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In Situ Observation Of Strained Bands And Ductile Damage In Thin AA2139-T3 Alloy Sheets

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Abstract

The interactions between plasticity and damage mechanisms are not clearly established concerning the fracture of ductile sheet materials (*e.g.,* flat to slant transition). The question addressed herein is to elucidate which mechanism is responsible for localized phenomena leading to the final failure. A mechanical test carried out on a notched plate made of 2139-T3 aluminum alloy is imaged thanks to synchrotron laminography at micrometer resolution. Ductile damage (*i.e.,* void nucleation, growth and coalescence) is analyzed via reconstructed volumes. Although the low volume fraction of secondary phases in the tested alloy is challenging, digital volume correlation is also utilized to measure displacement fields and estimate strain fields in the bulk of the alloy during the whole test. In the first part of this study, the resolution of the measurement technique is assessed under such conditions. Then strained bands are shown to occur very early on in what will be the slant region of the fracture path. Conversely, damage grows at very late loading steps.

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Keywords: Damage, Digital Volume Correlation, Flat-to-slant transition, Laminography, Plasticity

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1. Introduction

Ductile damage generally has three phases, namely, void nucleation, growth and coalescence. Unlike fracture mechanics, modeling such mechanisms calls for micromechanics-based approaches with more physical input. Various damage models successfully deal with high stress triaxialities[1,2,3]. However, lower triaxialities (*e.g.,* ductile failure in shear loading) are challenging[4,5]. Failure mechanisms responsible for cracking under such conditions are still poorly understood and quantified.

A typical example of the afore-mentioned challenges are flat-to-slant failures of thin samples under mode I loading[6,7,8,9,10,11]. In these specimens the crack starts to propagate perpendicular to the loading direction. Later on, it

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continues to propagate in a slant manner. This phenomenon may lead to reduced toughness compared with pure mode I opening. Numerically it has been shown that slant cracks propagate in plane strain conditions with respect to the crack propagation direction[12] and dissipate less energy during tearing than a flat crack[11]. The first observation has been experimentally confirmed[13]. The simultaneous match of load/displacement response and propagation path still remains very challenging. Shear bands as driving force for such type of failure have been theoretically studied[14]. It was found that materials showing a sharp vertex on the yield surface are prone to strain localization. Similarly, damage growth and (self)heating due to plastic flow (*i.e.,* thermal softening) are also mentioned as possible causes for localized strain patterns in materials.

Tomography has been successfully utilized to study bulk failure mechanisms in structural alloys[15]. Yet, tomography is by construction limited to cylinders where representative sheet loading conditions cannot be easily prescribed. Synchrotron radiation computed laminography[16,17,18] allows damage processes to be analyzed *in situ* in sheet-like specimens[10]. It is also possible to apply boundary conditions of engineering relevance. Further, thanks to Digital Volume Correlation (DVC), *e.g.,* with a global formulation[19], the bulk displacement fields can be measured. Hence, strain and damage interactions can be quantitatively assessed in naturally developing plastic bands on the order of several millimeters in front of the notch root[20,21] at micrometer resolutions.

In the present work a CT-like sample made of aeronautical aluminum alloy 2139 is monitored *in situ* by using laminography. It was shown that for another alloy (*i.e.,* AA2198-T8) early strained bands form before any sign of damage growth is detected in a Region of Interest (ROI) placed $\approx$ 800 μm ahead of the notch root[21]. The same type of analysis is reported herein for AA2139-T3, which contains a significant initial porosity (*i.e.,* $\approx$ 0.3 %) in comparison with the previous case, and displays a more progressive work hardening. The paper is structured as follows. The material properties, mechanical setup and laminography imaging technique are first introduced. The basic principles of DVC incorporating strain uncertainty assessments are discussed next. The results and conclusions are finally presented.

2. Experimental setup

The material of the CT-like specimen studied herein (AA 2139) is produced by Constellium C-Tech and represents the latest generation of Al-Cu-Mg alloys. The yield strength is $\approx$ 320 MPa and the ultimate tensile strength is $\approx$ 450 MPa. The chosen T3 heat treatment is responsible for the material high work hardening. The intermetallic particle volume fraction is found to be $\approx$ 0.45 % while the initial porosity is of the order of 0.3 vol %. The low volume fraction of secondary phases makes this material very challenging for DVC[20]. The material processing directions are the rolling direction (L), the transverse direction (T) and the short-transverse direction in the through thickness (S). In the experiment, the loading is applied in the T-direction and the L-direction corresponds to that of crack propagation. More details on the material properties can be found in Refs.[22,23].

Synchrotron radiation computed laminography enables laterally extended 3D objects to be imaged in a non-destructive way[24,25,26,27]. This technique is of particular interest in the field of mechanics of materials since using sheet-like samples allows a wide range of engineering relevant boundary conditions to be prescribed. The characteristic feature of laminography is the inclination of the sample with respect to the beam that can assume an angle θ different from 90°, while tomography is limited to 90° angle during the scanning procedure.

The testing machine with a stepwise loading procedure is shown in Fig. 1(a) without the anti-buckling system. The dimensions of the CT-like specimen are 60 × 70 × 1 mm (Fig. 1(b)). Electrical discharge machining is utilized to create a notch radius of 0.17 mm. The corresponding ligament is 24-mm in length. After applying each loading step (Fig. 1(c)), the object is scanned while rotating about the laminograph axis. The collected radiographs are used to reconstruct the 3D volume by using a filtered-back-projection algorithm[28]. The crack size is manually estimated on the reconstructed volumes (Fig. 1(d)) and the crack mouth opening displacement (CMOD) corresponds to the screw displacement. The beamline ID19 of the European Synchrotron Radiation Facility (Grenoble, France) with a 25 keV monochromatic beam allows a spatial resolution of 0.7 μm per voxel (which requires 1500 projections per scan) to be obtained. The rotation axis inclination angle is chosen to be $\theta \approx 65^\circ$.