Deformation and fracture of aluminum thin sheets with a Portevin–Le Chatelier model and comparison with DIC3D synchrotron tomography

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Abstract. Several models are combined in finite element analyses of a thin aluminum Compact Tension specimen: polycrystalline model for anisotropic plasticity, Portevin–Le Chatelier model, porous plasticity and Coulomb fracture models. Multiple strain bands are obtained, similar to the ones observed in laminography with 3D digital volume correlation. Strain rate bands appear and vanish in relation with the load-displacement curve serrations. Crack propagation occurs during strain rate surges. The strong relation between the Portevin–Le Chatelier phenomenon and the transition from flat to slant ductile fracture is emphasized.

1 Introduction

High-resolution in situ synchrotron X-ray laminography combined with digital volume correlation (DVC) is used to measure the strain fields and the damage ahead of a notch introduced within a 2198 Al-Cu-Li alloy thin sheet [1]. Synchrotron laminography is a generalization of tomography developed for large size sheet specimens. In the low stress triaxiality regime (i.e. <1), a transition from stable flat to unstable slant fracture is observed with negligible void growth or coalescence in the slant shear fracture. The relation with the multiple crossing shear strain bands observed ahead of the notch is questioned. To further investigate this hypothetical interaction, finite element (FE) analyses are performed with the combination of several material models: polycrystalline plasticity, dynamic strain aging (DSA) for the Portevin-Le-Chatelier (PLC) phenomenon, porous plasticity combined with the Coulomb fracture model for the slant fracture not related to void damage.

2 Experimental results for AA2198-T8R

The 2-mm thick aluminum sheet was provided in the recrystallized state and after an artificial ageing treatment (T8). The yield strength is ~440 MPa and the ultimate tensile strength is ~500 MPa. A significant negative strain rate sensitivity and serrations characteristic of DSA are observed in tension tests at room temperature and strain rate in the range 10^{-4} to 10^{-2} s^{-1}. The Compact Tension (CT) specimen (with dimensions 60x70x1 mm) contained a round notch with ~0.17-mm radius and a remaining 24-mm ligament. The loading configuration was T-L. A stepwise notch opening displacement (NOD) was applied with a screw. The applied NOD was measured using laminography images at a point ~200 μm behind the original notch tip for loading steps 1 to 5 and at unstable fracture, Table 1 [1].

Laminography imaging was performed at the European Synchrotron Radiation Facility (ESRF, Grenoble, France). The intermetallic particles provide a natural contrast pattern for DVC techniques to measure displacement and hence strain fields. A ~0.83x0.36x0.70 mm region ahead of the notch was considered for strain measurements.

The front L-section in Fig. 1 is at ~1 mm from the notch. Incremental strain fields between the loading steps better show the strain band patterns than the total strain [1]. (Incremental strain fields calculated by FE analysis are shown for comparison. They are discussed in Section 3.2.) For step 1-2, the main band is at +45° and several parallel bands appear at plus and minus 45° with “hot spots” at band intersections. The band pattern is not symmetric with respect to mid-height (notch plane) and mid-thickness. These features are preserved for steps 2-3 and 3-4 but strain is more and more localized in the main band region. The band activity is highly variable but the band locations seem to be fixed, probably in relation with the large load steps.

<table>
<thead>
<tr>
<th>Load step</th>
<th>0</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>failure</th>
</tr>
</thead>
<tbody>
<tr>
<td>NOD (μm)</td>
<td>0</td>
<td>56</td>
<td>101</td>
<td>127</td>
<td>177</td>
<td>210</td>
<td>245</td>
</tr>
</tbody>
</table>

Table 1. Applied NOD.

Fig. 2 shows the damage at the notch tip. A triangular flat crack with a mixture of dimples and intragranular fracture is seen in SEM images of the fracture surface. The stable flat crack is ~0.75 mm long just before unstable fracture. In the shear lips and in the slant fracture zone, no void damage is present in the SEM

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images. It is confirmed by DVC images of the slant fracture zone that show no voids prior unstable fracture.

![Image](image.png)

**Figure 1.** Incremental von Mises equivalent strain fields. Left: DVC. Right: FE analysis, fine mesh. Steps 1-2, 2-3 and 3-4. The scales in % are the same for DVC and FE.

**3 Finite element analyses**

The finite element mesh is shown in Fig. 3. In the "fine" mesh, the element size in the notch region is 0.125x0.10x0.125 mm, with 8 elements in the thickness. The mesh at the notch tip is designed to avoid the mesh size effect between crack initiation and propagation. In the "coarse" mesh, element dimensions are multiplied by 2 in the notch region, with 4 elements in the thickness. The two meshes are used to quantify the mesh size effect.

![Image](image.png)

**Figure 2.** Voids/cracks at the notch tip for steps 4 (left) and 5 (right). Top: laminography images investigated by DVC. Bottom: reconstructed from DVC mid-thickness sections normal to the S-direction.

**3.1 Models**

The results of Section 2 reveal two original features: (i) plastic deformation is heterogeneous at the macroscopic scale with the formation of several shear strain bands ahead of the notch, (ii) ductile fracture mechanisms in the CT specimen are not only void nucleation, growth and coalescence but also intragranular fracture. Prior calculations using von Mises plasticity or the Gurson-Tvergaard-Needleman porous plasticity and ductile fracture model did not capture the localization bands neither slant fracture [1]. To further investigate the first point, a DSA model, formulated at the slip system scale [2], is used in the analyses. In addition, the Coulomb fracture model at the slip system scale [3] is combined with porous plasticity to account for fracture mechanisms not related to void damage.

Although the fracture models involve many material parameters, most of them can be determined with the available material data. The main remaining fracture parameters are the mean strain for void initiation and the Coulomb critical shear stress. They are calibrated to match stable crack growth before final failure and the balance between void related and non-related ductile fracture mechanisms. The PLC amplitude is exaggerated in order to better investigate the interaction with fracture.

![Image](image.png)

**Figure 3.** 3D fine mesh of the CT specimen.

**3.2 Results**

In the calculations, "flashes" of mobile strain rate bands are separated by time periods without bands. The first
flashes correspond to load inflexions and the following ones to load decreases. Time integration between the load steps gives the cumulated strain bands of Fig. 1. The numerical strain fields are in good qualitative agreement with the measured fields. If the DSA model is not activated, multiple bands cannot be obtained. Fig. 4 enables a more quantitative comparison. Probably because of the exaggerated PLC amplitude in FE analyses, the strain rate bands are more mobile and consequently the cumulated strain is less localized, but the trends are identical.

The fine mesh calculation was stopped at step 4 because of very large CPU time. It gives the same results with slightly more rapid crack propagation.

4 Conclusions

Laminography images investigated by DVC showed that deformation of thin aluminum sheets at room temperature can be heterogeneous, with several inclined strain rate and strain bands [1]. This observation and the transition from stable flat to unstable slant fracture in a CT specimen could be related to the PLC phenomenon.

FE analyses have been performed. To match all experimental results, it is necessary to combine several models. The PLC-DSA model and the Coulomb fracture model are formulated at the slip system scale within a polycrystalline framework. The combination with the Rousselier porous plasticity model describes mixed fracture mechanisms: void growth and coalescence and intragranular fracture.

Numerical results are in good agreement with the experiments. They support the interaction of PLC with both plasticity and ductile fracture for the investigated material. This interaction would probably lead to unstable slant fracture in the analyses, but numerical problems have prevented this verification. The mesh size and mesh orientation effects in slant fracture also need further investigations.

References