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CRACK TIP FLIPPING UNDER MODE I/III TEARING

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Summary Crack tip flipping, where the fracture surface alternates from side to side in 45° shear bands, seems to be an overlooked propagation mode in Mode I sheet tearing often disregarded as "transitional" or tied to randomness in the material. In fact, such observations rarely make it to the literature. However, crack tip flipping is a true propagation mode, but unlike those already established: i) it never settles in a steady-state as the near tip stress/strain field continuously change, and ii) the mechanism governing failure evolves behind the leading crack tip. Recent research has revealed new insight into this intriguing behavior of a crack propagating by the void nucleation and growth mechanism, and the work presented compiles both published and unpublished experimental and numerical findings. E.g. in a recent attempt to gain control of the flipping crack a slight Mode III was imposed with interesting results.

INTRODUCTION

The fracture surface morphology that results from Mode I tearing of ductile thin sheet metals depends heavily on both the elastic-plastic material properties and the micro-structure. Low strength/low strain hardening metals typically display severe tunneling of the advancing crack, and favor a cup-cup (bath-tub like) propagation mode, whereas tearing of high strength sheet metals is governed by the shear band failure mechanism (slanting). However, most fracture surfaces display a mixture of morphologies. Slant crack propagation can be accompanied by large shear lips near the free sheet surface or a complete shear band switch – seemingly distributed randomly on the fracture surface (Rivalin et al., 2001; Simonsen and Törnqvist, 2004; Gruben et al., 2013). However, it has become clear that the occasionally observed shear band switch of Mode I slant cracks, in relation to ductile thin sheet tearing, is far from random as the crack can flip systematically from one side to the other in roughly 45 degree shear bands (El-Naaman and Nielsen, 2013). The "flipping" action of a slanted crack remains to be fully understood and the work presented serves to share details on the phenomenon – partly through unpublished experimental observations, and partly from detailed numerical modeling. Nielsen and Gundlach (2016) recently exploited X-ray tomography scanning to access the sheet interior and study the very tip of a slanted crack where a flip is underway. From their study it has become clear that the crack tip flipping initiates by the formation of shear-lips near the outer surface behind the leading tip.

What sets the formation of such shear-lips remains to be fully understood. However, it is obvious that once plastic flow localizes into a single shear band, and the crack propagates in a slanted manner, the symmetry of the system is lost. Thus, an asymmetry in the near tip stress/strain field arises, and a slight Mode III loading develops. It is this out-of-plane action which the authors believe to set of the crack tip flipping. *So why not deliberately induce a small Mode III loading to investigate its effect?* By doing so, one might even be able to provoke a flip! The present work focuses on ductile tearing in double edge notch tension specimens (DENTs), but with an added torque (see Fig. 1b).

EXPERIMENTAL PROCEDURE AND FINDINGS

Samples that primarily display slant crack propagation to one side only, under Mode I loading, was first created so that any flip later on can be tied to the applied Mode III. This was achieve by cutting DENT samples from 3 mm rolled 6082-T6 aluminum sheets (the rolling direction was found to have no significance), and through repeated heat treatments develop a material with the striven behavior (heated at 180°C for 16 hours from the super-saturated solid solution state and quenched). Standard tensile testing was then performed for DENT samples, both with/without a slight torque to induce a Mode III on the crack tip. The experimental set-up essentially mimics the out-of-plane behavior that is expected to set of the crack tip flipping.

Test results for monotonic proportionally increasing tension/torque are displayed in Fig. 1a. By applying the torque clockwise (CW) on the lower part consistent slant crack propagation to one side is obtained, as depicted on the figure, whereas it was found that by altering the direction of the torque slanting occurs to the opposite side. What is important is that only a very small change in the twist of the sample is needed to alter the direction of the shear localization. This has also been confirmed in a simplified 2D plane strain Gurson type model (Gurson, 1977), along the lines of Nielsen and Hutchinson (2013), which easily captures the shift in localization. These modeling results indicate good reason to believe that a full 3D Gurson type model will capture the provoked flipping behavior.

Subsequently, experiments were performed by changing the direction of the introduced torque mid-way through the test, see Fig. 1b. This particular test is carried out by: i) initially adding loading through tension (1 mm/min) and clock-wise torque (1°/min), while, ii) a counter-clock-wise torque (3°/min) is started after crack propagation has initiated (final axial strain of

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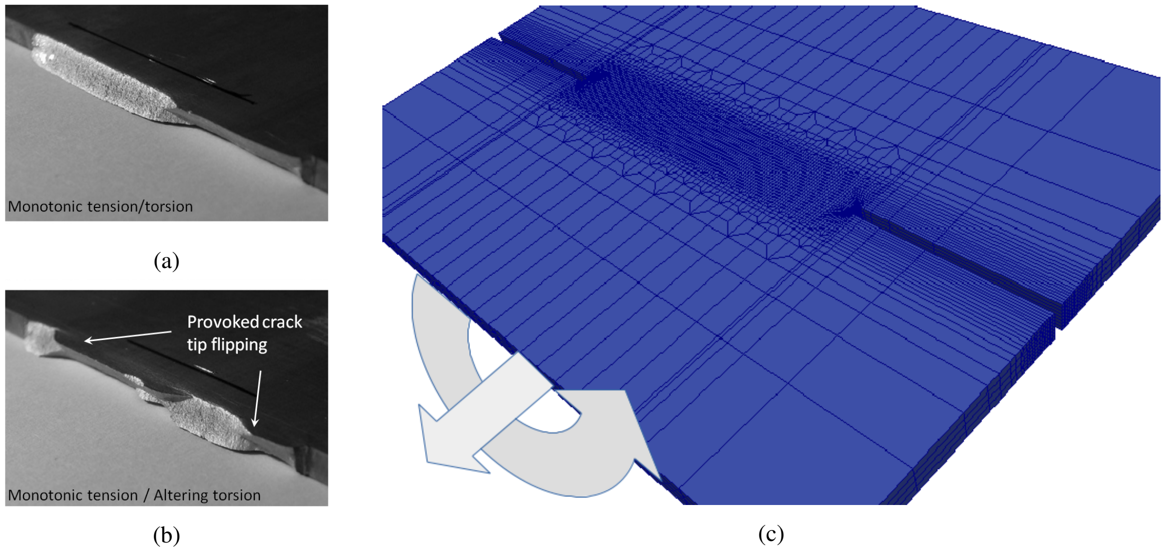

Figure 1: Axial displacement 1 mm/min. (a) 1°/min CW twist, (b) 1°/min CW twist followed by 3°/min CCW twist, (c) Mesh for numerical analysis at initial condition indicating axial displacement and clock-wise (CW) twist of lower part.

0.02). Clearly, the change in the torque (hence the change in Mode III) gives rise to a provoked flip of the crack face. In fact, by simply observing the fracture surfaces it is hard to tell the difference between this artificially flip and a "natural" one – leading the authors to believe that both have been triggered by the out-of-plane action.

MODELING EFFORTS

The modeling effort aims at accurately describing the full sequence of events that comes with the ductile tearing process in thin sheet metals. Here, employing the micro-mechanics based Gurson material model that rests on void nucleation and growth to coalescence. The computational task is by no means trivial as the Gurson model outputs a mesh dependent result, and hence an accurate resolution of the fracture process itself requires the mesh to scale with the dominant void spacing (e.g. $50 - 100$ micron). That is, an accurate model requires on the order of 50 elements through the plate thickness (Nielsen and Hutchinson, 2012). To approach the challenge, an in-house explicit finite element program has been developed and is massively parallelized using the Message Parsing Interface (MPI) library. The program allows for 3D transient analysis and takes into account finite strains/displacements with the use of 20-node iso-parametric elements using reduced Gauss integration. Eventually, the individual elements may reach a critical level of damage after which it is removed completely by an element erosion technique. A schematic of the model set-up in Fig. 1c.

ACKNOWLEDGMENT

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