Identification and validation of constitutive model and fracture criterion for AlMgSi alloy with application to sheet forming

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Introduction
Background

• Rolled, heat treatable Al alloys are increasingly used for automotive skin sheets.
• These alloys obtain their preference due to the combination of good formability in solid solution and high strength in artificial aged conditions.
• Recent development has concentrated on the age hardening 6xxx series (AlMgSi–(Cu)) alloys.
• The present work focuses on the mechanical behaviour of the alloy AA6016 in temper T4
• This alloy is the preferred alloy in these applications within the European automotive industry
Objectives

- To characterize the AA6016-T4 material with respect to its constitutive response and fracture characteristics
- To validate the predictive capability of a shell-based modelling approach using a series of generic forming and formability tests

- The material model is aimed at design of automotive parts based on large-scale FE simulations → robustness and efficiency are important features together with accuracy
Alloy AA6016 – temper T4

• Nominal chemical composition in wt%:
  – Si: 1.0–1.5, Fe: 0.5, Cu: 0.2, Mn: 0.2, Mg: 0.25–0.6, Cr: 0.10, Zn: 0.20, Ti: 0.15, Al: balance.

• The aluminium alloy was produced as 1 mm thick sheet.

• The material was hot and cold rolled to final gauge, solution heat treated in a continuous annealing line and quenched.

• During room temperature storage between quenching and testing, the material will undergo natural ageing, which affects the strength and work hardening of the material.
Constitutive model and fracture criterion
Elastic-plastic model

- Anisotropic yield criterion with high-exponent
- Associated flow rule
- Nonlinear isotropic hardening
- Uncoupled fracture criterion

- Corotational stress formulation
  - To fulfil principle of material-frame indifference
- Non-local regularization
  - To improve mesh convergence in simulations of plastic instability and fracture with shell elements
- Element erosion for crack propagation

- High-exponent yield criterion:
  \[ |\sigma_1'|^m + |\sigma_2'|^m + |\sigma_1'' - \sigma_2''|^m = 2\sigma_y^m \]

- Principal stresses based on linear transformations of the stress tensor to account for plastic anisotropy:
  \[
  \begin{align*}
  \sigma_1' &= \frac{a_8 \cdot \sigma_x + a_1 \cdot \sigma_y}{2} \pm \sqrt{\left(\frac{a_2 \cdot \sigma_x - a_3 \cdot \sigma_y}{2}\right)^2 + \left(a_4 \sigma_{xy}\right)^2} \\
  \sigma_2' &= \frac{\sigma_x + \sigma_y}{2} \pm \sqrt{\left(\frac{a_5 \cdot \sigma_x - a_6 \cdot \sigma_y}{2}\right)^2 + \left(a_7 \sigma_{xy}\right)^2}
  \end{align*}
  \]
Yield surfaces for Al alloys

Equi-axed, recrystallized microstructure with strong cube texture

Fibrous, non-recrystallized microstructure with strong fibre texture
Extended Voce work-hardening rule

• Flow stress:
  \[ \sigma_Y = \sigma_0 + R(\varepsilon) \]

• Evolution rule for the isotropic hardening variable:
  \[ dR = H_R(\varepsilon) \cdot d\varepsilon \]

• Hardening modulus:
  \[ H_R(\varepsilon) = \max \left\{ \sum_{i=1}^{2} C_{Ri} Q_{Ri} \exp(-C_{Ri} \varepsilon), H_{R,\text{min}} \right\} \]
  - Voce-type hardening rule for small to medium strains and linear hardening rule for large strains
Cockcroft-Latham criterion

\[ \sigma_\alpha = \frac{F}{A} \]

\[ W = \int_0^{\varepsilon} \max (\sigma_1, 0) d\bar{\varepsilon} \]

\[ = \int_0^{\varepsilon_a} \sigma_\alpha d\varepsilon_a \leq W_c \]

\[ \varepsilon_a = -\ln \frac{A}{A_0} \]

• Ductile damage criterion (Cockcroft and Latham, 1967):

\[ W = \int_0^{\bar{\varepsilon}} \langle \sigma_1 \rangle d\bar{\varepsilon} > W_c \quad \Rightarrow \quad \sigma = 0 \]
Parameter identification
Material parameters

- Elastic constants: $E, \nu$
- Reference yield strength: $\sigma_0$
- Isotropic hardening: $Q_{R1}, Q_{R2}, C_{R1}, H_{R,\text{min}}$
- Yield criterion: $m, a_1, a_2, \ldots, a_8$
- Fracture criterion: $W_C$
Identification procedure

- Elastic constants
  - $E, \nu$
  - $\sigma_0$
  - $Q_{R1}, C_{R1}, Q_{R2}, C_{R_{min}}$

- Yield criterion
  - $a_1, a_2, \ldots, a_8, m$

- Fracture criterion + large-strain hardening
  - $W_C, H_{R_{min}}$
Hybrid method

- Tensile tests in three directions
  - Three yield stresses
  - Three strain ratios

- Crystal plasticity calculations
  - Yield stress and strain ratio in equi-biaxial tension

- Homogenization scheme:
  - VPSC = Visco Plastic Self Consistent
Tensile data + ODF

Fitted work-hardening curve (extended Voce rule)

ODF displays a quite sharp cube texture together with weak intensities of the component
Yield locus

Yield locus obtained from entirely VPSC calculations (red dots)
Yield locus fitted to VPSC data (dashed line)
Yield locus determined by the hybrid method (solid line)
Directional variation of flow stress ratio and plastic strain ratio with yield function determined entirely from VPSC data (solid line) and by the hybrid method (dashed line). Experimental data are given by blue asterisks.
Shear test (1)

Experimental results and simulations with two identification methods of the yield criterion and three different minimum hardening rate.
Shear test (2)

Experimental results and simulations with coarse and refined mesh without non-local shell thinning and non-local shell thinning and fracture criterion activated.
Shear test (3)

Experimental and predicted fracture modes using the CL fracture criterion, non-local regularization and element erosion.
Validation study
FE simulations

• Nonlinear FE code LS-DYNA
• Explicit solver
• Mass scaling
• Corotational shell elements
• Non-local regularization of shell thinning (averaging radius about half the shell thickness)
• Element erosion
“Plane-strain” tension

Failure occurred by local necking in tests and simulation.
Plane-strain bending

Failure occurred by ductile fracture in tests and simulation.
Bulge test (1)
Bulge test (2)

Failure occurs by ductile fracture in tests and simulation.

Maximum bulge height without failure was 17 mm and 16 mm in tests and simulation, respectively.
Square-cup drawing (1)
Square-cup drawing (2)

Maximum blank diameter without failure was about 79 mm in tests and simulation.
Square-cup drawing (3)

Experimental and predicted principal strains along the 0°, 45° and 90° intersections.
Nakajima and Marciniak–Kuczynski formability tests
Fractured samples from Nakajima tests
Forming limit diagram

Patch of finite elements with thickness variations + nonlocal instability criterion and CL fracture criterion
Summary

• Modelling framework:
  – Elastic-plastic model with anisotropic yield criterion, associated flow rule and nonlinear isotropic hardening
  – Non-local regularization to introduce a length scale and avoid spurious localization
  – One-parameter fracture model for ductile fracture

• Parameter identification:
  – Mechanical tests (uniaxial tension, shear, ...)
  – Crystal plasticity calculations (rate-dependent Taylor model or VPSC)

• Validation study:
  – Notched tension tests
  – Three-point bending tests
  – Bulge tests
  – Square-cup drawing tests
  – Formability tests

Current activities:
• Extending constitutive model to account for DSA/PLC
• Conducting the validation study for 5xxx alloy