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Micro-computed tomographic imaging of void damage in a hot-rolled complex phase sheet steel

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ABSTRACT

Interrupted hole tension tests were carried out on four samples of hot-rolled complex phase Advanced High Strength Steel (AHSS) sheet (UTS=780 MPa) to investigate the evolution of void damage at the edge of an expanding hole. Optical microscopy and micro-computed tomographic (microCT) imaging of plastically deformed hole tension specimens indicated that voids nucleate at TiN particles and grow primarily in the direction of tensile loading, developing ellipsoidal shapes as plastic strain accumulates. Larger, cubic particles are associated with larger voids in one of the four sheets under study, culminating in a single, large coalescence event at high plastic strains. Several smaller coalescence events are observed in the other three sheets containing small, irregularly-shaped TiN particles. Coalescence of closely spaced voids was found to occur through necking of the inter-void ligament while void sheet formation was the primary mode of coalescence for large voids spaced farther apart and at an angle of ~45° between the loading and through-thickness directions. A peak in the void volume fraction was observed approximately 0.6 mm from the hole edge as a result of the competing influences of plastic strain and triaxiality.

1. Introduction

In response to rising standards for vehicle fuel economy and passenger safety, automotive manufacturers continue to increase their use of advanced high strength steels (AHSS) to achieve lightweighting. The high strength of these materials allows for reductions in part thickness, but it also results in an increased susceptibility to damage-related failure during forming processes [1–3]. One such forming process is stretch-flanging. During stretch flanging, a complex stress state develops at the hole edge which suppresses necking. The resulting combination of high triaxiality and elevated plastic strain typically leads to damage in the form of microcracks and/or microvoids.

The industry standard for evaluation of stretch flangeability is the hole expansion test. Hole expansion data generally exhibit higher levels of variability than other mechanical test data [4–7]. It is possible to conduct hole expansion tests with non-punched (e.g. reamed) holes to reduce this variability and focus on the role of microstructure on the development of damage. An alternative test geometry is the hole tension test, which simulates the stress state present at the hole edge in the hole expansion test and is capable of achieving higher levels of strain prior to failure than standard uniaxial tensile tests [7,8]. Micro-computed tomographic (microCT) imaging is a powerful technique for observation of void damage evolution in metals [9–11]. Scanning of a deformed sample provides data on the size, morphology and distribution of voids. Since the scanning process is non-destructive, in-situ tests can be performed to observe void damage evolution in a single specimen [12–14]. In cases where large sample dimensions prohibit in-situ scanning, such as a hole tension test, coupons must be extracted from a series of interrupted test samples. An added benefit of the hole tension test is its in-plane deformation, which provides a flat coupon geometry that is well suited for microCT scanning.

The hole expansion performance of complex phase steels is affected by several microstructural features, including the morphology and distribution of (Ti,Nb)(C,N) precipitates [3,15], grain size and homogeneity [16–18], and microbanding of microstructure [16,19]. In traditional dual-phase steels, damage is found to initiate within the soft ferritic matrix, typically at the hard martensitic phase interface [5,20,21]. However, little has been reported about the development of damage in complex phase steels.

The aim of the current study was to investigate the evolution of void damage in four microstructural variants of a commercially produced complex phase sheet steel. Interrupted hole tension tests were performed and void damage evolution in the region surrounding the hole edge was examined through microCT imaging. The size, distribution and morphology of voids were compared among the four sheet samples at plastic strains ranging from 0% to 90%.

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Table 1
Chemical composition of steel used in this study.

Element	C	Mn	Si	Nb	Ti	Cr
wt%	0.05	1.5	0.55	0.03	0.15	0.6

2. Experimental

2.1. Material

The steel examined in this study was a 3.2 mm thick hot-rolled and controlled-cooled complex phase sheet steel (UTS=780 MPa) provided by ArcelorMittal Dofasco. The chemical composition of the steel is given in Table 1. Four samples of this steel were investigated, corresponding to the leading and trailing edges of two different coils, where the leading edge is the first to exit the rolling mill. The coils had two different finish-rolling temperatures, resulting in a range of microstructures and mechanical properties for the four sheet samples. The microstructures are described elsewhere [22], while the mechanical properties are given in Table 2.

2.2. Hole tension tests

A series of interrupted hole tension tests were carried out to observe the evolution of void damage with plastic strain through ex-situ microCT imaging.

2.2.1. Specimen preparation

The hole tension specimen geometry is specified in Fig. 1. Test specimens were extracted from the steel sheets using a waterjet cutter with the tensile axis aligned in the transverse sheet direction. The central hole was subsequently reamed and the hole edge was lightly hand polished to remove surface defects. A grid of dots was applied to both sides of the hole, as illustrated in Fig. 1, using a custom 2-axis micro-controlled stage equipped with a spring-loaded pen. Each array consisted of rows of 5 dots in the transverse sheet direction (TD) and 12 in the rolling direction (RD) with a spacing of 0.5 mm between dots. The grids were located at a distance of 0.3 mm from the hole edge.

2.2.2. Mechanical testing procedure

Tests were performed on an Instron 8521 tensile testing machine with custom grips and an extension rate of 4.5 mm/min, which is similar to the rate of deformation in a hole expansion test. Interrupted hole tension tests were used to obtain void damage data at a range of plastic strain levels for a sample volume adjacent to the hole edge.

Strain measurements were based on images of deformed and undeformed grids, where measures of true major and minor strain values were obtained for each originally square group of four dots in the grid array. The true effective (von Mises) plastic strain (ϵ_{eff}^{P}) for each strain element was calculated from the major and minor strain values and used to plot a strain map. Strain measurements for the two grid squares closest to the hole edge were averaged to represent the value of ϵ_{eff}^{P} for the region of interest scanned in the microCT.

2.3. Micro-computed tomographic (microCT) imaging of void damage

Small coupons (0.8 mm×0.8 mm×12.5 mm) were extracted from the hole edge, as indicated by the dashed lines in Fig. 1, through a series of cutting and grinding steps and mounted onto an extension rod with LePage Epoxy Steel for imaging in an Xradia MicroXCT-400 scanner. These scans produced 3-D reconstructed renderings (voxel size=1.15 µm×1.15 µm×1.15 µm) of the void population within the region of interest (shaded region in Fig. 1), from which details of void size, shape and distribution were obtained. Scans were typically run at an X-ray beam energy of 100 kV and a power of 10 W. For each scan, a set of 2000 projections was taken over 184° of sample rotation with an acquisition time of approximately 70 s per projection. The energy and acquisition time were optimized for each coupon.

The microCT images were passed through a de-speckling filter, while center shift and beam hardening artifacts were corrected within the Xradia software. A non-local means de-noising algorithm [23] was applied before the void voxels were separated from the material background using a locally adaptive threshold. The slices were imported into Avizo Fire 8.1 and compiled to create a 3-D rendering of the void population. Voids measuring fewer than the volumetric equivalent of 2×2×2 voxels (13 µm^3) were considered to be noise and therefore removed from the data set. A subvolume measuring 400 µm×400 µm×400 µm was isolated from the 3-D renderings of the void population for calculation of void volume fraction and size distribution. The edge of the subvolume was located 0.3 mm from the hole edge.

2.4. Metallography and particle analysis

Metallographic coupons were cut from interrupted hole tension test specimens (ϵ_{eff}^{P}≈60%) parallel to the transverse/through-thickness (TD/TT) plane in the region around the hole edge. The coupons were polished down to 0.06 µm colloidal silica with ammonium hydroxide added at a concentration of 5% to reduce pitting of particles. All samples were etched in a 2% Nital solution and observed in a Zeiss Axioskop 2 MAT optical microscope.

Coupons were cut from the as-received sheets and polished for analysis in an ASPEX SEM/EDX system, which yielded details of particle composition, size and distribution within the 50 mm^2 area scanned in the RD/TD plane.

3. Results

MicroCT scans produced 3-D renderings of the voids present in each specimen adjacent to the hole edge. The sequence of images in Fig. 2 illustrates the development of void damage with increasing plastic strain for the 11T sheet material. As the level of plastic strain increases, the larger voids (> 100 µm^3) develop an ellipsoidal shape with growth occurring primarily in the direction of tensile loading as is evident in Fig. 3. Small, equiaxed voids (< 100 µm^3) are observed at all levels of plastic strain, indicating that nucleation continues throughout the test. At high levels of strain, some instances of void coalescence can

Table 2
Mechanical properties for the four sheet samples (data provided by ArcelorMittal Dofasco).

Sheet	Location	Sample ID	Hole expansion [%]		UTS [MPa]	0.2% YS [MPa]	Uniform Elongation [%]
			Average	+/−			
11	LEAD	11L	52.2	14.3	838	740	8.0
	TRAIL	11T	55.7	14.6	817	722	7.6
18	LEAD	18L	66.5	11.2	837	749	6.6
	TRAIL	18T	69.5	14.5	775	669	10.1