Ductile fracture of AA6111 alloy including the effect of bake-hardening

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Abstract. The thermal cycle of paint baking for auto bodies alters the mechanical properties of aluminum alloys including, possibly, their fracture behavior. In this study, the plasticity and fracture of AA6111 sheet after a 30 min heating cycle at 180 °C is investigated. Uniaxial tension, plane-strain tension and disk compression experiments are performed to assess the plasticity of the material. The results are used to calibrate Yld20004-18p anisotropic yield function. An evolution of the yield locus with plastic deformation is observed. This is represented by evolving the exponent of the yield function, rather than the coefficients themselves. The post-necking hardening curve is identified by numerically simulating a notched-tensile test. The fracture locus is probed using notched-tension, center-hole, and shear experiments. In every case, digital image correlation (DIC) is used to acquire the surface strain fields. In parallel, finite element simulations of the fracture specimens are used to approximate the fracture strains, triaxiality, and Lode angle parameter. Yld2004-18p model shows good overall agreement with the experiments; thus, the fracture locus is probed with this model.

1. Introduction

From the micromechanical point of view, the ductile fracture at high stress triaxialities is represented by void interaction [1,2]. This is associated with three evolutionary steps: void nucleation, growth, and coalescence to void sheets, which eventually results in crack propagation. Certain modes of ductile fracture can be described by the influence of hydrostatic pressure and deviatoric stress state. The normalized forms of the stress states can be represented by the stress triaxiality, i.e., \( \eta = \frac{\sigma_m}{\bar{\sigma}} \) and Lode angle parameter, i.e., \( \tilde{\theta} = 1 - 6 \cdot \theta / \pi \), where \( \theta = \frac{1}{3} \cdot \frac{\text{acos}(2 \cdot \frac{J_3}{2 \bar{\sigma}^3})}{3} \) [3,4], where \( \sigma_m \) and \( \bar{\sigma} \) are mean and equivalent stresses, respectively, and \( J_3 \) is the third invariant of the deviatoric stress. However, it is almost impossible to obtain these parameters in experiments at the location and instance of fracture, because of the non-homogeneous deformation and fracture initiation from the mid-plane of the specimen. Instead, a hybrid approach for the FE simulation-experiment has been adopted to determine the local fracture parameters in ductile fracture research [5,6]. This requires careful plasticity modeling such as plastic anisotropy [7,8], strain-rate effect [9], and temperature dependency [10] for the investigated material.

In this study, the ductile fracture behavior of the AA6111 aluminium sheet is investigated based on the Yld2004-18p plasticity model [11]. The experiments are conducted in room temperature and the strain-rate effect is ignored as it is known to have a minor effect on the current material. The fracture experiments are designed to cover a wide range of triaxiality through the notched-tension, center-hole,
and shear specimens. Based on the experimental observation, the fracture envelope is visualized as the fracture strain with respect to the triaxiality and Lode angle parameter.

2. Plasticity characterization and yield function calibration

Aluminum auto-body components are subjected to a paint-bake cycle during assembly. This artificial aging process can induce mechanical property changes, including plasticity and fracture behavior, due to the thermal effect on the precipitation kinetics. In laboratory scale, this process is replicated by baking the specimens in an oven for 30 min at 180 °C followed by air-cooling.

The material plastic anisotropy is characterized through extensive experiments (Figure 1): 7 uniaxial tensions in every 15° from the RD (Figure 2 (a)), 3 plane-strain tensions in the RD, 45°, and TD (Figure 3) [12], and disk compression tests (Figure 2 (b)). The anisotropy is calculated with respect to the uniaxial tension in the RD, and the result is summarized in Table 1. Note that the anisotropy in the flow stresses is not significant, which is more obvious in the r-values. Based on the experiments, the Yld2004-18p and Swift–Voce combined (SV) hardening models parameters are calibrated, and the results are described in Figure 4 and Tables 2-3. Two different SV parameters are found for Yld2004-18p and von-Mises (VM) models.

**Figure 1.** Specimen geometry for plasticity (a)-(c) and fracture (e)-(h)

**Figure 2.** (a) Stress-strain curves of uniaxial tension tests and (b) \( r_h \) of disc compression tests
Figure 3. (a) Stress-strain curves of the plane-strain tension tests and (b) equivalent plastic strain dependent exponent of the yield function for Yld2004-18p

Figure 4. Plasticity characterization for (a) Yld2004-18p model and (b) hardening models

Table 1. Summary of mechanical properties

|                | E=70 [GPa] | Poisson’s ratio | ν =0.33 |
|----------------|------------|-----------------|--------|
| UT RD          | 1.000      | 0.988           | 0.978  |
| r-value        | 0.629      | 0.544           | 0.535  |
| UT RD 15°     | 1.073      | 1.067           | 1.078  |
| UT RD 30°     | 1.0967     | 1.1294          | 1.1089 |
| UT RD 45°     | 1.1294     | 1.1089          | 0.6011 |
| UT RD 60°     | 1.1089     | 0.6011          | 1.0388 |
| UT RD 75°     | 1.1089     | 0.6011          | 0.9931 |
| UT RD 90°     | 1.2160     | 0.6011          | 1.0051 |
| UT RD TD      | 0.7477     | 0.6823          | 0.9787 |

Table 2. Material parameters of Yld2004-18p model

| α₁  | α₂  | α₃  | α₄  | α₅  | α₆  | α₇  | α₈  | α₉  | α₁₀ | α₁₁ | α₁₂ | α₁₃ | α₁₄ | α₁₅ | α₁₆ | α₁₇ | α₁₈ |
|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| 1.0745 | 1.0967 | 1.1294 | 1.1089 | 0.6011 | 1.0388 | 0.9931 | 1.0051 | 1.2160 |
| 0.7477 | 0.7636 | 0.8425 | 0.7998 | 1.1103 | 1.0177 | 1.0042 | 0.9787 | 0.6823 |
3. Fracture characterization based on the hybrid approach

Apart from the plasticity characterization, the fracture behavior is also examined by two notched-tension (NT20 and NT6), center-hole (CH), and shear (SH) specimens (Figure 1(c)-(h)). The force-displacement curves and the corresponding local strain evolution captured by DIC from the surface are shown in Figure 5(a)-(d), and they are compared with the FE prediction by Yld2004-18p and VM models. The curves from the numerical simulations are plotted until the displacement corresponded to the measured displacement in the experiments at the onset of failure. Note that the SV model is calibrated by the uniaxial tension curve in the RD up to the uniform deformation and then, by the force-displacement curve of NT20 past the localization. Compared to VM, Yld2004-18p model shows good agreement with experiments, which means that Yld2004-18p model can describe the actual material behavior for the stress-strain state than VM. Using the hybrid method [5,7], the fracture strains with respect to the triaxiality and Lode angle parameter are determined by the Yld2004-18p model (Figure 6). Triaxiality near the theoretical plane-strain shows the lowest fracture strain level, as expected from sheet formability studies [13], while CH has the highest fracture resistance [7].

Table 3. Material parameters for Swift, Voce, and SV hardening models

| Model | Swift $\sigma = k_0 (\varepsilon_0 + \varepsilon_p)^n$ | Voce $\sigma = k_0 q \exp(-\beta \varepsilon_p)$ | SV $\sigma = W_a \sigma_s + (1 - W_a) \sigma_v$ |
|-------|---------------------------------|---------------------------------|---------------------------------|
|       | $k_0$ | $\varepsilon_0$ | $n$ | $k_0$ | $q$ | $\beta$ | $W_a$ | $\sigma_s$ | $\sigma_v$ |
| SV1   | 537.2 | 0.017 | 0.245 | 384.2 | 212.4 | 9.036 | 0.3 | Swift | Voce |
| SV2   | 531.7 | 0.019 | 0.241 | 352.5 | 177.5 | 11.06 | 0.4 | Swift | Voce |

Figure 5. Comparison of experiments with FE simulations for (a) NT20, (b) NT6, (c) CH, and (d) SH.
4. Conclusion
The ductile fracture of AA6111 sheet is studied based on the hybrid experimental-numerical approach. The material plasticity is characterized through uniaxial tension, plane-strain tension, and disk compression tests, and the ductile fracture is investigated by notched-tension, central-hole and shear tests. In the FEA, the Yld2004-18p model shows a good agreement with the experiments in the force-displacement and surface strain-displacement curves of fracture tests. This validates the performance of adopted models for the material property description. Based on the FEA, the final fracture locus is estimated as a vertex-shape fracture locus with a high fracture resistance near CH.

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