences, and macro fracture under different loading states and histories ([Anderson, 1991](#)). This void nucleation-growth-coalescence process can occur at different length scales depending on particle sizes and distributions. With the rapid development of computational materials science, it is even possible to directly simulate alloy multi-scale failure

processes. One such example is the nested localization prediction with inclusions at 1 μm , precipitates at 50nm, micro-void coalescence at 5nm to assist alloy design by bridging physical mechanisms from nanometer quantum mechanics to the continuum mechanics at micron and mm levels through a representative volume element (RVE) based homogenization approach (Hao, Liu, Moran, Vernerey, and Olson, 2004; Liu and McVeigh, 2008).

Strictly speaking, metal fracture at large strain originates from material inhomogeneity. In the early stages of loading, a strain gradient is generated at interfaces and a strain concentration zone is developed. With increased loading, voids begin to be generated and deformed in this strain concentration zone. These voids are triggers for material separations at microscopic scales. Material inhomogeneity comes from multiple sources at different length scales. These sources include material processing defects (i.e., porosity, shrinkage cavity, quench crack, segregation-caused banded structure), material processing induced property inhomogeneity (i.e., solidification, heat treatment, rolling, forming, cutting, coating), strengthening-mechanism desired micro structure (i.e., multiphase structure, alloying elements and precipitates), and deformation driven microstructure (i.e., dislocations and substructures). There are multiple competing fracture mechanisms / modes existing in the metal fracture process under large strain. These mechanisms / modes are associated with complex mechanical and metallurgical processes causing inhomogeneity.

It is well known that the dominant mechanism for AHSS fracture at large strain is the micro-voids or cracks which originate from the ferrite-martensite interfaces as shown in [Figure 1](#) and propagate either along interfaces or into the ferrite or martensite phase, depending on interface bonding strengths, phase properties, volumes, sizes and morphologies (i.e., Karellova et al, 2006; Hasegawa et al, 2004). The other significant mechanism is due to the fracture of the banded martensite phase induced by segregation as shown in [Figure 2](#) (Reche and Sturel, 2009). These mechanisms are different from IF steel's decohesion of ferrite and nonmetallic inclusions, and HSLA steel's decohesion of ferrite and cementite (Lee, 2005). Compared to IF and HSLA steels, AHSS's relatively low ductility can be partially attributed to its microstructure inhomogeneity from the large and hard second phase volume existing at the relative large length scale.

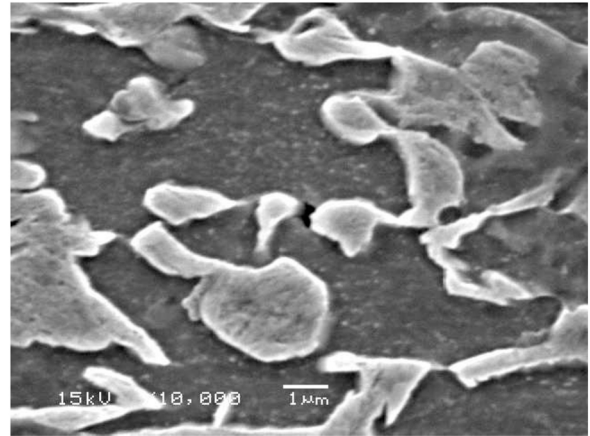


Figure 1. SEM micrograph of a sheet of DP780 after large strain



Figure 2. AHSS cracking initiates from the central segregation (from Reche and Sturel, 2009)

STATE OF THE ART OF MODELING OF METAL FRACTURE BEHAVIORS AT LARGE STRAIN

Although significant progress has been achieved in modeling metal fracture at large strain, no well accepted fracture criterion / modeling approach existed due to the complexity of fracture process. Existing modeling approaches / criteria for macro crack initiation can be categorized into three groups: physical-based coupled models, direct numerical failure modeling without criteria, and uncoupled fracture strain based approaches.

Physical-based coupled models include the porous model (Gurson, 1977; Tvergaard and Needleman, 1984), damage mechanics based model (Lemaitre, 1996) and other multi-scale homogenization models (i.e., Hao, Liu, Moran, Vernerey, Olson, 2004). In Gurson's porous model, the micro-void nucleation-growth-coalescence induced inhomogeneity is described by the porosity and its evolution, which is coupled with plasticity through the plastic potential.

In the frame of Lemaitre's damage mechanics, the micro-damage induced inhomogeneity is described by the damage parameter and its evolution, which influences the macro stress calculation through a transformation between the damaged frame and the undamaged frame. Beside the complex calibration procedures for these physical-based coupled models, it is also difficult to find the proper porous / damage evolution laws for the multiple fracture modes under the complex stress state and history. While multi-scale constitutive / fracture modeling provides a valuable tool for steel grade development, it is not feasible for multi-length scale vehicle crash analysis and stamping process simulation in the near future with the current progress of computational power and the knowledge of microstructures and their behaviors.

Direct numerical failure modeling without criterion includes plastic instability analysis such as M-K analysis ([Marciniak et al, 1967](#) and [1973](#)), shear-band localization simulation, and cohesive-zone approach ([Needleman, 1987](#); [Tvergaard and Hutchinson, 1992](#)). The common feature of these approaches is that the failure process is predicted by the proper constitutive behavior without introducing the explicit failure criterion.

By introducing inhomogeneity as a geometry imperfection embedded in an infinite plate at every material point, plastic instability analysis (i.e., M-K analysis) is used to predict the onset of necking and generate the FLD curve ([Keeler et al, 1964](#)), which is a core criterion for forming analysis. The major limitation of this type of analysis is that the result is highly dependent on the initial defect parameter and constitutive behaviors, including flow surface shape and strain rate effect, for which there is not enough information available when failure / fracture is approached ([Xue, Vaziri, and Hutchinson, 2008](#); [Cao, Yao, Karafillis, and Boyce, 2000](#)).

Many investigations have been performed on the mechanisms and predictions of shear band localization in the past 30 years, due to its importance in material fracture. Inhomogeneity is introduced in the simulation mainly through thermal softening. As pointed out in Shawki's review article ([Shawki, 1992](#)), there are complex interactive roles between inertia, rate-sensitivity, heat conduction, perturbation geometry, boundary conditions, thermal softening, strain hardening and constitutive description for the initiation and further intensification of flow localization with fine length and time scales. This fine length scale is much smaller than the element sizes used in the community of crash and forming simulation. Using a similar thermal softening concept, Wagoner and co-workers ([Kim, Sung, and Wagoner, 2009](#)) performed thermal-mechanical modeling for draw-bend fracture tests for several AHSS grades. The precondition for this type of analysis is accurate thermal-mechanical

behaviors, which require sophisticated material testing and modeling with temperature fields.

The cohesive-zone approach ([Needleman, 1987](#); [Tvergaard and Hutchinson, 1992](#)) has been shown to provide great potential for directly characterizing the entire fracture process, from crack initiation to final fracture, by combining strength and energy parameters. This approach is most suitable for modeling interface separation problems such as the spot weld pull-out process ([Zhou and Thouless, 2006](#)). Although there is some progress for thin-shell fracture and fragmentation using the cohesive approach ([Cirak, Ortiz and Pandolfi, 2005](#)), the special self-adaptive subdivision technique they developed is not available on commercial FEA codes yet (i.e., LSDYNA).

The most popular approaches for metal structure behavior with failure or fracture are based on failure or fracture strain without coupling with the plasticity theory. On one hand, the forming limit diagram or FLD ([Keeler, 1964](#)) associated with major and minor strains is widely used to assess the part forming feasibility. On the other hand, the effective plastic fracture strain based criteria, including Johnson-Cook's model ([Johnson and Cook, 1985](#)), MatFEM model ([Dell et al, 2006](#); [Hooputra et al, 2004](#)), Modified-Mohr-Coulomb model or MMC model ([Bai, 2008](#)), and LSDYNA material model 224 ([Buyuk, et al, 2008](#)), are adopted in the crash simulation community. For these criteria, the effective plastic fracture strain is assumed to be a function or table of stress triaxiality, and other stress parameters, such as the lode parameter ([Mendelson, 1968](#)), as well as strain rate and temperature, represent different stress-state, strain rate, and temperature influences on fracture. Although these criteria are considered as phenomenological models, their dependence on stress parameters such as stress triaxiality also originates from the early works on the ductile metal micro damage mechanism between small-size inclusions and a relatively large-size matrix (i.e., [Argon et al, 1975](#); [Schmitt and Jalinier, 1982](#); [Roy et al, 1981](#)). These criteria share great similarity except the variations on the equation formulas and calibration procedures. Among these criteria, MatFEM can be considered as the expansion of the Johnson-Cook one branch criterion to the two branch criterion, while the MMC model can be regarded as the simplified two-branch criterion of MatFEM. The LSDYNA material model 224 provides the most flexible and general formula due to its table-based format, if the calibrations are properly performed with the different stress state and other influential parameters. These effective plastic fracture strain based criteria are described in the mixed-space of stress and strain, which requires accurate stress and strain information available on both criteria calibration and application on large-scale crash and forming simulations.

STATE OF THE ART OF CRASH AND STAMPING SIMULATIONS IN THE AUTOMOTIVE INDUSTRY

Until today, both vehicle crash simulations and sheet metal stamping analysis have been based on the explicit time integration scheme, which is particularly suitable for large deformation and strain dominated phenomena such as folding, buckling, failure and fracture, occurring in vehicle crash and stamping processes. However, the stress field calculated from the explicit scheme features high oscillation and noise levels, which are partially attributed to a high-speed impact process and those special developed techniques such as the self-adaptive meshing algorithm and contact algorithms. In current industrial practices, constant-strain shell elements are chosen for sheet metal modeling with element size from 10mm to 2mm for crash simulations, and from 2mm to 0.5mm for stamping simulations. With these relatively coarse element sizes as well as simple element types, it is impossible to accurately model physical necking and localization processes, prior fracture, and small wrinkles occurring in the stamped parts. It also should be noted that stress components along sheet thickness are entirely ignored with shell element formulation, which are important for the criteria described in the mixed-space of stress and strain. As pointed out by Hora ([Hora, 2006](#)), advanced material behavior characterization and constitutive modeling are a precondition for an accurate FEM analysis. Although there has been some progress in this field (i.e., [Zhu, Sriram, Yan and Duroux, 2010](#)), lacking complete stress-strain behavior nearing failure / fracture, or history under complex loading path, poses a big challenge, and also triggers concurrent investigations such as the project supported by DOE through USAMP program ([Xia, 2009](#)). The effectiveness of those criteria described in the mixed-space of stress-strain could be partially diluted by the limitations of current crash and stamping simulation technology, material characterization and constitutive modeling.

MAJOR ISSUES FOR EXISTING EFFECTIVE PLASTIC FRACTURE STRAIN BASED CRITERIA FOR AHSS SHEET

Besides the natural limitation of these stress-based criteria discussed above, some important fracture modes such as bending-dominated fracture and tearing mode with initial inhomogeneity (damage) cannot be covered by the existing plastic strain based criteria. In addition, calibration of these criteria requires using an inverse FEA approach to determine stress parameters with pre-assumed constitutive equations. Moreover, considering that the early selection of distortional energy-based effective plastic strain is based on the inclusion-matrix fracture process of mild steel, it is not certain that effective plastic strain is still a good index for the

accumulated damage (i.e., [Wilkins, et al, 1980](#); [Bai, 2008](#)) of the fracture of AHSS with composite-type microstructure under a complex-loading path such as bending-unbending-stretch. Recent investigations from industry applications of these criteria show that these criteria are not suitable for fracture with initial damage ([Obayashi, et al, 2009](#)) and complex loading path ([Chen, et al, 2010](#)). It is desired that a fracture criterion can cover AHSS multiple fracture modes in the pure strain space, which can be calibrated directly from experimental measurement to eliminate the potential errors from stress calculation.

PRESENT WORK

Aligning with the current progress of material behavior characterizations and constitutive modeling, and the modeling practice of the automotive industry on crash and forming simulation, a comprehensive mixed-mode fracture criterion is proposed and developed here to cover AHSS multiple fracture modes induced by shearing and tearing, with or without strain gradient and initial damage effects. The associated calibration procedure is developed. This criterion is also implemented in a commercial FEA code and several lab validations have been performed. Results show that this criterion can be used as an alternative to the crash modeling and stamping feasibility evaluation of AHSS-intensive structures with cracking phenomena.

GENERAL MIXED-MODE FRACTURE CRITERION

With the objective of the proper modeling of vehicle crash behavior with AHSS sheet fracture, and fracture evaluation of AHSS part feasibility, three macro-fracture modes from the observed AHSS fracture phenomena under different stress / strain state and initial inhomogeneity are selected for this investigation. These modes are the cross-thickness shearing, in-plane shearing and tearing with or without initial damage, which are very common and can be found in the textbooks (i.e., [Hertzberg, 1996](#); [Marciniak and Duncan, 1992](#)). The sub-criterion for each mode is proposed on the pure strain space following Einstein's principle, "make everything as simple as possible, but not simpler." It is difficult to find a single mathematical equation to link them together, although there are some attempts to use a single-mathematical-equation based comprehensive theory to describe different failure modes for other materials (i.e., [Christensen, 2007](#)). In this work, these sub-criteria are working independently and competing with others to form a comprehensive criterion to cover multi macro-fracture modes of AHSS. Although these kinds of sub-criteria based approaches for failure and fracture predictions are relatively new for sheet metal, they are widely used for other macro-inhomogeneous materials such as reinforced concrete in civil engineering and fiber-based composites in the aerospace industry. The other advantage of a sub-criteria based approach is that it is easier to implement

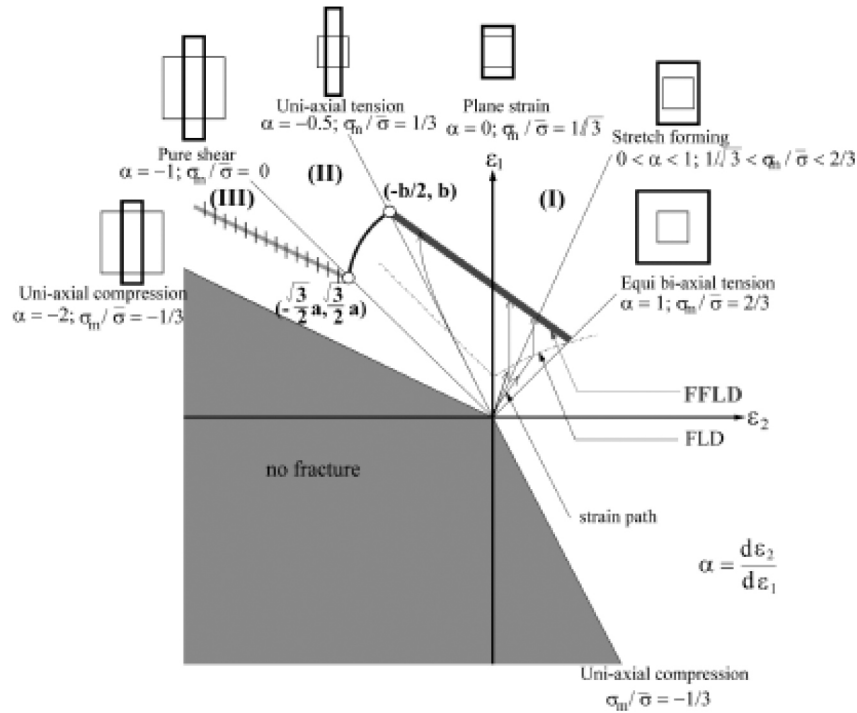


Figure 3. Fracture locus for simple strain path (from Lee, Y's Ph.D. Dissertation, MIT, 2004)

in large-scale computation codes and more efficient for computation than single-complex-equation criteria.

As shown in Figure 3, the fracture locus in the strain space for sheet metal can be divided into three regions (Lee, 2004). Region I covers strain states from uni-axial tensile to plane strain and bi-axial stretch with the ending on equi-bi-axial-stretch. This region can be described as $\epsilon_1 > 0.0$ and

$$-0.5 \leq \frac{\epsilon_2}{\epsilon_1} \leq 1.0$$

Region II starts from uni-axial tensile and ends with pure-shear state, which is described as $\epsilon_1 > 0.0$ and

$$-1.0 \leq \frac{\epsilon_2}{\epsilon_1} \leq -0.5$$

Region III is the remaining area in the strain space, which is buckling-dominated without fracture. This figure will serve as the basis for developing the criterion by considering various influential factors including strain-gradient, strain rate and initial damage.

SUB-CRITERION I FOR CROSS-THICKNESS SHEARING MODE

It is observed that cracks propagate along a 45 degree angle across the thickness after they have initiated on AHSS sheet surfaces (see Figure 4), which is the cross-thickness shearing mode dominating. The strain path for this fracture mode may vary from uni-axial tensile to plane strain and bi-axial tensile with or without bending effect, as in Region I in Figure 4. The maximum cross thickness shear strain is proposed as the

criterion for this fracture mode. The general description for this criterion is:

$$\gamma_{13} = \frac{\epsilon_1 - \epsilon_3}{2} \geq \gamma_{13}^c f_{13}^0(\epsilon_3 - \epsilon_3^a) f_{13}^1\left(\frac{\epsilon_2}{\epsilon_1}\right) f_{13}^2(l_e) f_{13}^3(\dot{\gamma}_{13}), \quad (1)$$

in which f_{13}^0 , f_{13}^1 , f_{13}^2 , f_{13}^3 are functions representing the influences from cross-thickness strain inhomogeneity, in-plane strain state, in-plane length effect and strain rate, respectively. These functions can be specified continuous functions or table-based points to describe piece-wise linear curves, depending on the availability of the specimens for calibration under different conditions. ϵ_1 , ϵ_2 , ϵ_3 , ϵ_3^a , γ_{13} , $\dot{\gamma}_{13}$ are in-plane major strain, in-plane minor strain, normal strain in thickness direction, averaged normal strain in thickness direction in element, maximum cross-thickness shear strain and maximum cross-thickness shear strain rate, respectively. γ_{13}^c is the maximum cross-thickness shear fracture parameter and l_e is the characteristic length of element. This criterion is only valid in Region I.

The effect of strain gradient, which is directly linked to the macroscopic inhomogeneity, is found to be important for AHSS sheet fracture (i.e., Sadagopan, and Yao, 2008). Considering that no strain gradient information is available at material points for constant-strain shell elements, two

functions, f_{13}^0 representing cross-thickness strain inhomogeneity or cross-thickness bending effect, and f_{13}^2 representing in-plane gauge-effect (gradient) on fracture strain (e.g., [Huang, Yan, and Zhu, 2009\(1\)](#)), are used as alternatives in [Equation \(1\)](#) to account for the effect of strain gradient.

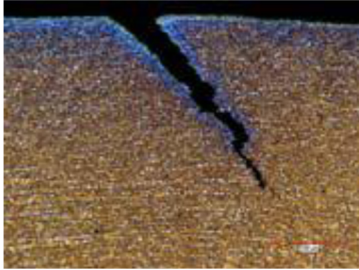


Figure 4. AHSS sheet fracture along cross thickness

SUB-CRITERION II FOR IN-PLANE SHEARING MODE

In-plane shearing fracture mode is observed for AHSS sheet from the strain conditions from the standard ASTM tensile test to the pure shearing test as shown in Region II in [Figure 3](#). For this mode, the AHSS sheet fractures along the maximum in-plane shear strain direction following the formation of shear band localization as shown in [Figure 5](#). This mode cannot be covered by conventional FLD for forming analysis because no specified specimen is used to calibrate this mode in the FLD calibration procedure. This mode can occur in the stamping process such as square-draw bottom corner fracture, although other deformation mechanisms, such as small wavelength wrinkling, are the competing modes. The maximum in-plane shearing strain is proposed as the criterion for this fracture mode. The general description for this criterion is:

$$\gamma_{12} = \frac{\varepsilon_1 - \varepsilon_2}{2} \geq \gamma_{12}^c f_{12}^1\left(\frac{\varepsilon_2}{\varepsilon_1}\right) f_{12}^2(l_e) f_{12}^3(\dot{\gamma}_{12}), \quad (2)$$

in which f_{12}^1 , f_{12}^2 , f_{12}^3 are functions representing the influences from in-plane strain state, in-plane length effect and strain rate, similar to [Equation \(1\)](#). γ_{12} and $\dot{\gamma}_{12}$ are maximum in-plane shear strain and in-plane shear strain rate. γ_{12}^c is the maximum in-plane shear fracture parameter. This criterion is only valid in Region II in [Figure 3](#).

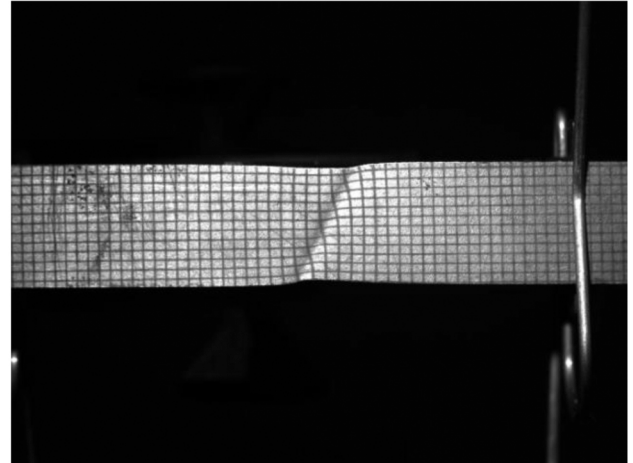


Figure 5. Shear band localization in DP980 tensile test

SUB-CRITERION III FOR TEARING MODE WITH OR WITHOUT INITIAL DAMAGE

Tearing mode occurs when AHSS sheet has considerable macroscopic inhomogeneity, either from initial damages on the material from cutting and welding processes, or from stress / strain concentrations from part geometry under tensile load. Our major focus here is on the cracking from the cut-out or sheared edge under a remote-field tension state, existing in both crash events and stamping processes, which is similar to the crack opening mode (Mode I) in fracture mechanics. Other edge cracking associated with the processes, such as flanging and hole-extrusion, is not considered in this investigation, due to their complex local deformation states and histories.

There are cutting affect zones (CAZ) existing around cutting edges, in which material is severely deformed and damaged with various macro / micro defects and cracks. These defects and cracks originate from second phases, carbides and inclusions ([Kircher, Goncalves, Jousserand and Blonde, 2009](#)). The size of this zone varies with the cutting process and is around 100 μm under the punching condition, in which the material property is significantly different from the initial one ([Ramisetti, et al, 2010](#)). The cracking initiated in this zone under remote-field tension is more dominated by the sub-crack propagation mechanism. This mechanism can be characterized by a number of mathematically-equivalent scalars, including the stress intensity factor K, the J-integral, the potential energy release rate, and the crack-tip opening displacement ([Shawki, 1990](#)). These scalars, composed of the information from the homogenous remote field and the inhomogeneous local field, cannot be directly calculated in the single constant-strain shell element. Instead, the maximum in-plane major strain is proposed here as the